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Abstract

Many advanced assemblies require high-volume and cost-effective selective cleaning during various stages of assembly or rework operations. Due to component compatibility problems and drying challenges, partially assembled devices cannot be immersed in or sprayed with aqueous cleaners or solvents. Newer dry cleaning techniques such as carbon dioxide (CO₂) aerosol spray cleaning processes (snow cleaning) have proven to be challenging to implement in automated high-volume manufacturing operations. Issues associated with conventional snow cleaning include high costs of operation, lack of process consistency, ineffective controls, and the requirements for a supply of high-purity liquid CO₂.

Advanced CO₂ composite spray [CO₂(solid)-compressed dry air (CDA)(gas)] cleaning is an effective alternative to traditional spray and immersion cleaning processes and to conventional snow cleaning for selectively removing contaminants and films from partially assembled hard disk drive (HDD) components during the remanufacturing or rework process. CO₂ consumption is reduced using a composite spray, while spray cleaning control and performance is improved. CO₂ composite spray cleaning performance is dependent on the position, speed, and motions of the spray applicator, which are matched to comply with HDD factory output. Stored spray cleaning programs deliver precise cleaning seven days a week, 24 hours per day, with uptimes exceeding 99.9% over a 6-month period. Monitoring and controlling composite spray cleaning process parameters including spray pressure and composition, scanning speed, and pallet/part identification are done automatically. Operator interaction is limited to loading and unloading pallets for continuous system operation.

KEYWORDS

HDD, rework, CO₂, cleaning, particle, robotics

INTRODUCTION

During the hard disk drive (HDD) manufacturing process, a small percentage of the production fails in the testing process, typically because of a problem associated with the head suspension assembly (HSA) or the disks (media). The failed HDDs can be torn down and the defective parts can be replaced; the rebuilt drives will then pass rigorous testing protocols.

The motor-base assembly (MBA), cover, and voice coil magnet (VCM) assembly can be reused, but during the disassembly process particle contamination is generated by the removal of the assembly screws. It has been demonstrated that if these parts are not precision cleaned prior to reassembly, rework yields and long-term reliability of the HDD can be adversely affected. This contamination-performance relationship is well known and understood by the HDD manufacturing industry.¹

The MBAs have an oil-filled fluid dynamic motor bearing that cannot be cleaned by immersion in either an aqueous or solvent cleaning system. Filters attached to the covers would have to be removed and replaced after aqueous or solvent cleaning and drying operations. The VCMs can be cleaned in an aqueous or solvent cleaning system, but the potential exposure to the transfer of magnet particles to other parts would drive the need for dedicated VCM cleaning systems. This prospect is difficult to cost-justify based on the number of parts to be cleaned. Therefore, a dry cleaning system is mandatory or highly desirable for these types of complex parts.

CO₂ snow cleaning has been commercialized over the past 20 years as a process for various cleaning applications. Properly designed systems can be effective for cleaning HDD parts that cannot or should not be cleaned by liquid immersion cleaning systems.² However, in HDD manufacturing, cost is always a prime concern; for an automated dry cleaning system to be acceptable, the system has to have high reliability with 24/7 usage and high throughput and excellent cleaning performance at a reasonable cost. This combination has proven to be a challenge for conventional snow cleaning processes.

Advanced CO₂ composite spray cleaning addresses the drawbacks and limitations of conventional snow spray cleaning, affording several spray cleaning process control and performance advantages—cleaning agent conservation and control, spray impact energy control, and easier adaptability to automation equipment and processes.

ADVANCED CO₂ COMPOSITE SPRAYS

A variety of CO₂ spray nozzles and delivery schemes have been developed for generating and delivering a high-velocity cleaning spray. The overall function of these nozzles is to generate and deliver a coherent and concentrated two-phase flow. The mechanical action of a gas-solid aerosol spray is effective for removing unwanted substances such as thin films and particles from critical surfaces. Such cleaning sprays have an ability to overcome boundary layer adhesion forces that predominate at the microscopic level.

Conventional cryogenic spray cleaning processes have traditionally employed supersonic DeLaval-type (convergent-divergent) spray nozzles. The main disadvantage of DeLaval cryogenic spray nozzles is an unbalancing effect at the nozzle exit of the fluid stream. As shown in Figure 1, the surrounding fluid (ambient atmosphere) tends to drag the nozzle fluid stream, causing the flow stream to diverge rapidly upon discharge from the nozzle exit. This action causes the liquid droplets or sublimable solid particles to expand quickly, resulting in a significant loss of cleaning agent (solid particles) through plume expansion or the production of numerous small solid particles, which generally requires the spray nozzle to be placed in close proximity to a substrate surface to be effective. DeLaval CO₂ spray nozzles produce a two-phase aerosol [CO₂(gas)-CO₂(liquid)] through a rapid Joule-Thompson expansion process that wastes liquid carbon dioxide, and spray cleaning energy is mainly controlled only by changing the distance between the nozzle exit and the surface. However, this practice is counterproductive because the carbon dioxide aerosol particles, already microscopic, are shrinking in size, quantity, and velocity, all of which adversely affects spray cleaning energy control and efficiency.

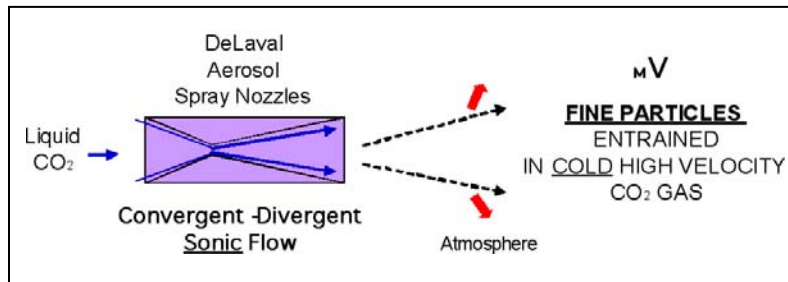


Figure 1. CO₂ aerosol spray process.

Another shortcoming common to conventional cryogenic spray techniques using DeLaval spray nozzle designs is the intrusion and entrainment of atmospheric contaminants into the cryogenic particle flow stream. The most important aspect of these contaminants is atmospheric moisture condensation in the spray plume. Wet atmosphere entrained within the cold spray plume boundary is delivered to the surface along with cleaning spray particles, which complicates the cleaning process. Wetness is caused by the lack of effective shielding of the sublimating particle stream from the ambient atmosphere and insufficient heat capacity within the spray boundary to prevent condensation.

Conventional CO₂ spray cleaning processes complicate the design and manufacture of automated spray cleaning systems. For example, in order to use conventional CO₂ spray designs with automation, abatement measures must be implemented to remove or alter the humidity of the ambient atmosphere in the vicinity of the treatment area. These measures may include, for example, an inert gas-purged environmental chamber or tunnel, hot plates, infrared (IR) heat lamp, hot gas purging streams, or a combination of these measures. All of these measures add complexity and cost to the final automated cleaning system design.

A more recent dry spray cleaning improvement that addresses many of the shortcomings of conventional snow spray systems in general, and the DeLaval CO₂ spray nozzle design in particular, is advanced CO₂ composite spray (Figure 2). Advanced CO₂ composite sprays employ coaxial or coaxial-Coanda two-phase composite spray nozzle designs with capillary condensation. Coaxial composite sprays produce cleaning sprays containing solid CO₂ particles (cleaning agent) of controllable size, density, concentration, heat capacity, and kinetic energy. To make solid CO₂ particles, a capillary condenser assembly with an elongated segment of thermally insulated polyetheretherketone (PEEK) capillary tubing is used. The capillary condenser assembly provides a means for subcooling (boiling) and condensing small amounts of liquid carbon dioxide into a low-velocity but dense mass of solid-phase particles. Varying the length and internal diameters of the capillary condenser, including stepping, produces particles having different particle size distribution ranges and density. Once formed, CO₂ particles are injected and vortically mixed into a heated propellant gas such as nitrogen or clean-dry air (optionally ionized), which flows coaxially with the capillary condenser assembly.

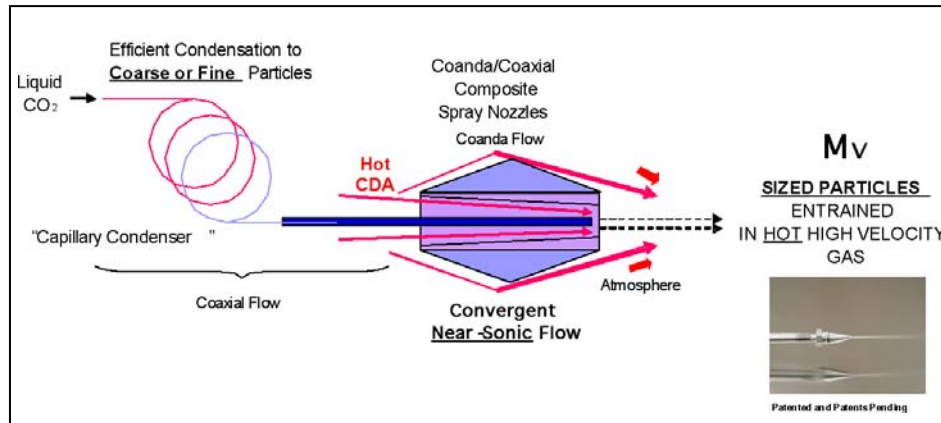


Figure 2. CO₂ composite spray process.

Figure 3 illustrates the CO₂ purification and spray generation process, which involves phase separation, subcooling, and momentum transfer mechanisms. CO₂ gas[1], supplied from a cold low-pressure liquid supply at approximately 20 atmospheres (atm) and -18 °Centigrade, is filtered using a micro-porous membrane (and optionally catalytically treated). The clean gas[1] is condensed into a clean liquid phase[2] at approximately 65 atm and 15 °C. The clean liquid phase[2] is subcooled and condensed to a solid particle phase[3] using the capillary condenser process. The clean CO₂ particles and a source of clean pressure- and temperature-regulated propellant gas are combined within a coaxial or Coanda-coaxial spray nozzle[4] to form a composite cleaning spray. The CO₂ composite spray components are individually adjusted to produce a range of spray compositions and energies. CO₂ particles are accelerated in a velocity range from subsonic to near-sonic in accordance with Bernoulli, Coanda, or both flowstream principles.

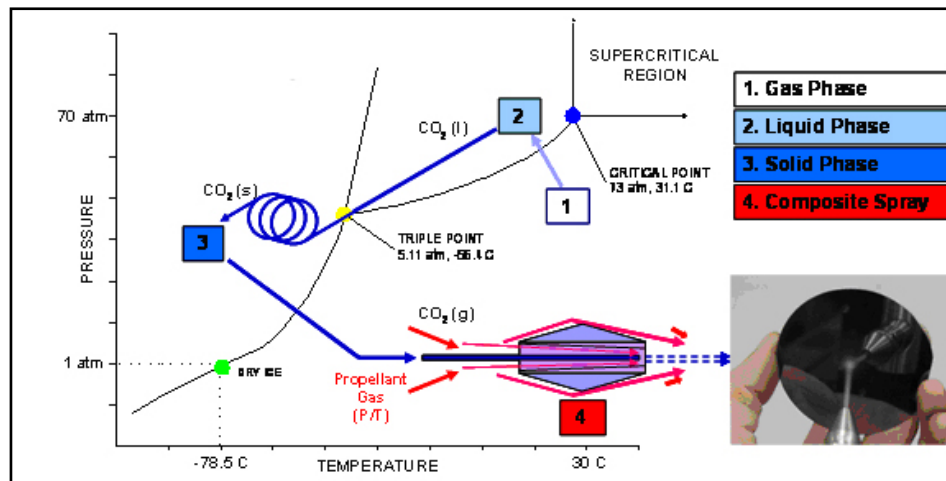


Figure 3. Forming a CO₂ composite spray.

CO₂ SPRAY CLEANING PRINCIPLES

The cleaning energy required to remove microscopic particles and thin films rises exponentially as the diameter of the particle or thickness of the film decreases: for example, increasing to several million *g*-forces for sub-micron particles.³ Fluid velocities rapidly decrease from turbulent flow (high energy) to laminar flow (low energy) at microscopic distances from the surface. This is where the small particles and thin films hide out. To overcome this energy barrier, commonly known as the wall or boundary layer, high fluid velocities must be achieved to increase fluid flow characteristics from laminar to turbulent, which increases viscous drag (also known as shear stress) upon the particle. Advanced composite cleaning sprays are different from conventional high-pressure spray cleaning using liquid solvents or blow-off gases in two important ways—a chemistry that provides physical scouring action plus chemical solvency and the capacity to directly impact a substrate surface, overcoming the energy barrier.

The physicochemical cleaning principles involved in advanced composite CO₂ spray cleaning are analogous to microabrasive cleaning, with some distinctions. One difference is the low hardness of CO₂ particles (< 1 Mohs); CO₂ composite spray cleaning using microscopic particles of CO₂ is a nonabrasive process. Another distinction is that CO₂ spray cleaning processes involve physical momentum transfer and phase change phenomenon, as well as solvent energy mechanisms to remove particulate and thin film contamination from a surface. For example, solid- or liquid-phase CO₂ exhibits a solvent chemistry similar to halogenated cleaning solvents,⁴ which enhances the surface cleaning effect. Recent performance testing, shown in Figure 4, using various composite spray nozzles, pressures, temperatures, flow rates, and capillary condenser types demonstrated that surface impact stresses (cleaning energy) can be controlled precisely from less than 1 megapascals (MPa) to as high as 60 MPa, which is more than sufficient shear stress to cause an impinging solid spray particle to change phase to liquid at the substrate surface.⁵ These tests also demonstrated that composite spray cleaning energy can be sustained for relatively long distances using coarse particle streams (large capillary condenser). Thus advanced composite sprays exhibit cleaning and control characteristics common to conventional high-pressure liquid spray processes.

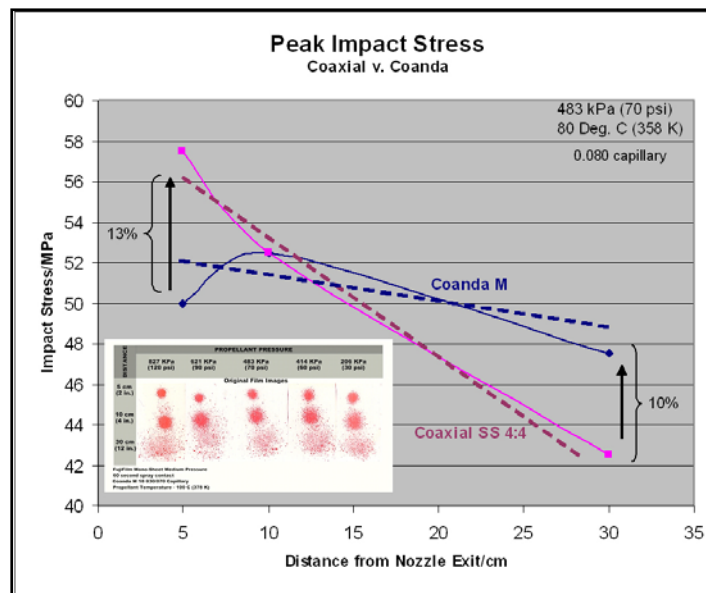


Figure 4. CO₂ composite spray cleaning energy.

AUTOMATED CLEANING SYSTEM

Superior spray cleaning process control and performance characteristics of a CO₂ composite cleaning spray have been combined in a high-speed robotic tool (Figure 5). Inexpensive bulk CO₂ gas is delivered to multi-channel composite spray generators with integrated CO₂ purification. Independent coaxial delivery of heated CDA as a propellant reduces potential condensation while separately adjustable flows of liquid CO₂ create precise amounts of solid carbon dioxide cleaning particles.



Figure 5. Automated CO₂ composite spray cleaning system.

Rapid multiple cleaning passes over each part employing variable trajectories, spray angles, and scan speeds provide effective and consistent cleaning results while keeping pallet cycle times short. Particle counts show significant and consistent particle count reductions. The cleaning system is engineered for cleanroom use including Class 10-rated robots. The system is sized to match standard ceiling high-efficiency particulate air (HEPA) filters and features open architecture to allow airflow out the bottom and easy maintenance as needed. Ionization systems placed above the cleaning zone reduce potential recontamination of parts. Non-contaminating materials are used throughout including anti-static fixtures and viewing windows.

To clean MBAs, covers, and VCMs, a high-speed cleaning system was developed featuring two robots with four CO₂ composite spray cleaning applicators and nozzles on each robot arm, a four-position rotating carousel, three pallet designs with barcode-controlled automatic pallet recognition, and a light curtain interlocked carousel for rotational safety. A significant amount of software development was needed to optimize the selective spray cleaning recipe for each type of pallet/part configuration. Concentrated cleaning on areas of particular interest as well as full sweep cleaning across each row of parts is a capability built into the cleaning system.

CLEANING CYCLE TIME AND COST

Pallets containing up to 72 parts are automatically detected and presented to a pair of opposed four-axis robots for thorough and selective spray cleaning of both sides simultaneously. Stored spray cleaning programs deliver precise cleaning, and the operator interaction is limited to loading and unloading pallets onto and from the system. The cleaning cycle time per pallet varies

from 2.5 to 6 minutes depending on the type and number of parts per pallet. The CO₂ cleaning cost per part is \$0.015–\$0.06 including the amortized cost of the machine and support facilities over a three-year depreciation period. As shown in Figure 6, the cost-per-clean for CO₂ compares favorably with more traditional immersion cleaning processes using deionized water.

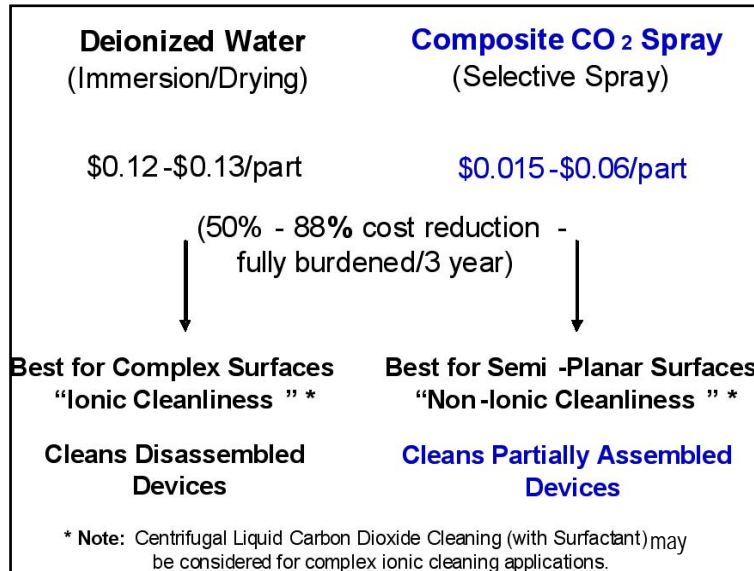


Figure 6. CO₂ composite spray cleaning cost comparison.

CLEANING AND SYSTEM PERFORMANCE

To evaluate cleaning performance, a number of qualification experiments were run. Once the cleaning recipes were optimized and the machine was installed at the factory of a major HDD manufacturer, ongoing testing on a weekly basis tracks the cleaning performance of the automated CO₂ cleaning system.

The testing uses ultrasonic extraction of parts and liquid particle counting (LPC) of the extractant, prior to cleaning and comparing the LPC results of parts after cleaning. The results have more than met expectations. The original goal given to the equipment design team was to return the reclaimed HDD parts to the cleanliness levels of prime HDD parts.

The ongoing testing has shown that the uncleaned, reclaimed parts frequently not only do not meet the cleanliness levels of prime parts, they do not meet the maximum particle specs for prime parts. On the other hand, the CO₂ cleaned parts consistently meet or exceed the cleanliness level of prime parts and are considerably cleaner than the maximum allowable specs. The typical particle count reduction is on the order of 15% to 25%.

The CO₂ cleaning has also been shown to be gentle and does not cause any physical damage to delicate components left on the MBA and cover sub-assemblies during cleaning. The pallets made of a static dissipative polymer material were also designed to hold the parts accurately while not marring the surface finish. Shown in Figure 7, yield data for the reworked drives is nearly as good as for prime drives and sometimes exceeds the yields for prime drives. Finally, uptime for the automated cleaning equipment has exceeded 99.9% over a 6-month period.

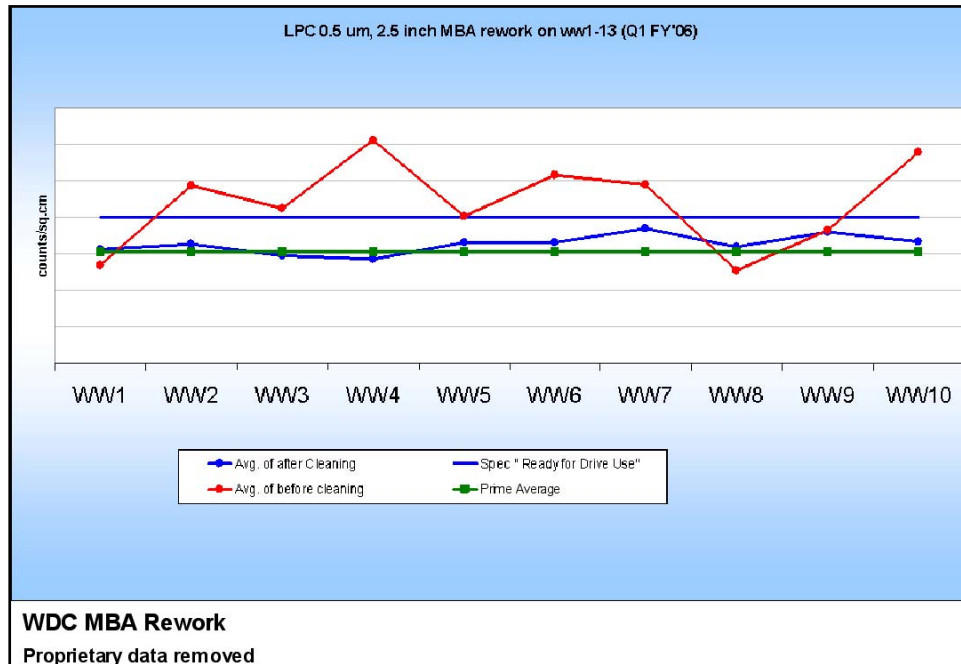


Figure 7. CO₂ composite spray cleaning consistency.

NEED FOR OPTIMIZATION

The only area where the automated CO₂ cleaning system does not completely meet expectations is the removal of particles from within blind holes. Photomicrographs of blind holes, before and after cleaning, have shown virtually no particle removal from within the holes. Vacuum cleaning the blind holes has also been shown to be ineffective for removing the particles. However, it is believed that optimizations such as improved programming, newer nozzle designs, articulating robots, composite spray delivery techniques (i.e., proximity), or a combination of any of these plans will provide improved and sufficient cleaning of blind holes. Further development in this area will be done as the second-generation automated CO₂ composite spray cleaning system is developed and tested.

CONCLUSION

Advanced and automated CO₂ composite spray cleaning has been shown to be a cost-effective, consistent, high-performance, and reliable process for precision cleaning assembled HDD components during the rework process. Further improvements in programming, spray delivery, and automation should advance the performance and versatility of this environmentally benign and effective dry cleaning technology.

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ABOUT THE AUTHORS

Gary Knoth began his involvement with contamination control in 1975 as facilities mechanical engineer with IBM, where his assignments included designing cleanrooms and high-purity water systems. In 1985, he was appointed the IBM San Jose Site contamination control engineer, a position he retained until his retirement from IBM in September 1995. In addition, from February 1992 until September 1995, he was chairman of the IBM World-Wide Corporate Contamination Control Council. During his career with IBM, Knoth also had a 1-year assignment with SEMATECH in Austin, Texas. In his present position as senior principal contamination control engineer with Western Digital Corporation, Knoth is involved with a wide range of contamination control programs including cleanroom consumables; design and testing of static dissipative cleanroom garments; cleanroom tooling design for cleanliness; CO₂ snow cleaning of hard drive components; cleanroom design and certification; and factory contamination control support. He is a Senior Member of IEST and Technical Vice President/Contamination Control. He is Chair of IEST Working Group 027 (Personnel Practices and Procedures in Cleanrooms and Controlled Environments) and a voting member of several other IEST Working Groups.

David Jackson began his career in the CO₂ development field in 1984. As group head of precision cleaning and contamination control at Hughes Aircraft Company, he developed several CO₂-based cleaning technologies that were patented and subsequently commercialized. Jackson founded the Deflex Corporation in 1992, a CO₂ cleaning technology development company, where he continued to develop and advance the field. He holds numerous patents and has successfully developed and commercialized several CO₂ cleaning products over the past 15 years. In his present position as senior vice president, marketing and technology development, at Cool Clean Technologies, Inc., PurCO₂ Division, he is responsible for CO₂ technology, market, and business development.

Nelson Sorbo, PhD, began his career in the CO₂ development field as a research scientist and manager of Raytheon's (formerly Hughes Aircraft) commercial textile cleaning, parts cleaning, and sterilization technology licensing programs called DryWash, SuperScrub, and DrySter. In his present position as vice president, distribution and licensee support at Cool Clean Technologies, Inc., PurCO₂ Division, Dr. Sorbo is responsible for developing technology support infrastructure and policies, including management of the licensee network and applications research and development programs. He also currently manages the company's CO₂ contract cleaning operation as well as new product engineering and development. He is a member of IEST.

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