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Progression of Cleanroom Standards Development, 1959-1970s

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white room, clean room, cleanroom, environmentally controlled spaces, processes, standards, history

It is my privilege to recognize all the thousands of experienced people who, during the past 60 years, developed the technical documents, trained new generations of specialists, and provided the best solutions for environmentally-controlled facilities and processes. Future generations, worldwide, will benefit as the requirements for revised standards are defined to meet the challenges. In my long career in the fields of ultra-clean spaces, ultra-pure water, chemicals and gasses required in laboratory and process applications, I can appreciate the partnerships that have been successful for their missions. The Institute of Environmental Sciences and Technology (IEST) will continue to be the leader. Thank you IEST and all those that volunteered to keep the clean room standards updated with technology.

Introduction

Prior to the launch of *Sputnik 1*, the Eisenhower Administration had been implementing their successful planning of the national Interstate Highway System. Space exploration had received some government funding for rockets, defense weapons, and more sophisticated computers, but the requirements and expenses were not focused on just space applications. Hundreds of millions of dollars had been spent by military and industrial contractors, as well as academic institutions, for controlled facilities. Projects centered on microelectronic and micromechanical components, some used in the Second World War, and various classified programs in advanced hardware and software. Projects also included technologies recovered from German manufacturing sites after the war secured by the United States in an agreement with Great Britian and the Soviet Union as the three nations divided up Germany's assets.

This administration also was credited for facilitating the armistice for the Korean War (1950-1953) and redirecting the federal budget to a technology economy. Much of the equipment used in the Korean War had been designed and manufactured with now outdated World War II era processes and less quality control (QC). Storage issues for outdated equipment since the Korean war had been reported by the Treasury Department to the Defense Department as needing a serious review of obsolete materials.

The Eisenhower Administration in the late 1950s initiated a major civilian space program and on July 29, 1958, President Eisenhower signed the National Aeronautics and Space Act into law. The act established the National Aeronautics and Space Administration (NASA), a national independent civilian administration. The United States Congress approved funding immediately, as our nation had only been focused on basic research and development (R&D) and many different organizations, including the four United States (US) military branches, had separate programs for developing support for their missions. For example, the United States Air Force (USAF), United States Navy, and United States Army had major maintenance depots with new advanced facilities for technology-based design, manufacturing, overhaul, and management in 1959.

In a speech at Rice University on September 12, 1962, President Kennedy articulated the vision that we would land a man on the moon by the end of the decade. This gave the green light for the US Congress to approve bigger budgets for NASA. For six plus decades since, various standards organizations have provided professional quality technology documents, education, and training. IEST has been a major leader because of its volunteer members and officers from industry and government, along with a headquarters staff supporting its mission.

Early Clean Room Facilities Standards

For many years, the term “white room” had been used to designate controlled spaces and areas. White rooms had smooth surfaces that were painted white but had few specifications for defined cleanliness levels. It was assumed that medical applications needed some control and regulations were available for disinfecting those spaces, but nothing existed for other ultra clean spaces. The term “clean room” was originally used for controlled areas with special filtered air.[2] In the 1960s, the specific term “cleanroom” was created to designate a controlled facility with much higher levels of environmental control than general “clean rooms.” As more documents were being published for controlled areas, it was important to separate the two words. These terms are now accepted to clarify the difference. The Institute of Environmental Sciences (IES)—founded in 1959 from the merging of the Institute of Environmental Engineers and the Society of Environmental Engineers—was credited with coining the term “cleanroom” and led the charge to clarify the difference.

Facility standards were being developed for micro-components, as their size and tolerances were rapidly decreasing. Particle control at the sub-micrometer level was needed, but there were no uniform standards for these controlled spaces or defined methods for monitoring in real time. Materials for the earlier manufacture of special industrial filters were developed in the late 1930s for chemical, biological, and radiological research facilities. In early 1940s, the radiological research and manufacturing for the Manhattan Project required high-efficiency particle control for atomic energy applications. The new HEPA (high efficiency particulate air) filters were manufactured to control 0.3-micrometer (µm) particles at a 99.97% efficiency level. Dioctyl phthalate (DOP) was the test material used to generate the aerosol particle required for this testing.

The clean room design specification of 0.3 µm as the smallest particle size was selected by (USAF) R&D at Wright-Patterson AFB, Ohio in 1960 to best meet the requirements of air filtration in controlled spaces. The HEPA test data justified this 0.3 µm, and was included in the first clean room document, USAF Technical Manual, Technical Order (TO) 00-25-203, Standard Functional Criteria for Design and Operation of Clean Rooms, published March 1, 1961.[1] This first standard stated:

> "Future publications on maintenance of delicate instruments, electronic devices and comparable high precision items were to specify the appropriate class of clean room as outlined herein that will be required for repair, assembly, calibration, or test of that item."

The purpose of this manual was to "establish criteria for the guidance of Air Force personnel and civil contractors in determining design and functional requirements for clean rooms." The manual further stated, "The term clean room as used herein is a laboratory or shop which incorporates high standards of environmental control and cleanliness necessary to meet exacting operations and tolerances during the repair, assembly, calibration and test of Air Force precision instruments, electronic/mechanical devices, and comparable high precision items." Content on clean room design factors and operating specifications was followed by Class designations (Classes I-IV) to identify levels of environmental control. Specifications included temperature, humidity, pressure differential, and air filtration for design and operating criteria, as well as particle count tolerance with a particle collection and a prescribed counting method. Class IV was designated for the highest level for environmental control with particle size lower limits of 0.3 µm for 'Design Criteria' and 0.5 µm for 'Operating Criteria'. Particle count tolerance was set at a maximum of 10,000 particles (between 0.3 µm and 10 µm) per cubic foot of air. Additionally, for Class IV clean rooms, the manual stated a maximum of 2,000 particles (between 0.5 µm and 10 µm) per cubic foot of air. This manual, TO 00-25-203(1961), also had the following provision:

> "Medical Standard-Personnel to be employed for Class II, III and IV Clean Room Operations should be given a medical examination prior to employment and when conditions warrant to eliminate those with a skin disease or high moisture of their hands which may be a hazard to precision parts during work."

For some facilities, the guidelines in the manual went even further and indicated: "Personnel with beards and mustaches should wear a full-face shield." However, this second statement was ruled by government personnel departments as illegal.

This 48-page technical manual also listed those USAF devices needing controlled areas by Air Force Item Nomenclature in the 25-page Appendix III. A second manual with minor corrections was issued February 7, 1962. Both manuals TO 00-25-203 (1961 and 1962) were under the supervision of Oklahoma City Air Material Area, Hill Air AFB, Oklahoma, and were published under the authority of the Secretary of the Air Force.

Certification Issue

The first major issue to be addressed in this manual was certification requirements regarding particle control. Manufacturers certified the performance of batches of HEPA filters at their facilities, but contractors had no practical method to test performance on-site after filter installation was complete. Further, local military maintenance depots were contracting construction firms without any testing for particle control at the specified level due to lack of qualified test methods. Additionally, early particle count methods used biological or medical testing procedures that did not measure submicron particles. Only 5.0 µm and larger particles could be measured. Even more challenging, the DOP test method to detect leaks at the filter manufacturer involved an aerosol photometer to sense large concentrations of DOP particle leaks, rather than the low counts of particles expected for a cleanroom. This and previously noted issues caused confusion for the contractors that designed, built, and certified such clean spaces. As a result, large sums were spent for these clean room facilities without proper testing to the Air Force manual specifications. Electronic particle counters used to measure submicron particles were not included in the manual in 1961-1962, as first models were just being tested for clean room monitoring.

The method for collecting samples 5.0 µm and larger used the Greenburg-Smith (G-S) type impinger, where the sample was drawn by vacuum and collected into a liquid for microscope sizing and counting. This G-S collection method for industrial hygiene air sampling had been used for decades. Collected samples were transported to the chemical laboratory, and transferred to a Dunn Cell for counting. This particle counting method also required a 30x microscope (300 particle diameter magnification) using the dark field technique. This procedure was not practical, as it required six to seven hours for a microscopist to manually count one sample and it was estimated that this counting method was less than 50 percent repeatable by different certifying specialists. This method was developed by the Industrial Engineering Division, Robin AFB, Georgia. A note referenced in the manual stated users should contact Robins Air Force Base AFB, Maintenance Engineering WRME, for assistance with this procedure.

First Resolutions

As a recent college graduate (1960) and commissioned USAF Chemical Engineering Officer assigned to the Quality Control Division, Directorate of Maintenance, I was tasked with studying and recommending changes to the published 1961 clean room manual. I employed resources from our Quality Assurance Branch and three engineering branches supporting four separate military clean room facilities. Management's instructions were "any extra Quality Control (QC) expenses to the military installation that would result from recommended changes had not been budgeted, so justifications were needed for changes". (In other words, 'do not increase operating costs in this fiscal year.') Additionally, the question of "How clean is clean?" at the lower level of particle control had not yet been defined as related to device tolerances for certain size particles and geometries. However, the need to know the source and type of smaller particles being detected was important. During my undergraduate education, I had had a strong interest in very small particles, but never imagined that my career would actually start in particle sciences.

Early Years for Particle Science

I remember as a young boy the significance of a "clean room". My mother, a first-grade school teacher, had a "Suggested Duty" every Saturday morning for my siblings and myself to "clean room" before going out. From a bright slit of sunlight in my bedroom, I noticed many very small objects floating. While shaking the sheets, they increased by THOUSANDS. I did not disclose this to Mom for many years as I was sure she would think I had not cleaned my room!

The USAF owned many downflow standard clean rooms at Robins AFB, Warner Robins, Georgia, with return air intake located at the bottom of the four walls. (Figure 1) At the time, this air base had more than 30,000 square feet dedicated to four different areas of Class III and IV clean rooms.

Figure 1. USAF Standard Class III Clean Room, Downflow. Robins AFB, Georgia. May 1962. (Return air at base of all four walls.)

The Class IV clean room in Figure 2 was modified with air changes per hour at 150 percent of the normal criteria. Operating test consoles with heat sinks and cooling fans created disruptive air turbulence. Increasing the air change rate improved the former particle counts and temperature conditions. Particle counters identified problem areas that were verified by stopping all equipment, essentially creating the 'cleanroom at-rest' condition. These rooms were designed in 1960 and constructed in 1961 to 1962. Approximately three months were required for each room's certification.

Figure 2. USAF Standard Class IV Clean Room, Downflow. Robins AFB, Georgia. July 1963.
(Same design as Figure 1, but air change per hour increased 150 percent.)

An experimental laminar flow (LF) tunnel (Figure 3) with a HEPA filter wall 10 feet high by 20 feet wide was designed to record actual particles generated as big components were moved into the tunnel (Figure 4) for disassembly.

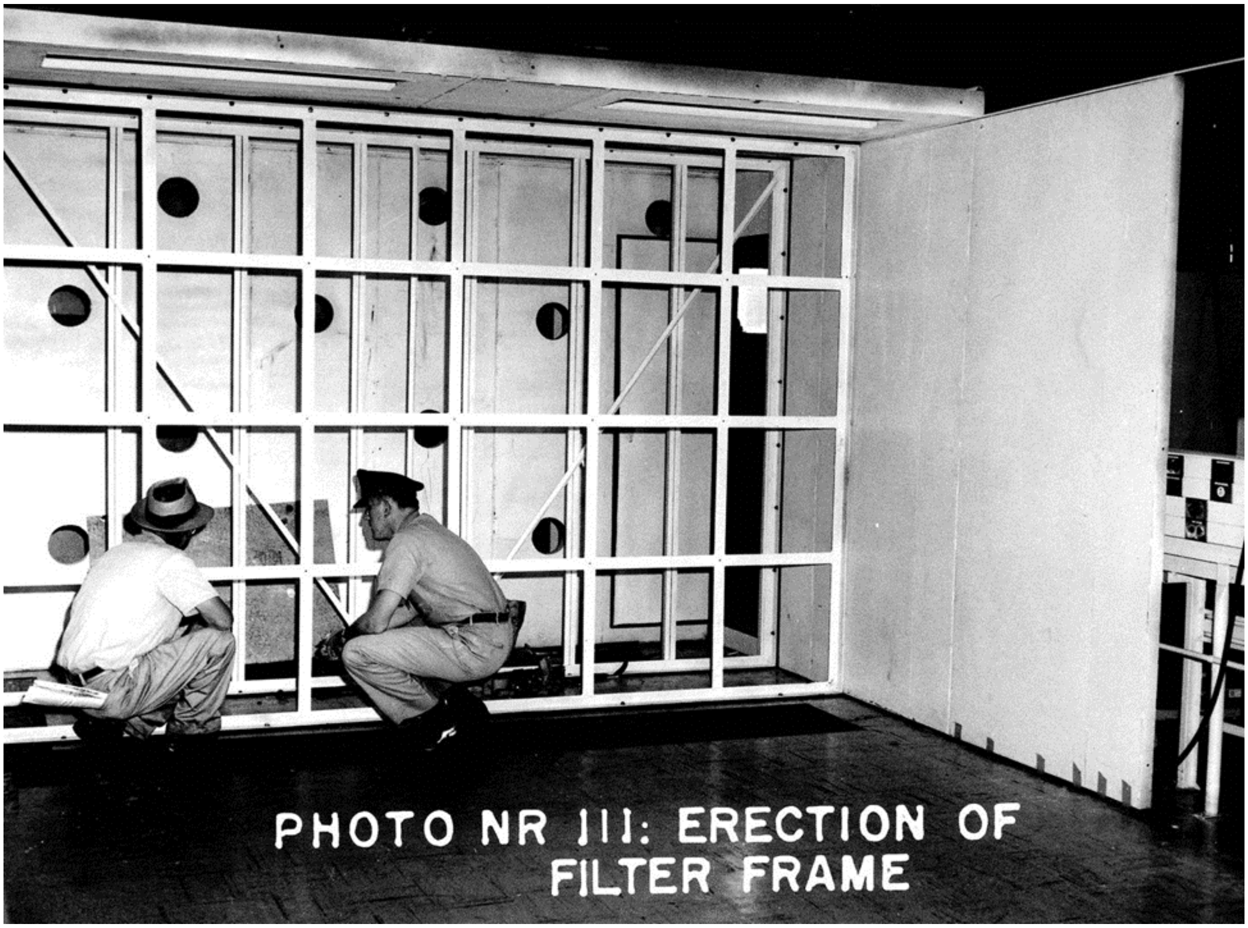

Figure 3. Laminar Flow Tunnel, Filter Frame. Robins AFB, Georgia, October 1962.

In 1962, the modular LF tunnel was designed to allow relocation of this unit for flexibility as new workloads were assigned to different clean rooms. This allowed disassembly of large equipment into smaller components for actual repair/modification in a higher-level clean room. The 18”x18” clean room pass-through openings in the LF tunnel allowed transfer of smaller components into the standard clean rooms.

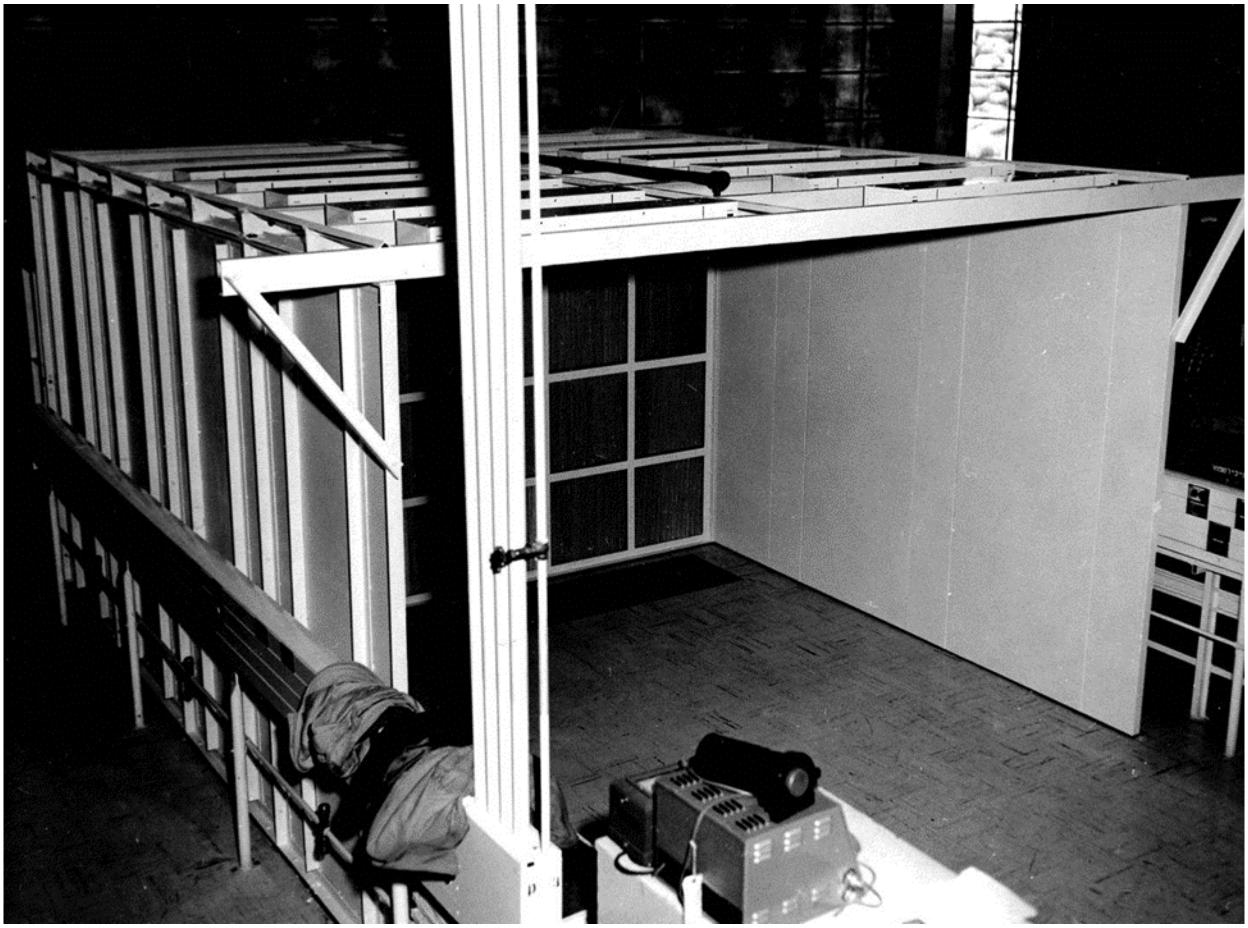

Figure 4. Completed Laminar Flow Tunnel. Robins AFB, Georgia. October 1962.

Clean Room Equipment Suppliers

Another issue was that the design and operation of contractors' inspection, modification, repair, and test equipment had often not been considered with respect to the generation of contamination and heat while the actual processes were being performed in the clean room. Frequently, on-site changes required contractors or facilities personnel to make modifications. WRAMA (Warner Robins Air Material Area) was the largest USAF micro-components repair and modification facility at that time and was an excellent place to study these clean room product changes. USAF engineering personnel and Original Equipment Manufacturers (OEM) were willing to cooperate about packaging and operations for their equipment, understanding they were doing operations in a special environment.

Many Difficult Times

The release of the original Air Force Manual in 1961, immediately got the attention of suppliers to the government. Many discussions were being shared about the concerns of the new standard and how soon it would be mandatory. The Air Force had been dealing with this certification situation for years and moved this document to a high priority. In fact, my management and personnel at Robins AFB described me as the “Clean Room Sheriff”. It was obvious that something needed to be done, but suppliers and contractors were not sure what they could do.

On September 15, 1961, the American Association of Contamination Control (AACC) held a special meeting in Chicago at the Illinois Institute of Technology. Representatives from the Department of Defense, contractors, academia, industry equipment suppliers, and several consulting firms attended this event. I was the only representative present for the USAF. The group in attendance had a difficult time covering all the issues during the day-and-a-half meeting. The meeting was a major event and provided many suggestions for a revised Air Force document.[3]

Following this meeting, USAF management immediately established a senior team of two officers and a USAF civilian engineer, Stewart Timmerman, to lead the project for revising the original 1961 Technical Order. Although changes to the manual were already in process at Hill AFB, no one from this team was present at the September 1961 AACC meeting. When official changes to the first TO manual were released on February 7, 1962, the disconnect between the group at Hill AFB and the team lead by Timmerman was noted. As a result, a new senior team was formed by two officers from Olmstead AFB, Middletown, Pennsylvania, and myself from Robins AFB, Georgia. USAF Lt. Philip “Doc” Austin, PhD, who later was a civilian cleanroom expert for 50 years,[2] became the fourth officer. The Director of Maintenance, a high-level USAF officer at Middletown Air Material Area, Olmstead AFB, was given responsibility to make changes to TO 00-25-203 (1961, and the pending changes, 1962), as soon as possible.

In July 1963, the revised Technical Order, TO 00-25-203, Standards and Guidelines for the Design and Operation of Clean Rooms and Clean Work Stations,[4] was released and it replaced the previous technical manuals. A new focus of this revised document was planning, design, operations, and testing to provide the various disciplines with their own standards and guidelines. This document also included two separate levels of design and operation for clean rooms and for clean work stations. The July 1963 version was published with a graph of particle size distribution curves.

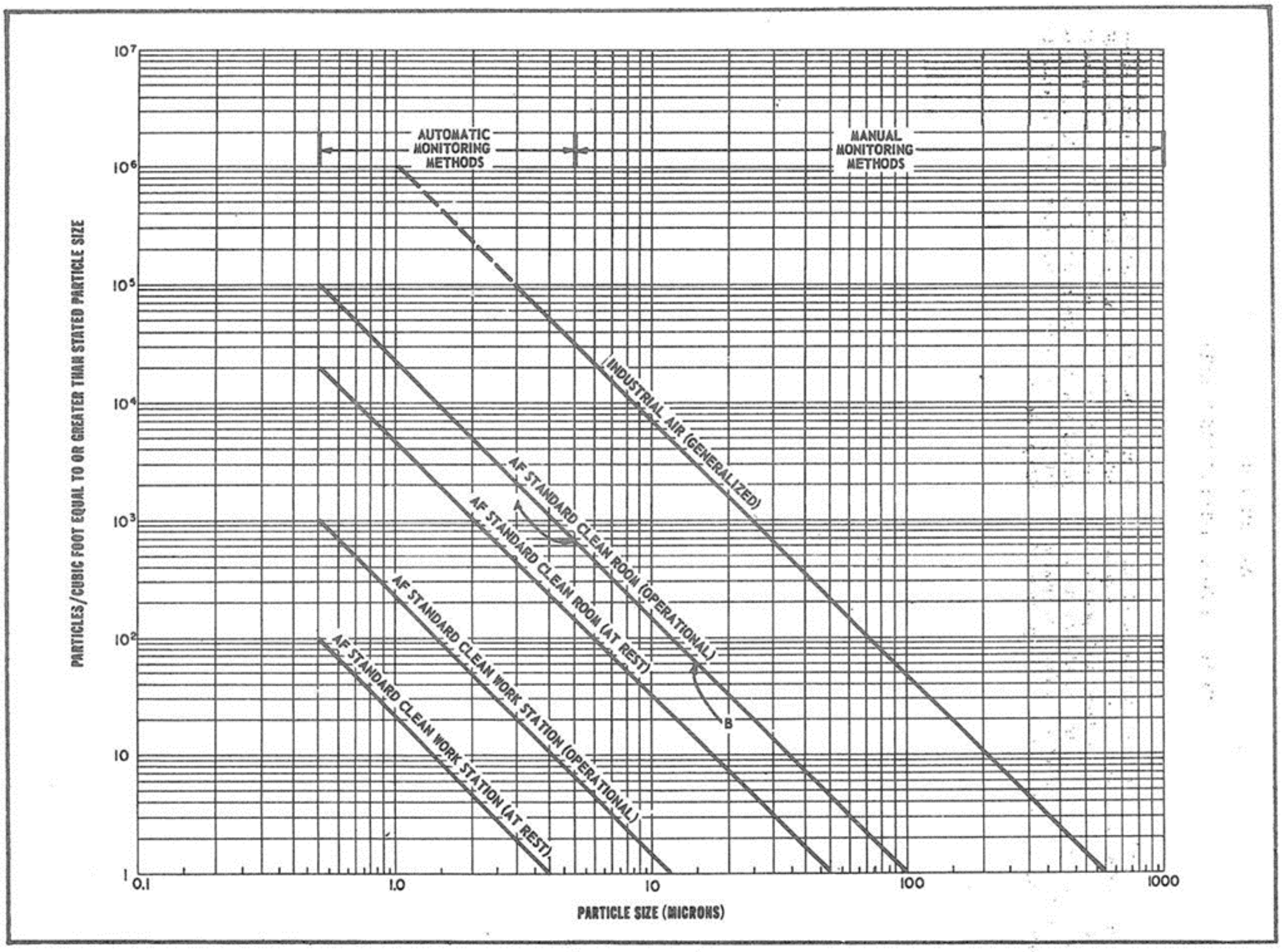

Figure 2A-1. Particle Size Distribution Curves

Figure 5. Excerpt from USAF TO 00-25-203 (July 1963) showing particle size distribution curves, Appendix II.

This graph (Figure 5) showed five curves, from 1.0 to 100,000 particles/cubic foot equal to or greater than stated particle size along the Y axis and 0.5 to 600 particle size (microns) µm along the X axis. The curves were as follows:

- Industrial Air (Generalized)
- USAF Standard Clean Room (Operational)
- USAF Standard Clean Room (At-Rest)
- Standard Clean Room (Operational)
- Standard Clean Room (At-Rest)

One of the biggest challenges encountered by the senior team was gathering data for verifying the size distributions curves in order to revise the original TO 00-25-203. This work took the majority of time for the testing and certification sections. Our USAF senior team set a starting point at 0.5 µm size particles as the lower limit using automatic monitoring methods for design and operations criteria. This was the lower limit that most USAF quality analysis laboratories had been attempting to validate using the manual count method and particle size distribution curves. The 100x microscope counting and sizing method had a lower limit of 5.0 µm resolution. [As noted below, electronic particle counters were being developed for clean room monitoring to the 0.3 µm lower limit to meet the first USAF Tech Manual (1961-1962).] The research for verifying the size distribution curves in the proposed revision involved testing in more than 1,000 clean room situations. Our literature search for small particle monitoring at the sub-micrometer level, and at low concentration levels in a cubic foot of air, revealed that existing test methods were not available to achieve our desired level of detection.

Lt. Austin led a project team at Olmsted AFB investigating the size distribution curves in clean rooms.[5] Robins AFB Quality Analysis Branch shared their data with Lt. Austin periodically. The Olmsted AFB group completed the revised publication and TO 00-25-203 (1963) was published July 15, 1963. One of the sites selected for testing was inside the astronaut's capsule before launch as part of Project Mercury. Once out of the earth's atmosphere, the intensity of the sunlight is approximately 100 times brighter than in a capsule before launch. One can see very small particles in a beam of high intensity light, such as sunlight, in normal room conditions. However, the perception to the eye is actually the scattered light from these small particles and not the physical particles. Only small particles in the 50-75 µm range can be seen by the unaided eye.

During the revision, it was my responsibility to travel to many industrial contractors, academic institutions, and military facilities to verify the methods, equipment, and QC reports. Two of the people I met at various places or conferences were Richard Cadle, PhD, from the National Oceanographic and Atmospheric Administration (NOAA) office in Boulder, CO, and Richard Feynman, PhD, from the California Institute of Technology (Caltech).

Dr. Cadle attended many AACC conferences and advised the military on new information they were collecting at NOAA. In 1960, NOAA sent its first satellite to collect data in the upper atmosphere. Dr. Cadle had hands-on particle counting experience and also designed methods and equipment for air analysis.

Dr. Feynman, a 1965 Nobel Laurate, known as the "Father of Nanotechnology", was a professor and international lecturer, who had also been involved in the Manhattan Project.[6] Dr. Feynman was a very interesting, humorous, and intellectual scientist and author. His well-known lecture in 1959, *There is Plenty of Room at the Bottom*, is credited as the concept for nanotechnology and nanoscience. His statement related to starting at the atomic and molecular size as building blocks for applications. I attended one of his lectures at Caltech in 1962 and afterwards talked with him about my assignment for clean room criteria and particle distributions. Since that was more than 60 years ago, I can only remember his humorous comment, which was along the lines of "WOW, that is impossible to generalize those particle distribution curves. There must be thousands of variables; and design at-rest is quite different than design in-use with equipment and people doing operations!" He was a theoretical physics professor teaching a course I never would have passed. At his death in 1988, he was considered one of the world's top five physicists.

New Test Method

The requirement to have a better method to count particles, 5.0 µm and larger, was a planned decision in revising the proposed Technical Order. This was one of the assignments I accepted. Personally, being trained by the Robins AFB Chemical Laboratory to perform the current method for counting particles in a Dunn Cell and being one of the qualified specialists, made me aware of the problems of the current published method. Researching the literature, I found a new method using the membrane filter (MF). A similar test method, but for liquids, had been developed by the Germans before WWII for sampling microbiological particles in drinking water. In 1952, the USPHS started testing the MF method for potable water. This MF method was used initially in the United States parallel to the approved MPN (Most Probable Number) procedure for determining safety of drinking water supplies. The USPHS gave final approval in 1962 for the US to accept this method for potable water. As a result, a new airborne particle test method using the MF had been tested for air sampling all small particles.

For air sampling, a stainless-steel filter holder with a disposable 47-mm plastic membrane filter disc with millions of 0.45-µm pores was used to collect particles on the filter's flat surface. The major advantage of this method was the use of a 100x magnification microscope that reliably measured 5.0 µm and larger particles, and simplified counting each particle's actual size. This procedure supported the size distribution curves to be included in the proposed July 1963 USAF Technical Order. Several different sized particles from 5.0 µm and larger could be counted and used on the log-log graph to determine much lower sized particle concentrations, below 5.0 µm. Also, the material of each particle could be identified and possibly verified as to a source. The MF procedure had been published as ASTM F25-63T, *Tentative Method for Sizing and Counting Airborne Contamination in Clean Rooms and Other Dust- Controlled Areas*.[7] The Society of Automotive Engineers' Aerospace Recommended Practice, ARP-743, *Procedure for the Determination of Particulate Contamination of Air in Dust Controlled Spaces by the Particle Count Method* [8] was also an approved membrane filter method for controlled spaces. Several years later, I was volunteer chairman of the ASTM (American Society for Testing and Materials) subcommittee that revised this test method to make the method easier for sampling and counting particles in cleanrooms.

Electronic Particle Counters in 1963

Electronic airborne particle counters were being developed in the early 1960s for the new cleanroom monitoring standards.[9] The selected measurement numbers were a 0.3 µm lower limit to a maximum of 10.0 µm for these instruments in an eight-channel register. A high-intensity visible light source was employed before laser instruments were developed. Robins AFB Manufacturing and Engineering had procured seven Royco particle counters in 1960 for the operating clean room facilities. Only three of these counters were actually being used to certify the newly constructed clean rooms. The contract also included a system of calibration, and specialists from the USAF Precision Measurement Laboratory (PML) at Robins AFB were trained by the Chemical Laboratory in the Quality Control Branch to perform the certification. Additionally, the contract provided for manufacturer's support through the periodic return of the instruments to their facility in California. Olmstead AFB had procured one of these units as well. Two significant issues occurred with the three instruments at Robins AFB:

1. The three units in the same identical sampling location in a clean room produced varying counts, as much as 100 percent difference.
2. The calibration procedure in Georgia for the three units gave varying results that were attributed to the transport of the units from the PML to the clean rooms by truck. In one case a distance of 3 miles, round trip.

Royco's technical services department was very responsive to critique, and Royco personnel visited Robins AFB. It was determined that the particle count range from 0.3 to 1.0 µm of the electronic instrument's 10 different counting settings were not reproduceable between the three particle counters. Therefore, the seven units at Robins AFB were returned to Royco, recertified, and returned to Robins PML for checking. The Robins Industrial Engineering Branch was given a task to develop a new method of calibration that was shared with Olmstead AFB PML. The seven particle counters were returned and activated in Georgia. It was also determined at Royco that the light source, a high-beam auto lamp, varied with different lots of lamps. This was reported, and a new specification was created for the purchasing of all future lamps by the USAF and by contractors.

Example of Quality Control Testing

QC testing within the various clean rooms at Robins AFB was interesting. When the original three instruments were brought to Robins, the facility management of each clean room had been offered a reward program for having the best clean room each month. The results were variable but predictable—not by management skills, but by the actual particle counter (tracked by serial number).

The highest instrument's counts were always high, and the lowest, always the lowest. The counts could also vary by more than 100 percent for the 0.3 and 0.5 µm channels of the counters. Also evaluated were the counts in clean rooms not in normal operations, as well as those where personnel were not working at night or on weekends. For the 0.3, 0.5, and 1.0 µm settings, results were less variable due to the low count levels. During these night and weekend periods, air handling, humidity, and temperature control were active. Manufacturing equipment and processes were inactive. In other words, this simulated design, or at-rest conditions.

From Robins AFB experiences across two years, it was recommended to the USAF senior team preparing the revised 1963 document that the lower limit be set at 0.5 µm, not 0.3 µm. Electronic particle counters were being used at this time in parallel with the manual testing method and size distribution curves.

Electronic particle counters for submicron monitoring in clean rooms were being developed using low-cost lasers in the late 1960s. This provided monitoring at < 0.3 µm. In the late 1970s, technology improved enough for the counters to monitor below 0.1 µm.[10] Sizing and counting individual particles with the laser-based instruments allowed lower detection with the illuminated region thousands of times brighter than the earlier visible light source. Microelectronics had improved to the point that the background noise level could be essentially cancelled. Test particles for this range were also defined for calibration of the laser units. Polystyrene latex microspheres were used and their size was verified with a transmission electron microscope. Therefore, the standards for monitoring and controlling particles below 0.3 µm were more reliable. Clean rooms for the semiconductor industry, where silicon particles in the < 0.1 µm range were present, justified these laser instruments. Ultra-low particulate air (ULPA) filters became available. Clean room standards were revised, and the laminar flow design of clean work stations and clean rooms were updated. (Note: A HEPA filter has a specification of 99.97% efficiency at 0.3 µm. An ULPA filter has a specification of 99.999% efficiency at 0.12 µm.)

Federal Standard 209

The September 1961 AACC meeting in Chicago (discussed in The First Resolutions section) was attended by representatives from the Department of Defense with concerns that TO 00-25-203 (1961) was not the only need and that a generalized federal document was justified. A separate group was selected to prepare a US federal standard using some information provided by the USAF senior team. Subsequently, Federal Standard 209 (FED-STD-209), *Clean Room and Work Station Requirements, Controlled Environment* was published on December 16, 1963.[11]

The initial difference between the two standards were the class designations: 1) Standard Clean Room (Operational and At-Rest) and Standard Work Station (Operational and At-Rest) for TO 00-25-203(1963) versus 2) FED-STD-209 particle classifications: Class 100, Class 10,000 and Class 100,000. Both standards relied on the size distribution curves and required automatic equipment for particle sizes 0.5 µm and larger employing light scattering principles. For particle sizes 5.0 µm and larger, microscopic counting of particles collected on a membrane filter, through which a sample of air had been drawn, was required. This caused confusion and TO 00-25-203(1963) was revised again and published on August 31, 1965, to follow Federal Standard 209 more closely.[12] However, because USAF and other military depots were focused on overhaul and repair, they generally did not require the lower particle control.

Department of Defense requirements now encompass design, construction, and operations of research, development, and new products facilities to meet International Organization for Standardization (ISO) 14644 requirements.[13] This ISO standard replaced FED-STD-209 when the official cancellation notice of FED-STD-209 was issued on November 29, 2001. USAF TO 00-25-203, TECHNICAL MANUAL, *CONTAMINATION CONTROL OF AEROSPACE FACILITIES*, *US AIRFORCE* (February 27, 2019), is currently revised and managed by Robins AFB, Georgia.[14]

A System Environmental Facilities Chart is provided as Table 1-1 in the revised TO 00-25-203 manual. Actually, this is the only document for cleanrooms that has a justification for the particle size relationship to the tolerances. The senior team preparing the draft for the 1963 Technical Order revision tried to include the relationship information, but due to time it was agreed the HEPA specification for particle size was acceptable.

The chart, titled MINIMUM MECHANICAL SYSTEM TOLERANCES and TYPE OF ENVIRONMENTAL FACILITY RECOMMENDED, is for USAF test, calibration, maintenance, and repair facilities only. Listed are minimum mechanical system tolerances (0.3 µm–25 µm) and Controlled Area (Class 300,000), Conventional Clean Room Class (100,000), Laminar Flow Clean Room (Class 10,000 or 1,000) and Laminar Flow chambers (Class 1,000 or 100). Any tolerance greater than 25 µm (0.001 inch) is considered air-conditioned space and is not covered by the

TO 00-25-203. The lower limit for particle size control is also 0.3 µm. The latest revision for the USAF standard was published on December 7, 2013, and Change 3 went into effect on February 27, 2019. It references ISO Standard 14644 for additional information. These latest revisions do not include the Conventional Clean Room Class 100,000 because the costs of laminar flow (unidirectional flow) clean room design and construction are lower than conventional clean rooms.

American Association for Contamination Control – Institute of Environmental Sciences, then Institute of Environmental Sciences and Technology

The AACC was a very active group and met several times a year at various locations. AACC members represented more than 1,000 specialists involved in controlled environments. Some had more than 15 years' experience in research, design, construction, testing, and operations for controlled areas. Figure 6 shows a semiannual group meeting at Robins AFB in March 1964. Lt. Frith is explaining to AACC members the particle counter research Robins AFB had performed in the early days and the modifications required. Some of the members looking on are Dr. John Anderson, Robert Peck, Walter Kenyon, Stewart Timmerman, Jack Eagleson, and Lt. Austin. This meeting was held to discuss the revised TO 00-25-203 (1963) and interview design, QC, and operations AFB personnel.

Early Pioneers

At the AACC meeting in Chicago, I met Alvin Lieberman, Amour Research. I had communicated with Mr. Lieberman by phone earlier and he gave me some very important basics about particle counters. A prototype counter was developed by Gucker in 1947, I believe at Indiana University, for single channel counting of 0.5 µm particles. In 1954, a multi-channel vacuum tube version of the previous design was produced at Amour Research Foundation. The Air Force had Amour Research build two R&D instruments (1954 and 1956) for cloud physics studies, but not commercially sized for portability. Lieberman and Stockham used these instruments for particle measurement in a clean room. Lieberman and Bill Zinke, (Royco Instruments) were my first particle mentors. I made two trips to review our AF Base results for calibration and statistical treatment with Al at Amour Research Foundation.

Willis Whitfield, Sandia National Laboratories, was a presenter at a AACC meeting in Boston in 1962. We discussed his methods for certifying LF clean rooms. He was attending to defend his Laminar Flow design for clean rooms, and many aerospace contractors were trying to prove their designs were better, since they had built and certified thousands of installations around the US. This meeting was before the 1963 publication of the revised Air Force TO. Lt. Austin and I chaired a discussion group, but we could not officially disclose the contents of the TO before its publication. I visited Willis in Albuquerque, NM, several times. Sandia personnel were involved in early work for the Federal Standard 209 and we shared our experiences with performance and cost of Laminar Flow Clean Rooms.

Figure 6. Lt. Frith Discussing the Calibration Procedure for Royco Particle Counters with AACC Members. AACC Meeting. Robins AFB, Georgia. March 1964.

AACC conducted conferences and training programs at the base. Figure 7 shows AACC members Frith, Austin, Mason Pilcher, Boyd Agnew, and AACC Executive Secretary Bill Maloney in a specially constructed LF tunnel at Robins AFB.

My original three years of active duty ended in July 1963, and the USAF management requested I extend my commitment to assist in the release of the revised TO 00-25-203 (1963). I extended my active duty nine months to support the particle counting requirements. I was promoted to captain and then served in the USAF Reserves for three years. This reserve assignment required two weeks' active duty, once a year. My civilian employer supported this commitment. I returned each year to Robins AFB, Georgia, and reported to the Directorate of Maintenance, Quality Control Branch. This was an interesting position as there were many requests for technical support for using the two levels of particle counting, manual and electronic.

Figure 7. AACC members Frith, Austin, Mason Pilcher, Boyd Agnew, and Bill Maloney (AACC Executive Secretary) in a specially constructed LF tunnel at Robins AFB. (The group was viewing particle counter data collected after AACC members in street clothing passed through the LF tunnel.) Robins AFB, Georgia. March 1964.

In 1974, a decision was made by the board of IES to merge AACC into its association. IES had been producing military and aerospace standards for many years, while AACC had become a clean room supplier-based organization. The space program, and landing a Man on the Moon in 1969, helped the associations focus on each of their missions. IES had proven its value over the years for successful, professional leadership. The merger between these two organizations proved very successful.

In the 1990s, the growth of IES and its membership brought together many new disciplines and specialists with an expanded knowledge base. In 1997, IES registered itself under a new name, Institute of Environmental Sciences and Technology (IEST) to eliminate confusion with another similarly-named association.

International Standards Organization

In the early 1990s, the need for a single standard to facilitate international trade was recognized. In 1993, based on a proposal written by IES, the American National Standards Institute (ANSI) was awarded the new cleanroom ISO technical committee. The Secretariat for ISO Technical Committee (ISO/TC) 209, Cleanrooms and associated controlled environments was delegated to

IES. Dick Matthews was the first chairman of the Technical Committee. Robert Mielke, was appointed secretary at its inception and continues to serve as the committee manager today. Anne Marie Dixon-Heathman serves as head of the United States delegation and chairman of the US Technical Advisory Group (US TAG) to ISO/TC 209.

IES was granted administrative responsibilities and the right to prepare and sell the published documents as part of its secretariat role. The similarity between the number for the ISO technical committee (ISO/TC 209) and FED-STD-209 was coincidence. Developed by IES, FED-STD-209, Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones was one of the key documents used by ISO/TC 209 to develop ISO 14644-1:1999, Cleanrooms and Associated Controlled Environments—Part 1: Classification of air cleanliness, and ISO 14644-2:2000, Cleanrooms and Associated Environments—Part 2: Specifications for testing and monitoring to prove continued compliance with ISO 14644-1.[13] Subsequently, ISO/TC 209 has published a total of 18 documents to provide guidance in the application of ISO 14644-1. Currently, ISO/TC 209 is comprised of 26 participating members (voting national standards bodies) and 22 observing (nonvoting) members, with Gordon Ely serving as the ISO/TC 209 chairperson.

FED-STD-209E was cancelled by the United States General Services Administration in 2001 as ISO 14644-1 replaced the need for two standards.

Summary

Many experienced professionals and members have contributed to these valuable documents across six decades. The aerospace, semiconductor, computer, medical devices, pharmaceutical, biotech, nanotech, and other industries, including the military, have benefitted from the volunteer effort to keep these standards current with the advancing technologies. The money saved by having standards and guidelines for controlled environments alone cannot be estimated, nor can the tireless efforts of many professional, skilled personnel be quantified. The dedicated work and progress to keep pace with technological changes and opportunities has herein been recorded. The longstanding contributions of IEST across all its divisions are recognized, and its leadership should be given credit for their accomplishments.

Thank you, IEST, for a job well done!

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References

1. Technical Manual TO 00-25-203, 1 March 1961, change 7 February 1962, *Standard Criteria for D*esign *and Operation of Clean Rooms*, Headquarters, US Air Force Air Material Command, OH, Published under the authority of Secretary of the Air Force.
2. Austin, Philip R, 1991, Encyclopedia of Clean Rooms/ White Rooms/Sterile Rooms, Contamination Control Seminars, Livonia, MI.
3. American Association of Contamination Control (AACC), September 15, 1961, *Proceedings of the Joint Meeting between the AACC and Members of the US Army*,

US Air Force, US Navy, National Aeronautics and Space Administration and the National Bureau of Standards. Armour Research Foundation, Illinois Institute of Technology, Chicago, AACC, Detroit, MI.

4. TECHNICAL ORDER, T.O. 00-25-203, 1 July 1963, *STANDARDS AND GUIDELINES FOR DESIGN AND OPERATION OF CLEAN ROOMS AND CLEAN WORK STATIONS*, Olmstead AFB, PA. Under the Authority of the Secretary of the Airforce.
5. SIZE DISTRIBUTION RELATIONSHIPS FOR AIRBORNE PARTICULATE MATTER (Report 17.0003.04.02) Project Manager Austin P.R, July 15, 1963, Industrial Engineering Division, Directorate of Maintenance, Headquarters MAAMA, Olmstead AFB, PA
6. Feynman, Richard, Feynman Biography, *Wikipedia*, October 13, 2023, Wikipedia.org/wiki/Richard Feynman
7. ASTM F25-63T, *Tentative Method for Sizing and Counting Airborne Contamination in Clean Rooms and Other Dust- Controlled Areas*, ASTM International, West Conshohocken, PA, (Replaced in 1968, reconfirmed in 1999 by ASTM)
8. ARP 743, 1960, *Procedure for Determination of Particulate Contamination of Air in Dust Controlled Spaces by the Particle Count Method*, Society of Automotive Engineers, Detroit, MI, (Method Cancelled, May 26, 2010 by SAE)
9. Liberman, Albert (2005), "Optical Particle Counters: Then, Now and Tomorrow," pp. 157-163. History and Reviews Aerosol Science, G.J. Sem, et al. (Editors) American Association for Aerosol Research.
10. Knollenberg, Robert, The Measurement of Particle Sizes Below 0.1 Micrometer, The *Journal of Environmental Sciences*, 32-47, January/February 1985. IEST, Schaumburg, IL.
11. FEDERAL SPECIFICATIONS, December 16, 1963, Federal Standard No 209, *CLEAN ROOMS AND WORK STATIONS REQUIRMENTS, CONTRILLED ENVIRONMENT*, GSA, Washington, DC.
12. TECHNICAL ORDER T.O. 00-25-203, 31 August 1965, *STANDARDS AND GUIDELINES FOR THE DESIGN & OPERATION OF CLEAN ROOMS AND CLEAN WORK STATIONS*, Headquarters WRAMA, Directorate of Materials Management, Robins AFB, GA, Published under Authority of the Secretary of the Air Force.
13. ISO 14644-1:1999, Cleanrooms and associated controlled environments—Part 1, Classification of air cleanliness; and 14644-2:2000, Cleanrooms and associated controlled environments—Part 2, Specifications for testing and monitoring to prove continued compliance with ISO 14644-1, International Standards Organization, Secretariat: IEST, Schaumburg, IL.
14. TECHANICAL MANUAL T.O. 00-25-203, 7 DECEMBER 2013, Changes 3, 27 February 2019, CONTAMINATION CONTROL OF AEROSPACE FACILITIES, Robins AFB, GA, Technical Order Management Agency. Published under the Authority of the Secretary of the Air Force.

About the Author

Clifford "Bud" Frith has enjoyed a challenging career focused on contamination control, environmental sciences, and standards for ultrapure processes and analytical applications. A 1960 graduate of the Virginia Military Institute and commissioned in the USAF, he was a pioneer in the space program as a Chemical Engineering Officer. Leading programs to develop new methods and standards for ultra-purity, he is an author and international lecturer. Bud is an IEST Fellow and a Technical Editor for the *Journal of the IEST*. Lt Frith was on the original team to develop major revisions for USAF TO 00-25-203, *Standards and Guidelines for Design and Operation of Clean Rooms and Clean Work Stations.* His focus and experiences were "how clean is clean." In the early 1980s, Bud was CEO and founder of two technology-based instrument companies for quality measurement and control of ultrapure water and environments. These companies focused on special facilities, processes, and analysis. ANATEL® Corp developed the first online, real-time instrument to measure total organic carbon (that is, TOC) in ultrapure water at the parts per billion level. The second company developed an industrial PC-based data acquisition system for monitoring critical fluids and controlled environments. He is a specialist in alternate methods for improving distilled water for the laboratory and critical process water. Bud has chaired ASTM and NCCLS [currently named Clinical Laboratory Standards Institute (CLSI)] subcommittees for laboratories developing standards. He has served on boards of private and nonprofit corporations and held senior executive positions in public corporations. He is currently involved in projects for nanotechnology applications and was a pioneer before this term was commonly used. He states "nanotechnology is becoming the next big advancement for our technologies and commercial economies."

IEST is the leading global nonprofit contamination control society and Secretariat for ISO Technical Committee 209 (ISO/TC 209), the committee developing the ISO 14644 Standards. IEST has served as the Secretariat for ISO/TC 209 for more than 30 years with an established international leadership role based on more than 50 years of expertise in cleanrooms and controlled environments.