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# A Design for Combining Biological and Semiconductor Cleanrooms for Nanotechnology Research

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# A Design for Combining Biological and Semiconductor Cleanrooms for Nanotechnology Research

John R. Weaver, Birck Nanotechnology Center at Purdue University (courtesy of Delphi Corporation)

## Abstract

*Nanotechnology brings together various functional areas for interdisciplinary research, making it necessary for them to reside in a single facility. The conjoining of biology, biomedical engineering, and bio-nano-micro-electro-mechanical systems (MEMS) with semiconductor and MEMS processing requires that these technologies coexist in ultraclean facilities, while the facility designs and operating practices are incompatible. This case study describes a design concept in a collaborative research environment that meets biocleanliness goals and International Organization for Standardization (ISO) Class 4 particle concentrations (as defined in ISO 14644-1, Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness).*

## KEYWORDS

Nanotechnology, facility design, cleanroom design, biological cleanroom, semiconductor cleanroom, university

## THE BIRCK NANOTECHNOLOGY CENTER

One of the exciting aspects of nanotechnology research is its collaborative, interdisciplinary nature. The Birck Nanotechnology Center (BNC) at Purdue University involves a wide variety of disciplines in its research activities (Figure 1). It is critical that the facility support these diverse research areas.

A fundamental concept driving new nanotechnology-based systems is the combination of diverse technologies involving uniquely different disciplines on a single device. A common example is the fabrication of devices that combine micro-electro-mechanical systems (MEMS) sensors, built using silicon microelectronics technology, with active biological agents. These new devices have a myriad of applications ranging from sensors to active electronic devices.

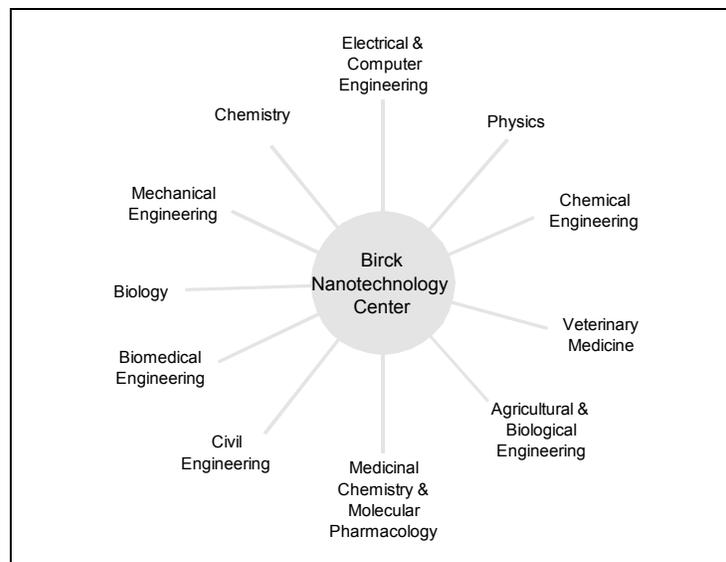


Figure 1. Research areas of the BNC.

In addition to the complexities of combining these technologies into working devices, there is an added complexity in fabricating the devices. To fabricate nano-MEMS devices, a semiconductor-style cleanroom is needed. To use viable biological species and maintain them as an uncontaminated single species requires a pharmaceutical-grade cleanroom with biosafety containment. These two cleanroom styles are not compatible in facility design or operating protocol.

In generating the overall plan for a nanotechnology research facility at Purdue University, this challenge was at the forefront of the conceptual design of the facility. In working with researchers from various disciplines, several conclusions were reached. First, the needs of current and future nanotechnology research would require equipment for deposition, patterning, etching, and doping of materials in a clean environment. The equipment, processes, and devices would require, in essence, an International Organization for Standardization (ISO) Class 4<sup>1</sup> semiconductor fabrication facility. Second, biological researchers would need a facility free of contaminating biological species—essentially a pharmaceutical cleanroom. Third, biological researchers would need the capability to work with potentially harmful biological species. It was decided that a Biosafety Level 2 (BL-2) capability would meet this need. Fourth, a method would be needed to move the biologically active species into and out of the fabrication area. Finally, it was clear that this facility would have to be versatile and productive well into the future, which meant it would be used for activities that were not conceived of at the time. The facility would have to accommodate a diverse tool set and the cleanroom cleanliness level should be able to be upgraded as required. This need for versatility also required that the division between the fabrication cleanroom and the biocleanroom could be changed, e.g., to expand the biocleanroom area.

These conflicting needs created significant challenges in the facility design. In addition to substantial differences in operating protocols, there are major structural differences between a fabrication cleanroom and a pharmaceutical cleanroom. It was decided that the structure of the cleanroom portion of the facility would be built to accommodate a fabrication cleanroom, with the biocleanroom area being a modification to this design. The fabrication cleanroom requires a more complex infrastructure and more flexibility was gained by designing the facility with this infrastructure in place.

Operating protocol was a significant driver in the physical cleanroom facility design. A research facility has unique issues that are not as significant in a manufacturing facility. For example, a research facility may have a large, diverse user base with a high turnover rate. Graduate students come and go each semester, which increases the importance of simple operating policies and minimal enforcement issues. Hand-in-glove with this issue is the desire to encourage, not stifle, creativity in the cleanroom occupants. This drives minimal rule enforcement in the cleanroom, replacing rules with physical barriers that require that proper procedures be followed. Additionally, a significant amount of glass was designed into the cleanroom perimeter and the cleanroom interior walls. This “fishbowl effect” has proven effective in other facilities (designed and operated by the author) to encourage protocol adherence. Glass enhances safety by making large portions of the cleanroom visible to the casual observer, enabling a timely response to safety issues inside the room that may go unnoticed in a cleanroom with little or no glass. Glass also exposes cleanroom activities without breaching the cleanroom. Potential donors, administrators, and other visitors can view cleanroom operations without entering the cleanroom, thus minimizing contamination levels in the cleanroom and reducing cleanroom costs (training, garments, etc.). A significant amount of glass in a cleanroom may improve the morale of cleanroom occupants. There is a strong belief, though it is hard to measure, that glass lessens the impact that a conventionally designed cleanroom has on the creativity of people working within a clean environment.

An additional factor in research facility design is the need to facilitate a continually changing equipment set. This factor has three significant implications: 1) Facility design should allow for installation of new equipment in proximity to existing equipment that is in operation, 2) The bay-chase arrangement should allow equipment to be bulkheaded through the chase wall with the mass of the equipment in the chase, or placed such that the entire piece of equipment is located in the cleanroom. Bay and chase sizes should accommodate both options and the wall system should be versatile enough to

allow varying the bay-chase size, i.e., making the chase larger and the bay smaller or vice versa, and 3) The facility should be designed to minimize the cost and complexity of the distribution of new utilities to an equipment location, thus facilitating the installation of previously unanticipated equipment.

A nanotechnology research facility has several factors in common with manufacturing facilities. The cleanliness and purity of utilities far supersede cleanroom cleanliness itself. These utilities, in intentional and intimate contact with critical surfaces of the devices, should not introduce contaminants that would confound research. Vibration is a major factor in the ability to create devices and to make nano-scale measurements. The cleanroom floor should be extremely “quiet” from a vibration standpoint.

## NANOFABRICATION CLEANROOM

The design factors previously described dictated a cleanroom design similar to that of a modern semiconductor cleanroom. The cleanroom itself would be supported by a subfab below that would provide utility distribution and a location for less-clean equipment and supported above by a penthouse that would provide the air handling necessary to maintain cleanroom cleanliness. While this design is not common in university cleanrooms, primarily due to cost issues, it provides the best solution for both protocol compliance and equipment-installation versatility. Figure 2 provides a section view of a typical ISO Class 4<sup>1</sup> cleanroom that provides maximum flexibility while maintaining the ability to upgrade.

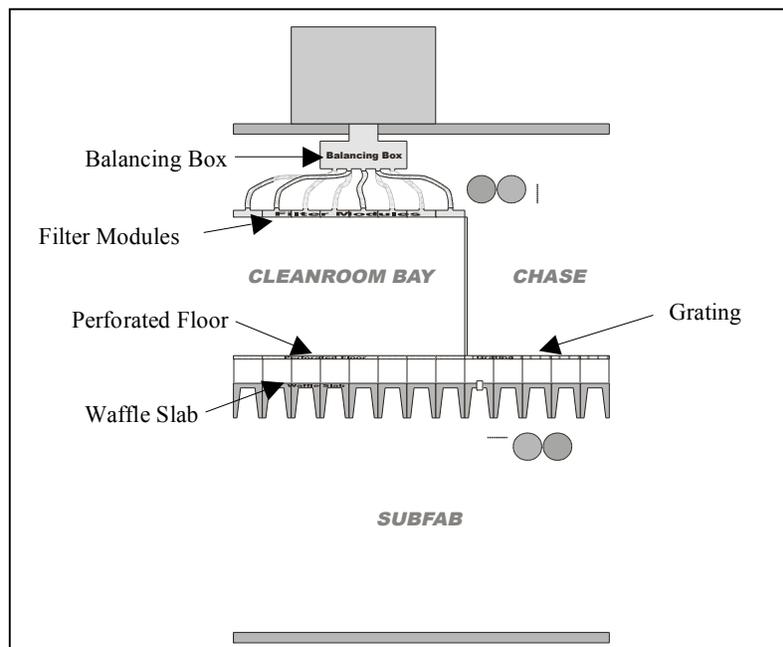


Figure 2. Typical ISO Class 4<sup>1</sup> cleanroom design.

To control vibration, the subfab has a dense column spacing, a deep waffle slab forming the cleanroom subfloor, and poured-concrete wing walls for structural rigidity. This design allows for a 3.175  $\mu\text{m}/\text{sec}$  (125  $\mu\text{-in.}/\text{sec}$ ) vibration specification, approximating slab-on-grade construction.

The primary role of the subfab is to house less-clean support equipment and utility distribution. When practical, support equipment is located in the subfab, minimizing traffic and contamination in the clean air path and reducing potential cleanroom protocol issues. Additional specific rules help determine what is placed in the cleanroom and what is placed in the subfab. In all cases, vacuum pumps and other highly contaminating equipment are located in the subfab. Also, items that would otherwise require cleanroom entry are located in the subfab when possible. For example, gas cabinets for inert gases are located in the

subfab below the equipment they service, allowing for changing a gas cylinder without breaching the cleanroom envelope. Finally, support functions that can be performed without cleanroom garments are located in the subfab when practical.

Utilities are manifolded throughout the subfab with capped valves located frequently along these manifolds. Penetration sleeves are strategically located through the waffle slab to simplify piping utilities to the cleanroom. These sleeves are sealed from airflow, but are easily drilled to accommodate new utility lines, thus minimizing the need to core-drill the waffle slab. This approach allows maximum flexibility in installing, removing, and relocating cleanroom equipment.

The penthouse above the cleanroom houses the recirculation and make-up air handlers. While this area is not a controlled environment, entry into an air handler requires contamination control precautions. The recirculation handlers use a multiple-fan system that has several advantages over single-fan units. First, the fans can be lifted by one or two people without the use of a hoist or forklift. This eases maintenance and makes replacement of a defective fan relatively simple. Second, there is an inherent “limp by” backup capability. If one fan in the bank fails, the other fans assume the load with only slightly reduced airflow. This capability allows continual cleanroom operation until the next maintenance opportunity. Finally, these systems operate more efficiently, reducing electrical costs.

The cleanroom design meets current ISO Class 4<sup>1</sup> cleanliness needs and allows for an improved cleanliness level if required. The area of the penthouse housing the recirculation units has designated locations for additional air handlers that would allow a substantial increase in airflow to the cleanroom. This design allows additional terminal-filter modules to be placed in the ceiling grid. With 100% (nominal) terminal-filter coverage, ISO Class 3<sup>1</sup> and better could be achieved, allowing increased cleanroom cleanliness flexibility if required.

The cleanroom cross section has three zones: the upper zone, the middle zone, and the lower zone. The upper zone, separated from the penthouse by a concrete floor, contains the above-ceiling portion of the cleanroom. This area houses the air distribution boxes and supply ducts for each filter module. Above the chase areas, the upper zone contains manifolds of key utilities used for overhead connection to equipment. In a university environment, a significant portion of the equipment is donated and there is no consistency in where utilities connect to the equipment. Utility access both above and below the equipment allows installation using the most suitable source, significantly reducing tool hook-up time and costs. The upper zone requires full gowning measures and is accessed from the cleanroom chases. Figure 3 shows a section of the cleanroom utility distribution from above and below the equipment.

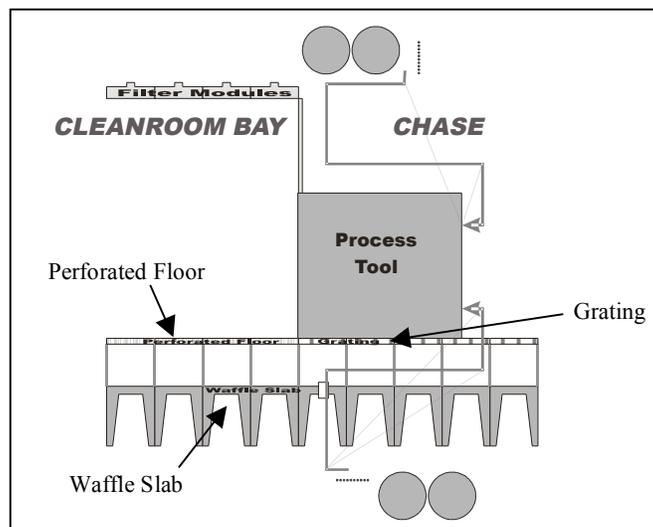


Figure 3. Manifolding utilities above and below the cleanroom.

The middle zone is the cleanroom itself. The cleanroom ceiling consists of a heavy T-bar grid system with a closed-cell compression seal between the filter modules and the T-bar. This seal prevents contamination from the middle zone, which is at lower pressure than the cleanroom, from reaching the cleanroom. The contaminants controlled by this seal are relatively large, dense particles that could overcome the pressure differential and particles drawn from the T-bar area by the Bernoulli Effect.

While maintaining a good seal at this point is important, the critical seal is built into the filter module, not the ceiling system. In this ducted supply system, the input to the module contains a balancing damper that can be controlled from within the cleanroom. The filter medium is potted to an aluminum extrusion using a low-outgassing potting material. This extrusion contains a gel track filled with a low-outgassing urethane gel. The filter module contains a downward-facing knife-edge that mates with this gel seal on the filter extrusion. Together, the filter potting and gel seal prevent supply air from bypassing the filter medium.

Because some areas of a cleanroom have less than 100% (nominal) filter coverage, blank panels are needed. Aluminum honeycomb panels are used for these blanks to allow for walking or crawling on the ceiling and to provide a durable, easily cleanable surface for the cleanroom ceiling.

The lower, 24-in.-deep zone is separated from the cleanroom by an access floor. A perforated panel in the cleanroom bays provides a cleanable surface that helps maintain unidirectional airflow throughout the cleanroom. Dampers below the panels combine with balancing dampers in the filter modules to allow precise airflow control. Locating equipment in the cleanroom creates turbulent zones and destroys unidirectional airflow. This damper system compensates for the equipment and restoration of unidirectionality necessary to maintain cleanroom cleanliness. A grating used in the chases allows better visual access to under-floor utilities and less return-air-path restriction. This zone also contains utility penetrations from the subfab and under-floor distribution of those utilities. This under-floor area may be used to route utilities coming to equipment and connections between equipment to the precise area they are needed. This arrangement minimizes clutter and trip-hazards within the chases.

The bay-chase design consists of bay and chase widths that accommodate both bulkhead-mounted equipment and cleanroom-only equipment, and uses a wall system that allows modification of a bay or chase. This design lowers initial and operating costs and minimizes the impact a bay-chase design typically has on cleanroom system versatility. Figure 4 provides a view of this bay-chase design in a photolithography area.

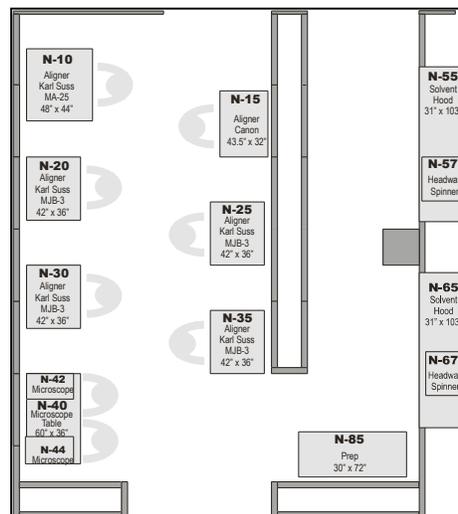


Figure 4. Bay-chase design in a photolithography area.

A large-chase, small-bay cleanroom layout is used in typical industrial facilities. A university facility requires more equipment to be mounted in the cleanroom due to the wide variety of equipment styles and ages. This requirement led to a design that provided several larger bays with smaller chases intermingled with the larger chases and smaller bays.

The flexible wall system allows for future installation of different equipment styles. The wall system is a standard cleanroom system with a honeycomb aluminum panel mounted to a stud system that accepts pipe hangers. While manifolding is accomplished below the raised floor, this system allows the flexibility to mount risers to the wall studs. The wall system is mounted to the raised floor and the ceiling grid with tracks that attach to the studs. The walls can be easily relocated if the wall locations match the ceiling grid. Terminal filters can be added or removed as the chase-bay area ratio changes.

Entry to the cleanroom is through a typical two-stage gowning process. First, a pregowning area provides a step-over bench for putting on shoe and hair covers. Next, the gowning room is entered through an air shower, where cleanroom garments are put on. A second air shower provides access into the cleanroom. Exit from the cleanroom is through the same gowning room, where exit air locks replace the air showers.

### **BIOCLEANROOM**

This cleanroom design works well for semiconductor-style processing, but is not acceptable for a pharmaceutical-grade facility. Because an area of the BNC cleanroom requires this type of biological cleanliness, the pharmaceutical-grade design was required to accommodate that cleanroom within the overall nanofabrication cleanroom.

It was decided in the planning phase that the biocleanroom would be a bacteria-free zone, confining active organism work to biosafety cabinets. It was also determined that BL-2 would be the highest pathogen level used in the facility. These concepts provided the basis for the biocleanroom design.

Biocleanroom air handling is segregated from that of the nanofabrication cleanroom, i.e., there is no air interchange between the cleanrooms. Unlike the nanofabrication cleanroom, however, the biocleanroom utilizes a low sidewall air return rather than through-the-floor airflow. Solid floor tiles are used instead of perforated tiles, with welded-seam sheet-vinyl flooring placed over the tiles. This flooring is coved at the walls and joined to the wall system. The wall system is specially designed for pharmaceutical-grade cleanrooms and minimizes locations that allow bacteria growth. Terminal filters are integral to the ceiling system, which coves to the wall system.

Air-return chases are provided, but unlike the large chases used in the nanofabrication cleanroom, these chases are narrow and provide only sufficient room for airflow. The air returns are lined with a gently curved stainless steel liner to three feet above the wall opening, making the entire system cleanable with bactericidal agents. Figure 5 provides a section view of a biocleanroom with this air-handling concept.

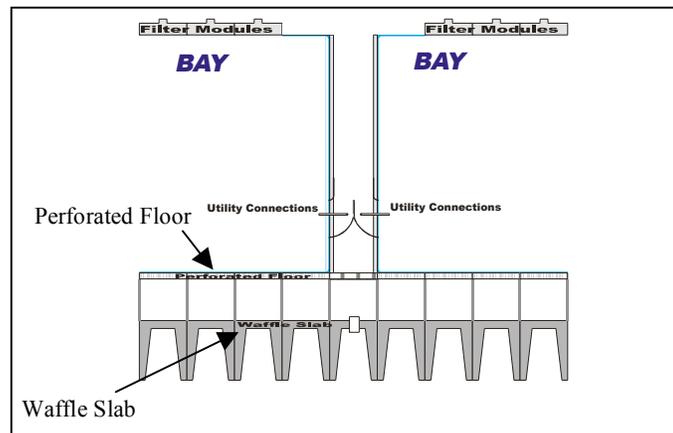


Figure 5. Biocleanroom with low sidewall air returns.

To minimize bio-entrapment areas, only wall penetrations were allowed for utility entry; no floor penetrations were allowed. Cores were intermingled with the chases to allow utilities to enter the biocleanroom from the subfab and under-floor area. These cores, although not part of the clean air path, bring utilities through the floor, allowing utilities to enter the biocleanroom through the chase-core wall. Utilities are run inside the air-return openings and connected directly to the equipment.

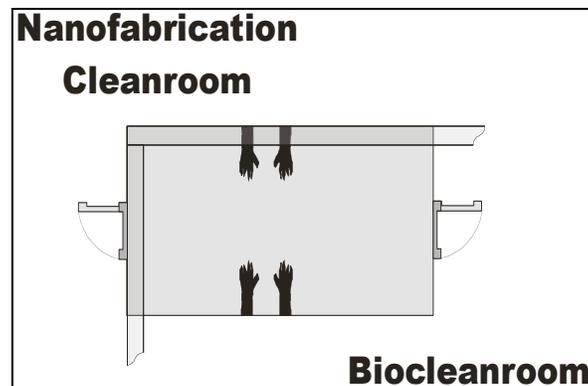
The biocleanroom entry and exit facilities differ significantly from those of the fabrication cleanroom. A once-through disposable garment system is used for bacteria control. This system allows for a smaller gowning room with no need for staging facilities for previously worn garments. The less-stringent ISO Class 5 facility eliminates the need for pregowning and allows the use of a single air shower between the gowning room and biocleanroom. The exit path is distinct from the entry path and provides for garment disposal upon exiting the biocleanroom.

The design allows for size expansion or reduction should requirements change. While expansion would be relatively complex, it can be accomplished. The entire wall, floor, and ceiling system could be removed and replaced by the biocleanroom system. Expansion would also involve redeploying the necessary recirculation air handler(s) to return air from and supply air to the biocleanroom only. A similar process would be used to reduce the biocleanroom size.

### **BIOCLEANROOM AND NANOFABRICATION CLEANROOM INTERFACE**

Because of the differences in gowning systems and protocols between the biocleanroom and the nanofabrication cleanroom, no personnel access is allowed between the two facilities; however, it is critical that devices that are in process be moved between the two cleanrooms. For non-critical items, e.g., devices that have not been exposed to biological species, a conventional pass-through is provided. For safety reasons, an ultraviolet light is used in the pass-through to ensure that there are no viable species on the item.

For critical items, a specially designed glovebox is used. This glovebox has glove ports in both the nanofabrication cleanroom and the biocleanroom and entry/exit ports in both cleanrooms. This design allows a researcher in one cleanroom to transfer an item into the other cleanroom, performing a decontamination or encapsulation process in the glovebox. This process provides versatility to researchers performing device development across both cleanroom facilities. Figure 6 provides a view of this “double glovebox” arrangement.



*Figure 6. The “double glovebox” arrangement.*

### **CONCLUSION**

With careful design, nanotechnology research that spans biological and semiconductor/MEMS processing can be supported within a single facility. The combination of these two technologies need not compromise the ultimate cleanliness of either cleanroom. The BNC provides a cleanroom design example that meets the needs of researchers in the short- and long-term. Through forethought in the design

process, flexibility has been built in to address technologies and equipment designs that are not yet defined. This facility provides an example of how a cleanroom design can support this vital field of research.

Facility construction is scheduled for completion in September 2005. An additional 11 months have been allocated for equipment installation and the facility should be fully functional in September 2006.

### **ACKNOWLEDGMENTS**

This project was completed with the cooperative effort of many individuals and organizations. Several companies and individuals played a large role in the unique cleanroom design of the BNC. The success of this project is a direct result of their tireless efforts.

### **REFERENCE**

1. *ISO 14644-1. Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness.* International Organization for Standardization (ISO).

### **ABOUT THE AUTHOR**

**John R. Weaver II** is facility manager for the Birck Nanotechnology Center at Purdue University. His role at Purdue is courtesy of the electronics and safety division of Delphi Corporation, Kokomo, Indiana. He has been involved in the design of the Birck Nanotechnology Center from its conceptual stages and in the construction process. Weaver is manager of contamination control at Delphi, responsible for cleanroom and clean manufacturing facility design, construction, and operation worldwide. He has participated in the design and construction of more than 25 clean facilities, including several wafer fabrication facilities. He worked for Hughes Aircraft Company before joining what is now Delphi. Previously, he worked in process engineering at RCA Solid State Division in the production complementary metal oxide semiconductor (CMOS) fabrication facility.

Weaver received his BS in chemistry from Adrian College. He has published numerous papers on process development and contamination control, has two patents in process development, and authored a book and two book chapters on contamination control technology. He has taught a variety of industry short-courses and received the Willis J. Whitfield Award from IEST for contributions to the field of contamination control. He has managed contamination control research contracts with the University of Minnesota Particle Technology Laboratory and the University of Arizona Center for Microcontamination Control.

Weaver is a senior member of IEST, president of the IEST Indiana chapter, and serves on the Editorial Advisory Board of the *Journal of the IEST*. He is a principal member of the National Fire Protection Association (NFPA) 318 Committee, the writers of fire standards for cleanrooms.