CARBON DIOXIDE CLEANING

GOING THROUGH PHASES

A Panel discussion of CO_2 Cleaning Technology

A panel recently convened at CleanTech '99 to examine the current state of carbon dioxide (CO_2)-based cleaning technology. Panel members discussed the typical applications appropriate to each system, the benefits of CO_2-based systems over other cleaning techniques, and the complexities of system operation and maintenance. Panelists also reviewed performance levels, relative costs, and specific application strategies.

Liquid Carbon Dioxide Systems

Panelist: Liz Hill
Research Triangle Institute

Liquid carbon dioxide (LCO_2) technology is one that can be classified as a "maturing" technology. At high pressures, CO_2 takes on a liquid form that is sustainable at, above, and below room temperatures (see **Figure 1,** page 28).

The equipment used in LCO_2 applications includes a vessel by which a constant pressure is maintained. Some form of agitation (eg, spinning, spraying, ultrasonics, etc) is generally required as well. To recycle and clean LCO_2 it must be transferred to another chamber, where pressure is released, allowing the CO_2 to expand back to a gas. This leaves behind only the contaminants that were removed from the parts, which are collected for disposal or re-use. The CO_2 is then returned and repressurized in the cleaning chamber. In many systems, such additives as organic solvents and surfactants are mixed with the LCO_2 improve performance.

Pure LCO_2 systems do not require any permits, but users must be aware that some additives, like certain organic solvents, may have permit issues. No water or sewer connections are required for these systems, and waste is collected at the recycling point. Carbon dioxide is a greenhouse gas, but it is not a net addition because it is gathered from other processes. Carbon dioxide is not an ozone-depleting compound (ODC) nor is it considered a volatile organic compound (VOC); it is nonflammable and is not considered a hazardous air pollutant (HAP).

Unlike many traditional systems that perform to limitations set by bath life and the effectiveness of the cleaning agent, LCO_2 systems feature cleaning cycles that employ fresh, clean CO_2 introduced from a recycling loop. It is a batch process, and cycle times can be long-10 to 25 minutes, depending on the size of the cleaning vessel, the size of the pumps, the nature of the contaminants, and the number of required cycles (ie, washes and rinses).

Efficacy is specific to the contaminants being addressed: however, pretreatment or additives (eg, solvents or surfactants) improve the range of cleaning. Some contaminants that respond well to LCO_2 removal include: light oils, hydrocarbons, machining fluids, and chips (due to agitation).

To date. reliable submicron particle removal (to this speaker's knowledge) has not yet been achieved by LCO_2 processes, but this limitation is likely a temporary one. Heavy hydrocarbon greases do not respond well; however, additives can remedy this shortcoming. Salts and many other inorganic soils continue to present a challenge to LCO_2 systems. Paint. rust, and carbon residues will likely never be ideal soils for this type of technology.

Liquid CO_2 systems have demonstrated success over a range of cleaning applications, including:

- Fiber optics
- Machined metal parts
- Hydrocarbon residues from electrical components
- Rag cleaning (even paper)
- Dry cleaning

In LCO_2 systems, the dimensions of the cleaning vessel will dictate the type of parts that can be cleaned efficiently. Parts must also be compatible with the high pressures of the cleaning chamber. Condensation is a possibility, and parts must be warmed properly before removal from the chamber to prevent this. Obviously, this step can increase cycle time. CO_2 has been known to strip certain plasticizers and penetrate some elastomers. When the pressure is dropped for removal. bubbles can form inside the elastomer and cause deformities.

Operation of LCO_2 equipment is fairly simple due to its high level of automation. Health and

BASED ON A PANEL PRESENTATION AT CleanTech'99 International Cleaning Technology Exposition

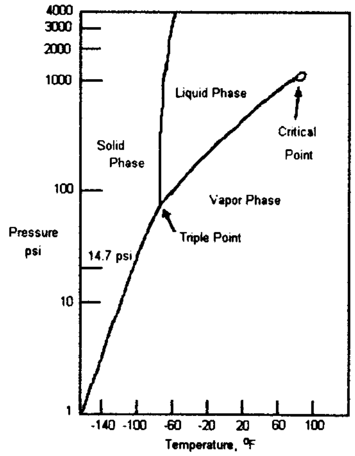

Figure 1. A phase diagram of carbon dioxide.

safety concerns include proper instruction in operating pressurized systems, close monitoring of CO_2 levels in the air, attention to possible overexposure to cold gas and liquid (resulting in possible skin bums), and temperature of parts being removed from the system.

Prices range from $100,000 and higher, with the CO_2 running $0.15 to $0.20 per gallon for bulk and about $0.85 per gallon in bottles.

LCO_2 systems have proven very successful in cleaning a variety of substrates. Even an intricate material like aluminum honeycomb has been cleaned down to practical standards without evidence of substrate damage.

Results also were favorable when the technology was employed on brass hydraulic filters from a helicopter; the filters were covered with a gritty/oily substance **(Figure 2).** Prior to investigating CO_2 technologies, the manufacturer originally cleaned these parts by soaking them for 24 hours in a hydrocarbon mixture, scrubbing by hand, soaking them for another 24 hours, and scrubbing again. With the new LCO_2 process, the parts were first soaked in a warm hydrocarbon oil/surfactant mixture for about 10 minutes, hand scrubbed, and then cleaned in LCO_2 for 20 minutes. This turned a P-day process into a 45-minute task.

The technique offers manufacturers a way to minimize waste streams, clean parts that are incompatible with water, and eliminate hazardous cleaning agents.

Cleaning With Supercritical CO_2

Panelist: *Yale West, Applied Separations*

Supercritical fluid is a very unique state of matter, almost a fourth state per se. It essentially refers to the point where the liquid and vapor phases become one (this is unlike the commonly held theory that a vapor phase becomes so dense that it acts like a liquid). As such, the fluid has the penetrating power of a gas, but the cleaning ability of a liquid.

As **Figure 1** shows, supercritical fluid begins at 73 atm and 31°C. Supercritical CO_2 ($SCCO_2$) possesses physical characteristics that allow it to relate with other more familiar substances. One of the attractive features of $SCCO_2$ is its reputation as a 'tunable" solvent-this is, as you change the pressure of the system (and thus the density of the $SCCO_2$ you change its solvating characteristics. In principle, $SCCO_2$ systems work in much the same manner as those for LCO_2

All of the environmental and safety issues that go along with LCO_2 apply to $SCCO_2$ The performance benefits of replacing traditional cleaning systems with $SCCO_2$ are also similar to those of LCO_2 Some of the more significant beneifts include the absence of cleaning agent residue, no required drying step, and high-temperature operation, which expedites solvency action. Applications for the technology are concentrated mostly in smaller, niche markets.

$SCCO_2$ is actually quite effective at removing particulate matter. Research has been carried out on integrated circuit wafers, where a concept dubbed "turbulent flow" has proved effective in removing micron to sub-micron particles. This is a significant benefit given that $SCCO_2$ will remove any organic residue helping the particles to adhere to the surface of the substrate being cleaned. Lower temperatures facilitate removal of smaller particles due to the greater density of the fluid at these temperatures.

For one manufacturer, an $SCCO_2$ system solved the challenging task of cleaning silicon wafers. The challenge came in cleaning the wafers after they were cut from the parent ingot with a wire saw. Contamination resulted from a machine containing silicon carbide, which was used as the abrasive to cut the individual wafers. The cut wafers had a tendency to lean against one another, and the oil at that contact point was difficult to remove again, at least with traditional cleaning agents. Correction of the wafer positions was not possible because they had to remain glued to a glass substrate from the point of cutting through cleaning.

Primary testing demonstrated immediate success and was accomplished by sandwiching two wafers with oil between them and then attempting to clean them with

CO_2 SUPPLY ISSUES

Carbon dioxide (CO_2) is recovered from natural gas wells and, as a by-product, from industrial processes such as refining and fertilizer production. The raw CO_2 gas is collected by industrial gas companies and cleaned up, or purified, at a CO_2 production facility before becoming available for resale to customers for secondary uses.

Standard commercial grade CO_2 is provided at 99.9% purity. The nature of the impurities remaining in the CO_2 vary from plant source to plant source and may include parts per million (ppm) or parts per billion (ppb) levels of contaminants (eg, moisture, sulfur, and light or heavy hydrocarbons). Distribution of the liquid CO_2 in trailers or railcars may also introduce contaminants or variability in CO_2 purity at ppm levels.

Commercial grade CO_2 is a very pure product. Customers that require purities exceeding 99.9% may need on-site purification systems to ensure consistent purity and to eliminate purity variations from one delivery to the next. For low-volume use applications, high-purity CO_2 is readily available in high-pressure cylinders or manifolded, multipack cylinders. However, newer applications requiring high-purity liquid CO_2 in the thousands-of-pounds-per-day (or higher) capacity require bulk supplies of standard, commercial-grade CO_2 combined with on-site purification of the product prior to utilization. The on-site purification step is an economical way to achieve reliable, consistent high-purity standards.

Reliability and consistency of pressure, flow, and temperature of CO_2 are important to many sub- and supercritical CO_2 applications. A small change in any of these parameters can result in small or potentially large variations in the end-use application. On-site pressurization systems might also be required to deliver CO_2 to precise specifications necessary for optimal performance of the application equipment. CO_2 snow cleaning and supercritical scrubbing are especially sensitive to variations in purity and pressure and therefore require on-site systems to achieve reliable performance.

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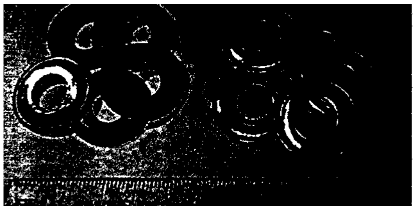

Figure 2. Helicopter hydraulic filters before and after cleaning with liquid carbon dioxide.

$SCCO_2$ Full implementation of an $SCCO_2$ system followed, and the wafer cleaning process showed considerably improved results.

$SCCO_2$ systems can be either fully manual or automatic. Another use for $SCCO_2$ is as a solvent/carrier for surface treatments.

Snow CO, Cleaning

Panelist: *Dr. Robert Sherman, Applied Surface Technologies*

Snow CO_2 (SCO_2) is generated by expanding liquid or gaseous CO, through an orifice. It removes both organic soils and particles as small as several hundred angstroms (1.0 X 10^{10} meters). It will not, however, remove substances that are chemically bonded to a surface (eg, paint, epoxies, evaporated metals, rust. etc). SCO_2 is nontoxic and nonflammable: it is not listed as an ODC or a VOC. To safely apply the technology, users should avoid skin contact, consider room oxygen displacement, and be aware of excessive CO, buildup in the room.

According to the phase diagram **(Figure 1).** SCO_2 formation takes place along the phase boundary lines separating gas, liquid, and solid. The thermodynamics of snow formation should be a constant enthalpy process. The expansion within and after the orifice leads to lower pressures and temperatures, creating a gaseous and solid-phase mix that can travel at high velocities.

Exposing a CO, gas source to the dropping pressure inside an orifice causes fluid droplets to nucleate: as a result, the percentage of liquid increases. The liquid converts to solid at the interface between the liquid-gas and gas-solid regions (near 80 psi), and this yields about 6% dry ice.

Beginning with a liquid CO_2 source, the pressure drop in the orifice generates gas bubbles. The percentage of gas increases until the gas-solid boundary is met. Here, the remaining liquid is transformed into solid, yielding about 45% dry ice.

Gas-fed systems tend to be cleaner (it is easier to filter a gas than a liquid), have less heavy hydrocarbon

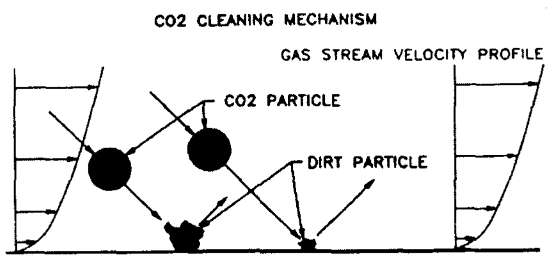

Figure 3. Particle removal by carbon dioxide snow based on momentum transfer.

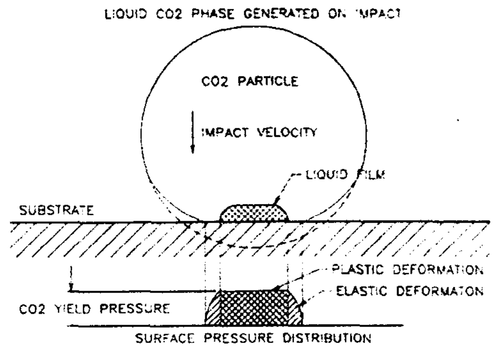

Figure 4. Removal of organic contaminants by solid-state carbon dioxide per the theory of liquid-phase solvency.

contamination, and have less consumption per unit of time. Liquid-fed systems produce more snow, allow for faster cleaning, but involve a higher consumption rate. The source state, as well as orifice and nozzle designs, will dictate the dry ice size, velocity, and percentage formed.

The actual cleaning mechanism of SCO_2 is not fully understood. The most popular theory is that the high exit velocity from the nozzle leads to momentum transfer from the solid CO_2 particles to the surface contamination, which essentially "knocks it off' the substrate. The aerodynamic drag force of the CO_2 gas stream adds to this removal effort. Organic material is removed presumably by a liquid CO_2 phase that can form on the surface as the surface pressures increase between the dry ice and substrate. **Figure** 3 demonstrates the particle removal mechanism following the momentum-transfer concept, while **Figure** 4 illustrates organic removal based on the theory of liquid-phase solvent removal.

An additional concept centers around the suggestion that particle removal is accomplished by a surface liquid phase. This process might be similar to high-pressure solvent spray methods. Furthermore, there is strong evidence that SCO_2 may freeze-fracture certain organic layers from substrates.

The basic SCO_2 cleaning setup is simple and includes: a source of CO_2 (in a cylinder); a hose to deliver the CO_2 from the cylinder to the on/off control device (ie, a valve or handgun); and a nozzle attached to or within the handgun.

SCO_2 cleaning technology has proven itself successful across many industries, including:

- Optics
- Disk drives
- Microelectronics
- Precision parts and assemblies
- Instrumentation

An example of a successful application is shown in **Figure 5** (page 33), which shows a silicon wafer that was intentionally scratched to generate particulate contamination in the micron-submicron range. After SCO_2 cleaning, all particles were removed.

Pellet and Supersonic Snow CO,

Panelist: *Jeff Sloan.*
Va-Tran Systems

Snow and pellet CO_2 $(PC0_2)$ cleaning is driven largely by kinetic energy which can be defined by the equation $E = \frac{1}{2}mvz^{2}$ (where E = kinetic energy, m = mass, and v = velocity). The energy that is imparted by these CO_2 cleaning mechanisms can thus be increased by increasing either the mass of the dry ice particle or the velocity at which it is delivered.

Pellet CO_2 cleaning is based on the concept of increasing mass. The primary dynamic of this mechanism is an impact/flushing action. The shock wave-or mass-energy coefficient of the initial impact-dislodges or fractures contaminants. The near instantaneous transformation of the pellets to a gas then increases its volume over 900 times to aerodynamically flush contaminants away. Supplementally, the thermal effects of the

TABLE: CO_2 SNOW CLEANING—ADVANTAGES AND DISADVANTAGES

The benefits

The ability to clean online and in-place because the CO_2 will not damage or contaminate working machinery or equipment. This prevents long and costly disassembly and reassembly steps prior to and after cleaning.

No rinsing or drying (provided moisture control is taken into account)

No additional waste other than what was cleaned from the part

High levels of energy can be used to clean without damaging surfaces

Cleaning systems are mobile, which again prevents long and costly disassembly and reassembly steps prior to and after cleaning.

Like all processes, there are limitations

Cleaning is line-of-sight, so blind holes and spaces are difficult if not impossible to clean

Significant compressed air is required to operate the system

Noise levels are ≥ 100 db

Need to address where the soil goes

cold pellets can help embrittle films, making them easier-to break off. The solvent characteristics of CO_2 can provide additional help in removing some hydrocarbons.

To perform PCO_z cleaning, a source of dry ice pellets is required. Unlike $SC0_2$. pellets must be generated prior to reaching the delivery nozzle. This can be accomplished via a pelletizer or some device that chips or grates blocks of dry ice (see **Figure 6,** page 34). Given the larger size of pelletized dry ice, it is often most efficient at removing thick contaminants faster, while the chipped pellets offer a gentler mode of cleaning for more delicate substrates.

The pellets are driven through nozzles by high-pressure air, which can be accomplished via two methods:

A *single-hose nozzle.* In this method, a high-pressure stream of air passes by an auger, which feeds pellets into it and thus generates a sonic velocity stream of dry ice pellets. It is slightly more aggressive, has lower noise levels, and delivers less dry ice per cubic foot than the dual hose system. The lower level of dry ice is due to abrasive loss inside the hose.

A dual-hose *nozzle.* In this method, dry ice is delivered using an eduction system in which the air passes by a Venturi and sucks dry ice pellets from another hose into its stream. This system uses less source dry ice, but delivers more to the surface. It also allows the user to use a heated source of air to minimize cooling effects on the surface being cleaned.

The **Table** lists some advantages that PCO_z blasting offers over traditional [grit, sand, etc) blasting as well as some limitations of the technology. Typical applications for PCO_2 are primarily industrial in nature. They include:

- Molds (tires, foundry, plastics)
- Decontamination (nuclear, heavy metals)
- "Hot" systems (ie, switchgears, insulators)
- Overhaul (motors, jet engines, robots)

The cost of equipment has a fairly wide range, from $8000 to $35,000 for portable units to $90,000 to $250,000 for fixed, automated ones. Average operational costs run from $0.50 to $1.00 per minute and include the cost of dry ice and compressed air.

Supersonic CO_2 ($SSCO_2$) blasting demonstrates higher levels of kinetic energy by increasing the velocity parameter of the kinetic energy equation. This is accomplished by velocities up to Mach 3.5 (2100 miles/hr or 938.8 meters/sec). The mass of the dry ice particles is very small, from 0.1 to 1.0 microns. These small, highly energetic particles are capable of deep penetration into layers of contamination without damaging substrate.

Highly compressed air acts as the 'accelerator" for the system and pushes an air/CO_2 mixture through an orifice to produce snow. Applications for this technology include small parts cleaning, graffiti removal, and layer selective coatings removal.

Questions From the Floor

Ql: *What is the best technology involving CO_2 for cleaning sub-micron particles (0.2 µm)? I am involved with precision cleaning of disk drive components and would like to explore CO, in greater detail?*

Hill: An effective technology to remove O.2-micron particles is snow. Both high-pressure and low-pressure snow can be used to remove particles. You will need to verify that the CO, source and gun do not deposit organics on the parts when you clean them, and protect the parts from moisture during cleaning. Test the effect of the process on static-sensitive parts.

West: Turbulent-flow $SCCO_2$ has been demonstrated to be effective here. It can dissolve and remove organic contaminants and thus eliminate adhesion of particles. Also. remember that due to its nature, it will be effective in blind holes

Sherman: SCO_2 is highly effective at removing submicron particulates from surfaces. The general limit expressed by the manufacturers of CO, snow cleaning equipment is generally about 0.1 microns. but new data show particle removal down to 0.03 microns. The addition of the solid dry-ice phase to the flowing gas has made momentum transfer an effective means for overcoming strong particulate surface adhesion forces.

Sloan: Snow cleaning is very effective at removing submicron particles. It may be helpful to use ionized air or nitrogen to help overcome the electrostatic attraction of the particles to the surface.

Q2: Please comment on the removal of trace metal impurities (eg, Al, Fe, Na, K) from ceramic surfaces (eg, Al_2 0_3, Si, glass) by any of these systems. Please recommend a feasible approach.

Hill: The phrasing of the question suggests that the problem is molecular contamination by metallic species, not particles or organic films containing metallic elements. Liquid and supercritical CO, will not remove metallic impurities bonded to a substrate. You need chemical dissolution of molecular traces of these metals. If the metals are part of particles. snow may work.

West: With the appropriate modifiers, like chelating agents, $SCCO_2$ can be very effective here. Successful applications include environmental extraction of metals from soil samples for contamination analysis and, in mining, the recovery of precious metals from waste slag.

Sherman: If these contaminants are particulate-based contamination, CO_2 snow cleaning should remove them. Recent work has shown particle removal from several ceramics such as sapphire, MgO. and a thermally sensitive substrate. Testing is necessary.

Sloan: Removal of trace metal impurities from ceramic substrates is not likely using dry ice blasting, as the surface is not directly modified.

Q3: What types of additives are being used in LCO_2 systems to achieve the following?

A. Improve ability of solvent to carry insoluble soils away from the substrate

B. Increase the range of nonpolar soils that are dissolved

C. Form oil-in-water emulsions

Hill: I know of nothing going on about item c. A and b are being pursued by several companies involved in snow, liquid, and supercritical CO_2 Dr. DeSimone is working on fluorinated surfactants, mainly for laundry applications. He has published some work on cleaning metal coupons with LCO_2 and surfactants. Some work has been done using cosolvents, both in snow and L- or $SCCO_2$.

West: A. There are two modes of processing with $SCCO_2$ static and dynamic. When the process is dynamic, the $SCCO_2$ is continuously pumped through the cleaning vessel and collected in the separator. This continuous flow is what enables removal of insoluble contaminants. If the contaminant is merely insoluble in $SCCO_2$ the addition of an appropriate modifier may provide a solution.

B. $SCCO_2$ is nonpolar. so nonpolar soils should not be a problem. For polar ones, the addition of a small percentage of polar cosolvent or a modifier, such as methanol, has proven successful.

C. Due to its nonpolar nature, $SCCO_2$ will form a water-in-oil emulsion. There are suitable surfactants for accomplishing this.

Q4: How does one generate ultrasonic "bubbles" in an LCO_2 vessel under 1000 psi?

Hill: As long as the pressure and temperature maintain the CO, in the liquid state, cavitation is possible. Cavitation has been verified using low frequency ultrasonics. Los Alamos National Lab did some of the early work in cavitating LCO_2 .

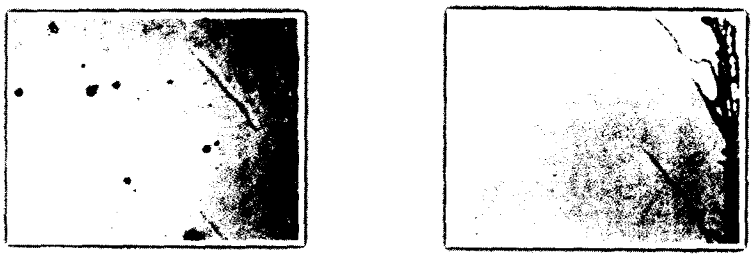

Figure 8. Photomicrograph of a silicone wafer demonstrating removal of micron-level particulate by carbon dioxide snow (A, prior to cleaning; B, postcleaning).

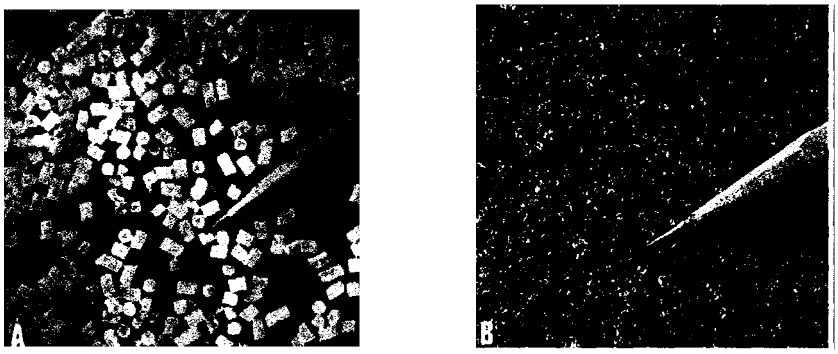

Figure 6. Dry ice pellets produced by a pelletizer (A) and created via a chipping process (6).

Q5: How is *turbulent flow achieved in the vessel? How is redeposition prevented? How are particulates transferred from the cleaning vessel to the depressurization tank; would they not tend to accumulate?*

West: First, designing or specifying the appropriate pump to achieve the flow velocities (200-1000 cm/sec) is required. Second, designing or specifying the flow pattern or path will determine the level of turbulence in the flow. Redeposition is prevented because dynamic flow of $SCCO_2$ deposits contamination in the separator vessel and returns clean to the cleaning vessel. Particulates only accumulate in the separator, from which they are removed periodically.

Q6: Could dry-ice blasting remove aluminum "solder" from tool steel molds? In an aluminum die-casting operation, the aluminum will build up on mold surfaces through mechanical bonding to mold imperfections and microcracks. Would there be enough momentum or thermal cracking to remove solid aluminum without damaging the tooling?

Sloan: Dry-ice blasting will not remove the metal-metal adhesion described here. It will remove the old mold release so that more can be applied to the mold, however.

Q7: Many potential end-users feel hindered by the initial cost of carbon dioxide systems. Could you please address this concern and also discuss maintenance costs compared to traditional cleaning methods?

West: For $SCCO_2$ capital costs can be a concern, but operating costs are usually significantly lower than other processes due to no energy input to isolate the contaminants from the cleaning fluid. Maintenance costs are dependent on level of automation (the more automated a system is, the higher the maintenance costs) and the design and construction of the system (build a robust system, maintenance costs will be low).

Sherman: Costs for CO_2 snow systems can start at about $1,600 and about $10,000 for manual pellet systems. The LCO_2 and $SCCO_2$ systems are much more expensive because of the high-pressure design requirements. As Jeff said, automated pellet systems cost above $30,000 and can easily go higher. Automation for nozzle or part movements can increase costs. Try snow cleaning first if there is a chance of it working.

Sloan: Dry-ice snow is a low-cost alternative. A number of entry-level systems exist at a price level below $2000. Dry-ice blasting systems have many applications in the sub-$10,000 price range, and the maintenance costs of both of these alternatives is very low.

Q8: I have heard that CO, is a very time-consuming process compared to traditional aqueous and solvent cleaning. 1s that so?

Hill: I have seen that aqueous is slower than snow but faster than LCO_2 or $SCCO_2$ mainly because of the time required to pressurize and depressurize the latter systems.

West: $SCCO_2$ for precision cleaning is a process to be used when other processes don't work. If it is the only process that works, processing time is probably not going to be an issue. Drawing from other $SCCO_2$ applications, one of the major advantages of using $SCCO_2$ is that it is a faster process because of its low viscosity, variable density. and higher diffusivity.

Sherman: This question must be examined for each method. With CO_2 snow cleaning, part size is a determining factor in cleaning time. For small parts, CO, snow can be quicker than solvent or ultrasonic cleaning; a simple, fast on-off cycle will work if the part is supported and amenable to an in-line process. For larger parts, clearing times per part can be comparable for in-line individual situations. Eventually, part size can dictate the need for the aqueous cleaning methods unless there are special circumstances for one-time parts of unique geometry.

Q9: How do you determine which type of CO_2 (liquid, snow, etc) is right for your application?

Hill: Read the available literature and talk to manufacturers. Before buying any system, watch parts being cleaned in it. Very roughly. pellets are good for tightly adhered gross surface contamination, like rust and carbon. Snow is good for loosely bound particles and some organics. LCO_2 and $SCCO_2$ are good for some organics.

West: Experimentation!

Sherman: Understand the nature of your contamination and test. If particulate or thin organic layers, CO_2 snow cleaning should be considered, especially when one part at a time can be cleaned. If overlayer removal is needed for parts that can survive the pellet impact, then pellet systems are considered. For greases, oils, batch processing situations, LCO_2 has initial consideration factors, while smaller parts and special removal needs can be addressed by $SCCO_2$. **PC**

About the Panelists

Liz Hill is senior research engineer at Research Triangle Institute, Research Triangle Park, NC.

Yale West is national sales manager at Applied Separations, Allentown. Pa.

Dr. Robert Sherman is head of Applied Surface Technologies, New Providence, NJ.

Jeff Sloan is director of engineering at VA-Tran Systems, Chula Vista, Calif.

Suggested Reading

Jackson J, Carver B. Today's forecast: it looks like snow. *Precision Cleaning.* May 1999: 17-29.

Jackson J, Carver B. Liquid CO, immersion cleaning: the user's point of view. Parts *Cleaning.* April 1999: **32-37.**

Editor's Note: For a comprehensive list of vendors who specialize in CO,-based technologies, visit the Knowledge Base of www.PrecisionCleaningWeb.com and select such Product Categories as Liquid Carbon Dioxide, Carbon Dioxide Pellets, Carbon Dioxide Snow, and Supercritical Carbon Dioxide.

New EAP Member

Not only did Dr. Robert Sherman serve on this CO, panel, he has now become a member of the *Precision Cleaning* Editorial Advisory Panel. The author of over 30 papers and holder of several patents, Dr. Sherman obtained a BS in Physics from The Cooper Union and an MS and PhD in Material Science from the University of Illinois.