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Standard Practice for Design and Construction of Aerospace Cleanrooms and Contamination Controlled Areas[1]

This standard is issued under the fixed designation E 2217; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 The purpose of this practice is to provide design and construction guidelines for contamination controlled facilities used in the assembly and integration of aerospace hardware. The guidelines herein are intended to ensure that the facilities, when used properly, will meet the cleanliness requirements of aerospace hardware and processes. The objective is to limit contamination due to the deposition of particulate and molecular contaminants on flight hardware surfaces.

1.2 One cleanliness classification of a facility is the airborne particle concentrations in accordance with ISO 14644-1 and 14644-2. Airborne particle concentrations in accordance with FED-STD-209E are included for reference. This simple classification is inadequate to describe a facility that will support the assembly and integration of spacecraft. The extended duration of hardware exposure during fabrication and testing, the sensitivity of the hardware to hydrocarbons and other molecular contaminants, and the changing requirements during assembly and integration must be considered in addition to the airborne particle concentrations.

1.3 The guidelines specified herein are intended to provide facilities that will effectively restrict contaminants from entering the facility, limit contamination generated by and within the facility, and continuously remove airborne contaminants generated during normal operations. Some items of support hardware, such as lifting equipment, stands, and shoe cleaners, are addressed since these items are often purchased and installed with the facility and may require accommodation in the design of the facility.

1.4 Active filtration of molecular contaminants (such as hydrocarbons, silicones, and other chemicals) is discussed. Such active filtration of molecular contaminants may be required for the processing of highly sensitive optical devices, especially infrared and cryogenic sensors. Control of microbiological contamination is not included although HEPA (High Efficiency Particulate Air) filtration will provide some control of airborne bacteria, spores, and other viable contaminants that are typically carried on particles of sizes 0.3 μm and larger. Control of radioactive contamination and accommodation of very hazardous materials such as propellants, strong acids or caustics, or carcinogens are not addressed.

1.5 No facility will compensate for excessive contamination generated inside the facility. In addition to an effective facility design, the user must also institute a routine maintenance program (see Practice E 2042) for the facility, and personnel and operational disciplines that limit the transfer of contaminants through entry doors and contaminant generation inside the facility.

1.6 This practice only addresses guidelines for contamination control in facility design. It must be implemented in compliance with all mandatory government and regulatory building and safety codes. References to related cleanroom standards and U.S. building codes and standards may be found in IEST-RP-CC012.

1.7 The values stated in SI units are to be regarded as the standard. The values given in parentheses are provided for information only and are not considered standard.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 595 Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment[2]

E 1216 Practice for Sampling for Particulate Contamination by Tape Lift[2]

E 1234 Practice for Handling, Transporting, and Installing Nonvolatile Residue (NVR) Sample Plates Used in Environmentally Controlled Areas for Spacecraft[2]

E 1235 Methods for Gravimetric Determination of Nonvolatile Residue (NVR) in Environmentally Controlled Areas for Spacecraft[2]

E 1548 Practice for Preparation of Aerospace Contamination Control Plans[2]

E 2042 Practice for Cleaning and Maintaining of Controlled

[1] This practice is under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.05 on Contamination.

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[2] *Annual Book of ASTM Standards*, Vol 15.03.

Areas and Cleanrooms[2]
E 2088 Practice for Selecting, Preparing, Exposing, and Analyzing Witness Surfaces for Measuring Particle Deposition in Cleanrooms and Associated Controlled Environments[2]
F 24 Method for Measuring and Counting Particulate Contamination on Surfaces[2]
F 25 Test Method for Sizing and Counting Airborne Particulate Contamination in Cleanrooms and Other Dust-Controlled Areas Designed for Electronic and Similar Applications[2]
F 50 Practice for Continuous Sizing and Counting of Airborne Particles in Dust-Controlled Areas and Cleanrooms Using Instruments Capable of Detecting Single Sub-Micrometer and Larger Particles[2]

2.2 *ISO Standards:*[3]

ISO 14644-1 Cleanrooms and Associated Controlled Environments Part 1: Classification of Air Cleanliness
ISO 14644-2 Cleanrooms and Associated Controlled Environments Part 2: Specifications for Testing and Monitoring to Provide Continued Compliance with ISO 14644-1
ISO 14644-3 Cleanrooms and Associated Controlled Environments Part 3: Metrology and Test Methods
ISO 14644-4 Cleanrooms and Associated Controlled Environments Part 4: Design, Construction and Start-up

2.3 *Institute of Environmental Science and Technology Standards:*

IEST-RP-CC001 HEPA and ULPA Filters[4]
IEST-RP-CC006 Testing Cleanrooms[4]
IEST-RP-CC007 Testing ULPA Filters[4]
IEST-RP-CC012 Considerations in Cleanroom Design[4]
IEST-RP-CC022 Electrostatic Charge in Cleanrooms and Other Controlled Environments[4]
IEST-RP-CC034 HEPA and ULPA Filter Leak Tests[4]
IEST-STD-CC1246 Product Cleanliness Levels and Contamination Control Program[5]

2.4 *U.S Government Standards:*

FED-STD-209E Airborne Particulate Classes for Cleanrooms and Clean Zones[6]

2.5 *Other Publications:*

Procedural Standards for Certified Testing of Cleanrooms, National Environmental Balancing Bureau (NEBB)[7]

3. Terminology

3.1 *Definitions:*

3.1.1 *aerosol, n*—a gaseous suspension of fine solid or liquid particles.

3.1.2 *airfilters:*

3.1.2.1 *HEPA (High Efficiency Particulate Air) filter, n*—a particulate air filter having a minimum particle collection efficiency of 99.97 % of particles greater than 0.3 µm in accordance with IEST-RP-CC001.

3.1.2.2 *ULPA (Ultra Low Penetration Air) filter, n*—a particulate air filter having a minimum particle collection efficiency of 99.999 % of particles of sizes equal to and larger than 0.12 µm.

3.1.2.3 *prefilters, n*—air filters that are installed upstream of the HEPA or ULPA filters.

3.1.2.4 *Discussion*—These usually consist of rough filters and medium efficiency filters that remove larger particles than are removed by the HEPA and ULPA filters; They are used to reduce the number of particles trapped on the high efficiency filters, thereby extending the lifetimes of the HEPA and ULPA filters.

3.1.3 *airflow:*

3.1.3.1 *unidirectional airflow, n*—controlled airflow through the entire cross-section of a cleanroom or clean zone with a steady velocity and approximately equal streamlines.

3.1.3.2 *Discussion*—The airflow in a cleanroom may be either vertical down-flow or horizontal with air leaving the room either through nearly continuous floor or wall vents. Equipment and personnel in the room will cause air turbulence, but the airflow is still considered unidirectional.

3.1.3.3 *nonunidirectional airflow, n*—air distribution where the supply air entering the cleanroom or clean zone mixes with the internal air by means of induction.

3.1.3.4 *Discussion*—Air typically enters through registers distributed around the room above the working area and exits through registers at floor level.

3.1.3.5 *mixed airflow, n*—air distribution in a cleanroom or clean zone in which the airflow is a mixture of both unidirectional and nonunidirectional.

3.1.3.6 *Discussion*—Different locations in a cleanroom can have different types of airflow. This is especially true in large cleanrooms. A cleanroom design may include mixed airflow.

3.1.4 *changing room, n*—room where people using a cleanroom change into, or out of, cleanroom apparel.

3.1.5 *cleanroom, n*—a specialized enclosed room employing control over the airborne particle concentrations, temperature, humidity, pressure, molecular contaminants, and operations.

3.1.5.1 *cleanroom (alternate), n*—a room in which the concentration of airborne particles, temperature, humidity, pressure, molecular contaminants, and operations are controlled, and which is constructed and used in a manner to minimize the introduction, generation, and retention of contaminants inside the room.

3.1.6 *cleanroom occupancy states:*

3.1.6.1 *as-built, adj*—condition where the installation is complete with all services connected and functioning but with no equipment, flight hardware and materials, or personnel present.

3.1.6.2 *Discussion*—For contractual purposes, the parties involved should have an agreement that defines this state.

3.1.6.3 *at-rest, adj*—condition where the installation is complete with equipment installed and operating in a manner

[3] Available from International Organization for Standardization (ISO), 1 rue de Varembé, Case postale 56, CH-1211, Geneva 20, Switzerland.
[4] Available from the Institute of Environmental Sciences and Technology, 940 East Northwest Highway, Mount Prospect, IL 60056.
[5] This replaces MIL-STD-1246C which is inactive.
[6] This standard was cancelled 29 Nov. 2001 and is replaced by ISO 14644-1 and ISO 14644-2. Copies of FED-STD-209E are available from the Institute of Environmental Sciences and Technology, 940 East Northwest Highway, Mount Prospect, IL 60036, and from U.S. government sources.
[7] National Environmental Balancing Bureau, 8575 Grovemont Circle, Gaithersburg, MD 20877-4121.

agreed upon by the customer and supplier, but with no personnel present.

3.1.6.4 *operational, adj*—condition where the installation is functioning in the specified manner, with the specified number of personnel present and working in the agreed upon manner.

3.1.7 *clean zone, n*—dedicated space in which the concentration of airborne particles is controlled, which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the zone, and in which other relevant parameters, for example, temperature, humidity, pressure, and molecular contaminants, are controlled as necessary.

3.1.8 *contaminant, n*—any particulate, molecular, nonparticulate, and biological entity that can adversely affect the product or process.

3.1.9 *contaminant deposition, n*—particulate and molecular contaminants that form on surfaces resulting from processes such as fallout, condensation, electrostatic attraction, and other mechanisms.

3.1.10 *contamination controlled area, n*—a specialized enclosed facility employing control over the particulate matter in air, temperature, and humidity that may not meet the requirements of ISO 14644-1 or FED-STD-209E because of no HEPA or ULPA type filters.

3.1.10.1 *Discussion*—For example, without a final stage of HEPA or ULPA filters, the airborne particle concentrations may only meet ISO Class 8.5 (FS209E Class 300 000) for particles equal to and greater than 0.3 µm but may meet ISO Class 8 (FS209E Class 100 000) for particles equal to and greater than 5 µm.

3.1.11 *electrostatic discharge (ESD), n*—the rapid, spontaneous transfer of electrostatic charge induced by a high electrostatic field.

3.1.11.1 *Discussion*—Usually, the charge flows through a spark between two bodies at different electrostatic potentials as they approach one another.

3.1.12 *electromagnetic interference (EMI), n*—interference, generally at radio frequencies, that is generated inside systems, as contrasted to radio-frequency interference coming from sources outside a system.

3.1.13 *facility (clean facility), n*—the total real property required to accomplish the cleanroom functions.

3.1.13.1 *Discussion*—This includes all the buildings, cleanrooms, offices, laboratories, storage areas, HVAC equipment, and other support areas for operations and personnel.

3.1.14 *gas phase adsorber cell, n*—a modular container for an adsorbent to trap contaminant gases from air and other gases used in processing.

3.1.15 *installation, n*—cleanroom or one or more clean zones, together with all associated structures, air-treatment systems, services, and utilities.

3.1.16 *macroparticle, n*—a particle with an equivalent diameter greater than 5 µm.

3.1.16.1 *Discussion*—The M descriptor defines the measured or specified concentrations of macroparticles per cubic meter of air. This is defined in ISO 14644-1.

3.1.17 *monitoring, n*—observations made by measurement in accordance with a defined method and plan to provide evidence of the performance of an installation.

3.1.18 *nonvolatile residue (NVR), n*—contaminant residue without distinct dimensions. It typically consists of hydrocarbons, silicones, and other higher molecular weight species deposited through condensation, direct contact transmission (that is, fingerprints) or as residue remaining after evaporation of a liquid.

3.1.19 *outgassing, n*—the evolution of gas from a material, usually in a vacuum. Outgassing also occurs in a higher pressure environment.

3.1.19.1 *Discussion*—While outgassing is typically considered a vacuum phenomenon, some materials, such as polyvinyl chloride, contain volatile components, such as plasticizers, that will diffuse from bulk materials and evaporate under standard temperatures and pressures. These volatile components are highly contaminating to sensitive aerospace hardware.

3.1.20 *particle fallout, n*—particulate matter that accumulates on surfaces due to gravity settling. This matter is often of a particulate size larger than that measured by airborne particle counters.

3.1.21 *radio-frequency interference (RFI), n*—interference from sources of energy outside a system or systems, as contrasted from electromagnetic interference generated inside systems.

3.1.22 *test aerosol, n*—a gaseous suspension of solid or liquid particles, or both, with known and controlled size distribution and concentration.

4. Significance and Use

4.1 This practice describes and defines factors to be taken into consideration when designing and fabricating a cleanroom or controlled area that is used for aerospace operations and fabrication. Following the suggestions herein should provide a facility that is more capable of meeting performance requirements and that will offer protection against contamination for objects fabricated and processed in such a facility.

5. Planning and Development of Performance and Design Requirements

5.1 *Purpose of a Cleanroom*—A cleanroom provides three functions for a process:

5.1.1 Clean air with temperature and humidity control,

5.1.2 Control of contaminants generated within the room, and

5.1.3 Control of the transfer of contaminants from outside the room.

5.2 *Planning*—The first step is to determine the types of operations to be performed in the cleanroom and cleanliness requirements of the hardware to be processed. Alternative designs are studied and preliminary requirements are developed during the planning phase.

5.3 *Performance and Design Requirements*:

5.3.1 The cognizant program materials and processes engineer or contamination control engineer and facility engineer determine the requirements for a cleanroom or contamination-controlled area. These requirements may include, but are not limited to the following:

5.3.1.1 Maximum allowable airborne particle concentrations in the operational condition,

5.3.1.2 Types of airflow,

5.3.1.3 Room air change rates or air velocities,

5.3.1.4 Maximum allowable particle deposition,

5.3.1.5 Maximum allowable airborne and surface concentrations of molecular contaminants,

5.3.1.6 Types of air filters,

5.3.1.7 Need for and properties of piped in fluids (compressed air, nitrogen, helium, water, and so forth),

5.3.1.8 Need for built-in equipment (cranes, platforms, hoists, and so forth),

5.3.1.9 Overall layout and process flow,

5.3.1.10 EMI and RFI requirements, and

5.3.1.11 ESD requirements.

5.3.2 The cleanroom and clean facility requirements are based on the cleanliness requirements of the hardware to be processed and the types of operations to be performed in the cleanroom. The requirements should consider, as much as possible, future changes in requirements so that the facility does not become obsolete in a short time. Some enhancements do not result in a significant increase in cost if implemented in the original design. Another approach is designing to allow enhancements to be added later if required.

5.3.3 A contamination sensitivity analysis may be performed and contaminant allocations derived to determine facility cleanliness requirements during each phase of assembly and integration. Further information on determining cleanliness requirements is found in Practice E 1548.

5.3.4 Cost analyses are necessary to evaluate the alternative design approaches.

6. General Design Practice

6.1 *Design Considerations*:

6.1.1 The purpose of a cleanroom is to protect the hardware and processes. Ideally, the cleanroom should be designed around the processes and operations to be performed in the cleanroom. However, a typical situation involves designing a multipurpose cleanroom. Each space system is unique and may have different requirements. Consideration should be given to including multiple requirements in the design. This can be accomplished in the initial construction or by allowing for the inclusion of additional performance in the future when needed. Cost-benefit analyses should be used to evaluate alternative designs.

6.1.2 Spacecraft assembly and integration are usually considered batch processes. Operations are performed sequentially on each spacecraft, and different operations may have different cleanliness requirements. Design of the clean facility should consider these different operations and requirements.

6.2 ISO 14644-4 and IEST-RP-CC012 provide guidelines for the design and construction of cleanrooms. The cognizant contamination control and facility engineers should do detailed design and operational analyses to select the design that meets the spacecraft processing requirements.

6.3 *Clean Zones*:

6.3.1 Under some circumstances, cleanliness requirements can be achieved using inexpensive localized controls such as soft wall enclosures (clean tents) and portable hard-walled enclosures. These can provide either unidirectional or nonunidirectional, filtered airflow. They must be located within a facility that provides the necessary temperature, humidity and molecular contaminant controls required to support the requirements for the hardware unless they have their own HVAC system. When required, self-contained temperature and humidity control can be provided.

6.3.2 Air curtains and other methods of controlling air distribution can be used to protect clean zones from airborne contaminants.

6.3.3 Operations and procedures can be controlled to reduce contamination from people and activities in the specified clean zone.

6.4 *Hazards*:

6.4.1 Cleanroom facility design should consider potential hazards to personnel and products. Risk-cost-benefit analyses should be performed to determine the design features that are required to achieve acceptable risks. Operational solutions to meeting the risk requirements should be considered in coordination with design solutions.

6.4.2 Equipment failures and human errors can result in damage to hardware and injuries to personnel. It is important to consider single point failure modes, equipment and human, and their possible effects on products, processes, and personnel. Designing so that two or more failures are required to result in a system failure reduce the probability for a system failure.

6.4.3 *Electrical Power*—Electrical power failures will shut down equipment, instrumentation, and lighting. Critical items should have an alternative source of power. The switch from the main power source to the alternative power source may result in a short time of power interruption and transient effects. Equipment and processes should be able to survive these effects. Equipment that is not critical should automatically shut down in a safe mode. Restart when power resumes should not damage equipment or processes. Manual restart should be considered to ensure that the equipment is operating properly.

6.4.4 *Cooling Water*—Cooling water failure can shut down many types of equipment. Equipment should be able to shut down safely without damage to the equipment or to the process.

6.4.5 *HVAC*—The shut down of the HVAC system or failures of components such as filters, fans, and air conditioning should be evaluated for effects on hardware and processes. Both facility design and operational procedure solutions should be considered.

6.4.6 *Seismic and Weather Events*—Severe natural events, such as earthquakes and hurricanes, should be considered in the design of clean facilities. The probability of occurrences and severities should be considered. Design should consider various levels of severity. One level is the ability for the hardware and processes to survive with no damage or down time. The next level is the ability for the facility to survive, but some damage to hardware and processes is allowed. The third level is that damage to hardware, processes, and facility structure is allowed, but personnel are protected.

7. Detail Design Guidelines

7.1 *Airflow and Pressure*:

7.1.1 *Airflow Parameters*—The airflow patterns and velocities and room air change rates in a cleanroom affects the class of cleanliness that can be maintained during a given operation.

Non-unidirectional flow cleanrooms rely on air dilution to continuously remove contaminants generated within the room. Unidirectional flow is more effective in continuously sweeping particles from the air, but must be properly balanced and maintained with associated higher airflows and thus higher operating costs.

7.1.1.1 *Air Change Rate*—The desired air change rate is based on the required cleanliness class of the room air under operational conditions and the generation of contaminants (density of operations) expected in the room. The level and types of activities in the room affect the numbers of particles generated. Five to twenty air changes per hour are typical for a large, low density nonunidirectional airflow cleanroom. The lower the class of air for operational conditions, the greater the number of air changes is required to remove sufficient particles to meet requirements. In unidirectional flow cleanrooms, the air change rate is a result of the required filter face velocity and the size of the room. The design may allow for variable air change rates. This can be used to reduce electrical power consumption when the process does not require the high air change rates or when the cleanroom is not being used.

7.1.1.2 *Filter Face Velocity*—Filter face velocity is specified in unidirectional flow cleanrooms. Typical filter face velocities are 0.46 to 0.56 m/s (90 to 110 ft/min). Lower face velocities may not be effective in removing airborne particles but may reduce air turbulence. Higher face velocities may stress the filters and cause excessive air turbulence.

7.1.1.3 *Unidirectional Flow*—Filter face velocities must be balanced to within ±10 % to achieve effective, uniform, unidirectional airflow. The configuration of the room and the location of large equipment must also be carefully considered to prevent dead zones, turbulence, and reverse flow. A "smoke test," in which a cleanroom compatible white vapor is released from a capsule or a smoke generator to indicate air currents, may be useful to reveal problem areas. Water droplets have been used to avoid permanent contamination from solid and liquid aerosols. Strips of thin metallized films may also be used to determine the directions of flowing air.

7.1.2 *Positive Pressure*:

7.1.2.1 A positive pressure must be maintained over the pressure in adjacent areas of lesser cleanliness to prevent infiltration of external contamination through leaks and during the opening and closing of personnel doors. Pressure differentials in the range of 5 to 20 Pa (0.02 to 0.08 in. of water) are frequently used. Where several cleanrooms of varying levels of cleanliness are joined as one complex, a positive pressure hierarchy of cleanliness levels should be maintained, including airlocks and changing rooms.

7.1.2.2 Higher pressures may be required when outside air pressures exceed inside pressures and result in an increased leakage into the cleanroom. An example is higher pressures resulting from high winds.

7.1.2.3 When hazardous materials, such as propellants and some biological materials, are being processed, it is necessary to maintain the room at a lower pressure than surrounding rooms. This is necessary to reduce the probability of the hazardous material escaping from the room. The design of facilities for the handling of hazardous materials must consider the required operations to be performed as well as the type of hazards involved.

7.2 *Materials of Construction*:

7.2.1 *General Materials Selection*—Cleanrooms must be constructed of abrasion resistant, non-shedding materials. Conventional materials of construction such as wood, carpet, flat latex paint, and acoustic tile shed particles continuously during their life and are not acceptable for use in cleanrooms.

NOTE 1—Materials and equipment specified for use in cleanrooms are sometimes described as compatible with or meeting the requirements of a particular class of cleanroom air per ISO 14644-1 or FED-STD-209. These documents only apply to concentrations of airborne particles and do not contain any requirements for materials and equipment.

7.2.2 *Outgassing*—Outgassing from materials is a potential contaminant for spacecraft. Materials of construction should be selected to minimize outgassing and VCM at the expected operating temperatures in the cleanroom. Additional requirements may be added if the spacecraft contains components that have specific, known sensitivities. Materials maybe selected based on the Test Method E 595 screening test, and existing databases for spacecraft materials may be used. However, some materials suitable for use at normal cleanroom temperatures will decompose when subjected to the 125°C test temperature. Performing the Test Method E 595 test at a lower temperature, such as 65°C, has been successful for the screening of cleanroom materials.

7.2.3 *Cleaning*—Due to the frequent cleaning performed on cleanroom surfaces, materials that are hydrophilic or degrade in water are generally unacceptable.

7.2.4 *Textured Surfaces*—All materials shall have a smooth, cleanable finish. Textured surfaces should be limited to those required for safety reasons (such as floors). Textures used must be compatible with planned cleaning methods.

7.2.5 *Preferred Materials*—Uncoated materials recommended for use in cleanrooms include stainless steels, Formica, fluoropolymers, polypropylene, polyester, and anodized aluminum. Bare polished or brushed aluminum may be acceptable provided it is protected from exposure to relative humidities above 60 %. Properly anodized aluminum is recommended to control corrosion and reduce particle generation.

7.2.6 *Electrostatic Discharge (ESD)*—Many of the nonmetallic materials suitable for use in a cleanroom will also generate an electrostatic charge. Precautions must be taken in facility design and operations to prevent damage to ESD sensitive equipment from facility materials of construction.

7.2.7 *Excluded Materials*—Materials that are unacceptable for use in cleanrooms include wood, cork, carpet, fabric curtains, exposed gypsum board, exposed plaster, and acoustic tile. Steel and other non-corrosion resistant metals must be painted or treated to prevent corrosion. Zinc and cadmium treated steels are not recommended for use in spacecraft cleanrooms since particles released from these materials are unstable in a vacuum. Cadmium is toxic and is being removed from use per federal mandate.

NOTE 2—Fabrics impregnated with low outgassing, cleanable polymers, such as fluorocarbons, are acceptable in cleanrooms. These are frequently used as movable walls and other enclosures.

7.3 *Materials Application*:

7.3.1 *Surface Preparation*—Proper surface preparation prior to the application of a paint or coating in a cleanroom is critical to the success of the application. The manufacturer's instructions must be followed precisely, including all precleaning and surface texturing. For applications such as troweled epoxy flooring, only experienced and qualified contractors should be used.

7.3.2 *Corrosion Protection*—All cleanroom materials and equipment must be protected from corrosion prior to and during installation. At no time should cleanroom interior material, equipment, ducts, or HVAC system components be stored outdoors without proper protection.

7.4 *Enclosure*:

7.4.1 *Floors*—All cleanroom floors must, as a minimum, provide a complete air seal and vapor barrier. Cleanrooms built over non-humidity-controlled basements, as well as those on exposed or slab foundation, must protect the floor treatment or paint from moisture permeation.

7.4.1.1 *Floor Finishes*—The preferred floor finish for aerospace cleanrooms is a troweled epoxy. A primer must be used to ensure proper adhesion to the base material. Melamine laminate, including melamine laminate computer flooring, is also acceptable. These materials are also available with static-dissipative additives. Vinyl flooring may be unacceptable in some aerospace cleanrooms due to the presence of plasticizers. Compatibility with solvents and chemicals to be used in the room must be considered.

7.4.1.2 *Coving*—A coving or fillet seal should be used between the floor and the wall. A radius of 25 mm (1 in.) or greater is recommended. This may be provided in a troweled epoxy installation using a cove filler. Cleanrooms where hazardous chemicals are used may require special coving for spill containment.

7.4.1.3 *Floor Treatments*—Floors should never be waxed. Acrylic floor coatings may be used for static dissipation in controlled areas or ISO Class 8 (FS209E class 100 000) cleanrooms.[8] These materials will wear with traffic and must be reapplied periodically. Reapplication must be performed only on an off shift, with cleanroom hardware and work surfaces covered and protected and flight hardware removed.

7.4.2 *Walls*—Conventional wood construction is not recommended for cleanrooms because the expansion and contraction of the wood will cause leaks to develop over time and may crack some paints. Because cleanrooms are generally maintained at a lower humidity than conventional office or manufacturing areas, all walls must incorporate a moisture barrier to prevent humidity from sweating through the walls. Prefabricated walls containing insulation, utilities (such as electrical wiring), and factory applied cleanroom compatible finishes may be suitable.

7.4.2.1 *Wall Finishes*—Inexpensive latex wall paints will powder over time and are unacceptable in cleanrooms. Acceptable wall finishes include epoxy paint, polyester, some latex, or baked enamel, of a semi-gloss or gloss type.

7.4.2.2 *Impact Protection*—All exposed corners and high traffic areas, such as entry airlocks, should have stainless steel facings or guards to prevent impact damage to the wall. Corner guards should extend from the floor to at least the 120 mm (4 ft) height.

7.4.2.3 *Colors*—Walls and ceilings shall be soft white, ivory, or other pale reflective color. Conventional epoxy colors such as gray are acceptable for floors. There is a common misconception that all cleanroom surfaces must be painted white. Although this may improve the illumination in the room and the ease of inspection, some color variety is recommended to help relieve fatigue and eye strain.

7.4.3 *Ceiling Materials*—The minimum acceptable ceiling material is a painted gypsum board or a suspended polyester film-coated panel. Suspended panels must be clipped or sealed in place to prevent movement due to air pressure changes. For rooms cleaner than ISO Class 8 (FS209E Class 100 000), full polyester film panels or continuous painted ceiling should be used. In unidirectional downflow cleanrooms, the ceiling will be nearly 100 % filter coverage.

7.4.4 *Doors*—All regular entry doors must enter through airlocks. Emergency exit doors must meet all of the following requirements and should incorporate crash-bar mechanisms (or similar emergency opening mechanism) with alarms for exit only. Emergency exit doors must be locked to exclude entry from the outside.

7.4.4.1 *Door Features*—All doors must include airtight seals. Neoprene seals are generally acceptable, but other materials, such as fluoroelastomers, may be appropriate for some applications that require chemical resistance or exposure to large temperature extremes. Large roll-up equipment doors may require inflatable seals to maintain room pressurization. Brush-type door seals should not be used. Foam rubber door seals are not recommended as these have been found to quickly deteriorate and shed particles or chunks of material. All personnel doors and swinging equipment doors must include self-closing mechanisms.

7.4.4.2 *High Bay Doors*—Sliding panel doors are recommended for high bay entry rather than roll-up doors. Horizontal opening sliding doors are preferred to vertical (lift up) sliding doors because they have fewer horizontal surfaces to collect dust. If a roll-up door must be used, cleanability of the door joints must be considered. In some applications, a heavy-duty laminated fabric door may be acceptable if it can withstand the internal room pressure. All motors, chains, and gear mechanisms must be enclosed as much as possible to contain lubricants and debris. A maintenance and cleaning schedule for these large doors must be established.

7.4.4.3 *Interlocks*—Interlocks are recommended for airlock door sets to prevent opening of both doors simultaneously. For equipment airlocks, an indicator light inside the cleanroom is recommended to show when the outside door is open.

7.4.5 *Windows*—Windows are recommended in aerospace cleanrooms unless prohibited for security reasons. Windows should be placed to permit viewing of the hardware and operations in order to minimize the need for non-production personnel to enter the cleanroom. Windows should be impact resistant glass or acrylic, fully glazed. Windows should be included if there is a public relations requirement for the general public to view the operations. Speaking diaphragms or

[8] Charleswater Statguard has been found to be acceptable.

intercom systems are recommended near all windows to facilitate communication with workers inside the cleanroom.

7.4.6 Closed circuit television systems may be used to provide views of many areas within the cleanroom and can be connected to intranet and internet systems for viewing on computer screens.

7.5 *Location of Cleanrooms*—The location of a cleanroom within a facility may seriously impact its performance. Considerable planning is required to have all support equipment and services in optimum locations for ease of maintenance as well as minimizing contaminant generation within or ingestion into the cleanroom. Equipment added later, outside a cleanroom may degrade the performance of the cleanroom. All operations adjacent to the cleanroom should be evaluated for the following concerns:

7.5.1 *Vibration Sources*—Vibration sources inside or near a cleanroom will enhance particle release inside the room and under severe conditions may cause leaks in filters and ductwork. Heavy equipment including the HVAC system components and house vacuum system must be vibration isolated. Cleanrooms are incompatible with vibration and shock testing equipment. Location of a cleanroom directly adjacent to heavy presses, major roadways, or loading docks that see heavy truck traffic, and other sources of vibration and shock may increase contaminant generation in the cleanroom.

7.5.2 *Air Intake Location*—The air intake for the cleanroom makeup air must be carefully located to prevent overloading of filters or ingestion of contaminating gases that the filters will not remove. Cleanroom air intakes should not be located near loading docks, traffic lanes, or other areas where internal combustion engine powered vehicles may drive through or idle. Exhausts from diesel engines contain large quantities of molecular and particulate contaminants. The air intakes should not be located near the exhaust locations of other processing facilities.

7.5.3 *Support Services*—Access for the repair and maintenance of support services, such as utilities, fluid systems, and vacuum pumps, should be located outside the cleanroom so that cleanroom operations and hardware cleanliness are not affected.

7.6 *Heating Ventilation and Air Conditioning (HVAC) System*:

7.6.1 The cleanroom HVAC system must be designed and sized to maintain the required particulate cleanliness, temperature, humidity, and positive pressure at the expected outside environmental extremes and during the worst case expected use operations. Rapid recovery from upset conditions such as door openings and contaminant generating events is also a consideration. The quality of outside air in the facility location must be considered when selecting, sizing, and servicing filters. Atmospheric upset conditions have occurred because of fires, volcanic eruptions, and chemical spills.

7.6.2 *Recirculation*—Due to the high cost of conditioning outside air, and sizing of blowers to pass air through the filter stages, high use of recirculated air will minimize facility costs. The required quantity of makeup air is determined based on factors such as human occupancy requirements, expected solvent and chemical usage, and air pressure requirements. Recirculated air should be returned prior to the intermediate filters for maximum HEPA filter life and minimal shutdown time for filter servicing.

7.6.3 *Filtration*—The filtration system for a cleanroom typically consists of three or more stages of filters: a rough filter, one or more layers of intermediate or medium duty filters, and a final HEPA or ULPA filter. A screen should be included at the makeup inlet to keep out pests and large debris. The filtration system for a controlled area is the same, except that the HEPA filter stage may be omitted. Chemical and molecular adsorption filters should be considered when outside air contains unacceptable levels of molecular contaminants.

7.6.3.1 *HEPA Filter Specification*—High Efficiency Particulate Air (HEPA) filters must be 99.97 % efficient at removing 0.3 µm and larger particles in accordance with Type C of IEST-RP-CC001. HEPA filters will provide air at less than ISO Class 5 (FS209E Class 100) if in good condition and installed properly. In many cases, HEPA filters will approach the performance of ULPA filters but have not been certified to the higher performance.

7.6.3.2 ULPA filters may be used in place of HEPA filters when air cleaner than that certified for HEPA filters is required.

7.6.3.3 Construction of final filters should be in accordance with IEST-RP-CC001, type F, construction grade 1 (fire-resistant), with the following exceptions:

(1) Cadmium-plated cold-rolled steel sheet, galvanized steel sheet, and wood particle board are not recommended as frame materials for aerospace applications. Aluminum or stainless steel frames are recommended.

(2) Acetic acid curing silicone sealants are not recommended as they produce by-products that may be detrimental to some aerospace hardware. Low outgassing (controlled volatility) silicone sealants are recommended.

(3) Dioctyl phthalate (DOP) or other volatile aerosols should not be used at any time during the construction and testing of aerospace cleanroom filters. DOP has been found to evaporate and migrate through the filters over time, resulting in film contamination of optics and other sensitive surfaces. This exclusion must be specified on the filter purchase order since it is often standard practice. It is recommended that the filter be tested in accordance with IEST-RP-CC007 for penetration at rated airflow and leakage using an approved solid aerosol challenge. Leaks at the filter media or frame should be repaired at the factory. Excessive leaks at the filter face should be cause for rejection. The recommendations for ordering, testing, marking, and shipping of HEPA filters are found in Section A3 of Appendix A of IEST-RP-CC001.

7.6.3.4 *Pre-Filters*—Pre-filters are selected, sized, and installed to maximize the life of the final HEPA or ULPA filters and to minimize disruption to the cleanroom environment when filters are serviced. With proper design of pre-filters, the final filters should not require replacement within the life of the filter media and seal materials. Outgassing or volatile materials such as DOP and acetic acid curing silicones must be avoided in pre-filters.

7.6.3.5 *Filter Testing*—HEPA and ULPA filters should be tested at the factory and after installation using a solid aerosol challenge to verify the integrity of the filter media and the

seals. NEBB Procedural Standards for Certified Testing of Cleanrooms, section 8.2.4.2, and IEST-RP-CC007 provide guidelines for leak testing of HEPA filters, including repair and rejection criteria.

7.6.3.6 *Filter Installation*—To extend filter life, pressure sensors are recommended to indicate the need to service each stage of filters. Filters must be sealed upon installation using a gasket or a flexible sealing material. Filters may need to be mechanically fastened in place to prevent leaks caused by room pressurization or vibration.

7.6.3.7 *Molecular Adsorbers*—Molecular adsorbers (gas phase adsorber cells) should be considered when molecular contaminants are in the outside air or are generated within the cleanroom. These typically consist of activated carbon or zeolite, but other materials are also used. Adsorbers typically are selective; therefore, the selection should be based on the quantities and types of chemicals to be adsorbed and usable operational life before replacement or reactivation. Molecular adsorbers should be located upstream of the HEPA or ULPA filters because particles may be generated by the adsorber filter media. Instrumentation and procedures are required to determine when filters require replacement.

7.6.4 *Ducts*—Ducts must be sealed to prevent air leaks and ingestion of outside air into the clean air supply and recirculated air return. Duct sections should ideally be delivered to the job site pre-cleaned and with the ends capped. Duct openings should be protected during construction to prevent contamination of the interior surfaces. All air ducts and plenums must be designed to withstand the pressures imposed by the HVAC system and outside vibration sources. Duct interior materials must be smooth, non-shedding, moisture resistant and non-outgassing. The preferred duct material is anodized aluminum. Insulation material and organic compounds should not be inside the duct. These materials either collect organic matter from the air or contain organic matter that breed molds, bacteria, and viruses that can harm personnel and products.

7.6.5 *Final Filter Location*—HEPA filters may be installed in a facility either inside a distribution plenum or at the inlet to the cleanroom. Only one type of location should be used in a single cleanroom. An exception is the use of local HEPA filters to provide air to a clean zone, within the cleanroom, that has special requirements.

7.6.5.1 *Plenum Supply with Diffusers*—HEPA filters are commonly installed inside a distribution plenum outside the cleanroom and with diffuser type registers used at the point of entry to the room. This design is used in many large cleanrooms and nonunidirectional airflow cleanrooms. All ductwork downstream of the HEPA filters must be cleaned to a visibly clean level and protected during construction. “Blow down” of the ductwork may be required prior to certification to remove residual contamination. The plenum must provide access for scanning and inspection of the HEPA filter downstream face for certification and repair purposes. An alternate design approach has only the prefilters in the external plenum and a HEPA filter at each inlet register. The latter approach provides easier access to the HEPA filters for testing and repair.

7.6.5.2 *Ceiling Filters*—Partial coverage or full coverage ceiling filters are commonly used. Standard sized filters should be used. HEPA filters cannot be cut to fit without seriously degrading the performance of the filter media. Custom-size filters are available but are very expensive and create service availability problems. For unidirectional airflow, the floor should be perforated and located over the return air plenum.

7.6.5.3 *Wall Filters*—Full coverage wall filters are used for unidirectional, horizontal airflow rooms. The room should be sized to accept standard HEPA filters. Wall filters shall be fitted with a protective screen to prevent impact damage.

7.6.6 *Air Return*:

7.6.6.1 *Low Wall Return*—Low wall air return is commonly used in aerospace cleanrooms with nonunidirectional airflow, as it is the least expensive, easiest to maintain, and is compatible with heavy floor loading and wet processes. Return outlets should be covered with screens or louvers. Return ducts must be evenly distributed around the room to minimize dead zones. Return outlets should be placed as close as possible to the floor and well below work levels to minimize updrafts that might transport contaminants onto hardware surfaces. A maximum height of 0.6 m (2 ft) should be considered.

7.6.6.2 *Perforated Floor Return*—A perforated floor over an air plenum may be used to achieve ceiling-to-floor unidirectional airflow in a cleanroom. The perforated section is typically of the tile computer floor type, with smooth perforation holes. The underfloor plenum must be periodically cleaned to prevent contamination buildup. Some cleanrooms use a 2½ m (8 ft) high underfloor plenum to facilitate this cleaning. It should be noted that perforated floors may not be acceptable with some chemical operations due to the spill hazard and where heavy loads must be supported on the floor. Floor plenums may also require special fire detection and suppression provisions.

7.6.7 *HVAC System Construction Protocol*—To achieve the required cleanliness class on startup, and to minimize the possibility of certification problems, some cleanliness precautions are necessary during the construction phase. This is important for all cleanrooms, but greater efforts are required for the more stringent requirements for air and hardware cleanliness.

7.6.7.1 As a minimum, contaminant-generating operations must be performed off site, or with very good ventilation away from cleanroom materials of construction. This includes operations such as welding, wet machining, and so forth.

7.6.7.2 Gross debris must be removed on a daily basis. Under no circumstances should the contractor be permitted to enclose construction debris into ducts, trenches, or utility boxes.

7.6.7.3 All HVAC supply and return ducts must be installed in a clean and new condition. Ducts downstream of HEPA filter locations must be cleaned to a visibly clean level prior to installation while they are still accessible.

7.6.7.4 All duct entry and exit ports must be protected from dust entry during the construction process. Taped polyethylene sheet material is generally acceptable. In locations where puncture is likely (such as for floor level return air), a hard cover may be required, or the louver or diffuser may be temporarily installed over the plastic. The facility startup checklist should include a requirement to check all inlet and

exhaust ports to verify that temporary covers have been removed.

7.6.7.5 HEPA filters should remain packaged until ready for installation. The filters should not be installed until the room is complete and ready for HVAC system test and balancing.

7.6.8 *Temperature Control*—Temperature requirements and tolerances are as specified in Table 1. These levels may be changed in accordance with hardware requirements, but should provide for worker comfort to prevent hardware contamination or corrosion due to perspiration.

7.6.9 *Humidity Control*—Humidity requirements and tolerances are as specified in Table 1. Minimum humidity levels are established by the electrostatic sensitivity of the hardware. Upper limits are established primarily to prevent corrosion of and condensation on hardware and facilities. For some applications, dew point temperatures may be specified.

7.6.10 *HVAC System Certification*—The filters and HVAC system should be fully inspected for leaks and balanced prior to initial certification of the facility in the as-built condition. NEBB Procedural Standards for Certified Testing of Cleanrooms is a useful reference for the certification of cleanroom HVAC systems.

7.7 *Lighting and Electrical*:

7.7.1 The illumination levels, uniformities, and type of light (color balance) within the cleanroom should be specified.

7.7.2 General lighting in the cleanroom should provide for a minimum of approximately 750 lm/m^2 (70 fc) on all surfaces to facilitate the visual detection of contamination and for cleaning operations. Lighting at specified work locations should be approximately 1000 lm/m^2(100 fc). Local task lighting may provide illumination at the work locations.

7.7.3

If the program has a requirement for ultraviolet light inspection of hardware for contaminant detection, then the facility lighting system must provide the option to dim or turn off all lights except for required safety lights.

7.7.4 All lighting fixtures should be flush mounted and sealed, with covers that are smooth and easily cleanable. This includes emergency lights and lighted exit signs. The media used for the lamp (that is, mercury vapor) may be specified by the using organization to prevent a hazard to the hardware in case of breakage. Provision for replacement of lamps must consider accessibility without disturbing the cleanroom operations.

7.7.5 *Electrical Utilities*—Conduit, boxes, and electrical receptacles should be flush mounted and sealed to prevent air leakage. A breaker box, control panels, switches, and other utility panels should be installed in a utility area outside the cleanroom. If they must be installed inside the cleanroom, they must be flush mounted and sealed. Ceiling drops for utilities should be avoided since they are difficult to seal at the penetration and to keep clean.

7.7.6 *Floor Trenches*—Some large aerospace facilities use floor trenches to provide utility distribution. These floor trenches must be thoroughly cleaned of all debris and sealed prior to clean down and certification of the facility. The seal shall be selected to withstand frequent cleaning.

7.8 *Mechanical Utilities*:

7.8.1 Gases and fluids provided to the facility must be specified to limit particulate and molecular contaminants to within the cleanroom limits as a minimum. Plumbing lines must be constructed from corrosion resistant materials and

TABLE 1 Typical Cleanroom Design Considerations

NOTE—These comments and numbers should be considered as guidelines. Each cleanroom should be designed to meet the requirements of the process.

Cleanroom Air Class[A]	Controlled Area[B]				
ISO 14644-1	8.5 = 0.5 µm particle size 8 = 5 µm particle size	8	7	6	5
FED-STD-209E	300 000 = 0.5 µm part. size 100 000 = 5 µm part. size	100 000	10 000	1 000	100
Air filters	Rough Filter Medium Efficiency Filter HEPA Filter (Recommended)	Rough Filter Medium Efficiency Filter HEPA Filter (Required)	Rough Filter Medium Efficiency Filter HEPA Filter (Required)	Rough Filter Medium Efficiency Filter HEPA Filter (Required)	Rough Filter Medium Efficiency Filter HEPA Filter (Required)
Temperature[C]	16 to 24°C (62 to 76°F)	16 to 24°C (62 to 76°F)	16 to 24°C (62 to 76°F)	21 to 24°C (70 to 76°F)	21 to 24°C (70 to 76°F)
Relative Humidity	30 to 60 %	30 to 50 %	30 to 50 %	30 to 50 %	30 to 50 %
Changing room	Recommended	Required	Required	Required	Required
Airflow type	Nonunidirectional	Nonunidirectional, Mixed, or Unidirectional	Nonunidirectional, Mixed, or Unidirectional	Unidirectional Required	Unidirectional Required
Typical airflow rates					
Room air change rate[D] per hour	5 to 20	5 to 20	20 to 90	Not Applicable	Not applicable
Avg. airflow velocity[E] m/s (ft/min)	0.005 to 0.02 m/s (1 to 4 ft/min)	0.005 to 0.02 m/s (1 to 4 ft/min)	0.02 to 0.5 m/s (4 to 100 ft/min)	0.05 to 0.5 m/s (10 to 100 ft/min)	0.05 to 0.5 m/s (10 to 100 ft/min)

[A] This usually is specified as the maximum allowable airborne particle concentrations in the operational condition.

[B] Higher concentrations for the ≤0.5 µm particles can occur if HEPA or ULPA filters are not used in controlled areas. The concentration of ≤0.5 µm sized particles will increase if the concentration of particles in this size range increase in the outside air. The concentration of particles in the ≤5 µm size range do not show a significant increase because of the low and medium air filters that are contained in the HVAC system.

[C] The temperatures required for personnel comfort depends on the levels of physical activity and the types of garments being worn. Control of temperature is also important for personnel comfort. Allowable fluctuations on the order of ±1°C or ±1.5°C (±2°F or ±3°F) are typical.

[D] The air changes per hour is used for nonunidirectional cleanrooms, high bay, and unusually configured cleanrooms.

[E] The average airflow velocity applies to unidirectional airflow cleanrooms. The relationship between average airflow velocity and air change rate for a typical cleanroom with a regular shape (such as a rectangular crossection) is approximately:

$$\text{Airchange rate} = \frac{\text{Average airflow velocity} \times \text{Room cross sectional flow area}}{\text{Room volume}}$$

cleaned prior to installation. Provisions must be made for the venting or drainage of waste gases and liquids as required.

7.8.1.1 *Janitorial Water Supply*—A janitorial closet must be provided adjacent to the cleanroom (preferably in the changing room or entry alcove) with hot and cold water and a floor sink. Water provided for janitorial cleaning should be filtered to 30 µm and deionized to meet 50 000 σ/cm minimum.

7.8.1.2 *Purified Use Water*—Purified use water plumbed to the facility must meet the requirements as specified by the user, but should meet the janitorial water requirements as a minimum.

7.8.1.3 *Potable Water*—Potable water sources such as drinking fountains and deluge showers are allowed. These should be located to minimize hazards to the hardware when in use and to prevent substitution of this water source for hardware operations or facility cleaning.

7.8.2 *House Vacuum*—Most cleanrooms should incorporate a permanently-installed house vacuum system to exhaust contaminants outside of the facility. The vacuum system should be located in a support area outside the perimeter of the cleanroom. House vacuum ports should be located throughout the cleanroom and within airlocks and gowning rooms to facilitate maintenance. A house vacuum port may also be located just outside the personnel entry to the gowning room to service a shoe cleaner. When an existing facility must be used, or the cost of a house vacuum system cannot be justified, a portable HEPA filtered vacuum cleaner may be used.

7.8.3 *Communication Systems*—Provisions should be made for communications between external locations and the cleanroom and between entry antechambers, gowning rooms, or control rooms and the cleanroom. The availability of communication devices will help to limit traffic into the cleanroom. Communication devices that should be incorporated into the design of the cleanroom include wall-mounted telephones, intercoms, speaking diaphragms near windows or pass-through, and public address/warning systems. All communication devices should be recessed or flush mounted.

7.9 *Facility Layout*—To provide uniform airflow, rectangular construction of the facility is recommended. Alcoves, L-shapes, and other complex configurations may create airflow traps and dead zones that become high contamination areas. When non-rectangular configurations must be used, particular care must be taken to design and balance the HVAC system to prevent dead zones. Non-cleanroom areas must not be nested inside cleanrooms.

7.9.1 *Office Space*—Office space adjacent to the cleanroom but not within the controlled area is recommended to support shop management and paperwork activities. A pass-through to the cleanroom for the transfer of authorization and QA paperwork should be provided.

7.10 *Airlocks*—Airlocks must be provided at all entries to the cleanroom except for emergency exits. Airlocks should include pressure seals and interlocks to maintain pressurization in the cleanroom. Airlock interiors should be designed to the same standards as the cleanroom interior. The HVAC service to the airlocks must meet the same performance requirements as the cleanroom.

7.10.1 *Transport Airlocks*—Transport airlocks are required to process flight hardware, stands, production equipment, and lifting, handling and shipping fixtures from dirty areas into the cleanroom. The transport airlock, including doors, must be sized to accommodate the largest shipping container (including the trailer) or equipment expected to be processed into the cleanroom, or expected to be received with clean, unpackaged flight hardware. Separate personnel doors from the transport airlock into the cleanroom and to outside are recommended.

7.10.2 *Equipment Airlock*—In facilities where the transport airlock is vary large, a separate equipment airlock is recommended to process in equipment that can be hand carried or transported on a cart. This airlock may be the antechamber to the gowning room, or a separate facility. The equipment airlock should contain provisions for vacuuming, solvent cleaning, and unbagging of hardware to be moved into the cleanroom.

7.10.3 *Personnel Airlock*—A personnel airlock must be provided and sized to accommodate the traffic expected in the facility. Sometimes the changing room is used as an airlock, but this is not recommended. The airlock should be adjacent to the changing room. Air showers are often used as a part of the personnel airlock to remove particles from the personnel entering the cleanroom. The effectiveness of air showers has been debated for many years, but should be considered for the removal of large particles such as fibers from cleanroom garments. Air ionizers are frequently included in air showers to facilitate the removal of particles.

7.10.4 *Changing Rooms*—Changing rooms are required in conjunction with each personnel entry airlock. All changing rooms should include the following items:

7.10.4.1 Wall-mounted coat rack for clean garment storage located at a height to prevent dragging on the floor,

7.10.4.2 Bench,

7.10.4.3 A full-length mirror near the door to enable self-inspection of personnel compliance with dress requirements,

7.10.4.4 Storage for packaged garments,

7.10.4.5 Bins for packaging disposal and soiled garments,

7.10.4.6 Personal lockers and coat racks for the storage of notebooks, coats, and personal items shall be located outside changing room or in an antechamber separate from the clean changing area, and

7.10.4.7 Restroom facilities may also be located outside the changing room or in an antechamber adjacent to the clean changing area.

7.10.5 *Pass-throughs*—A pass-through airlock should be provided for the transfer of small articles from uncontrolled areas into the cleanroom. The pass-through shall include a speaking diaphragm, intercom, or telephone for communication when items are transferred, and interconnects to prevent both doors from being opened at the same time.

7.11 *Entry Control*:

7.11.1 *Shoe Cleaners and Tacky Mats*—Automatic shoe cleaners are recommended at the personnel entry to all cleanrooms. These should be located at the entry to the gowning room. The shoe cleaner should be designed to brush and vacuum the sole, sides, and toe of the shoe. A shoe cleaner that is attached to house vacuum is preferred to minimize maintenance of the unit. Tacky mats should be located at the entry from the changing room to the cleanroom, at all doors or

corridors between areas containing different operations or levels of cleanliness in the room, and wherever traffic borne cross-contamination between operations is a concern.

7.11.2 *Entry Locks*—Entry locks are recommended to limit facility access to certified personnel. These may also be required to limit access to classified secure areas. Entry locks should be located outside the personnel entry to the gowning area. Locks should use a keyless system, such as a cipher lock or badge reader.

7.12 *Fire Protection*—While meeting all building code and safety requirements, fire protection systems must be compatible with cleanroom operations. Portable fire extinguishers should be installed in flush wall mounted cabinets. Fire detection and annunciation systems should be flush mounted.

7.12.1 *Sprinkler Systems*—When required, fire sprinkler heads should be sealed airtight in the ceiling grid and installed without ventilation holes. In facilities where high value flight hardware will be present for extended periods below a sprinkler system, a normally dry system may be preferred to reduce the risk of accidental water damage to the hardware from leaks or system failure. This may require an exception from building codes. These systems require additional time to charge with water when a fire event is detected.

7.13 *Facility Monitoring Utilities*:

7.13.1 All cleanroom facilities should have a system to continuously monitor the critical environments. Commercial systems using standard desktop computers are available from many sources. The numbers and locations of each type of sensor in the cleanroom depend upon the size of the room, the criticality of the operations, and the contamination sensitivity of the hardware. Monitoring records should be capable of long term storage.

7.13.2 The environmental monitoring system has the following objectives:

7.13.2.1 Verify compliance with spacecraft processing requirements,

7.13.2.2 Provide an early warning of a trend towards out of compliance,

7.13.2.3 Provide long-term trend data on the performance of facility systems, and

7.13.2.4 Meet the requirements of ISO 14644-2 for continued compliance of the cleanroom.

7.13.3 The following items should be included in the environmental monitoring system:

7.13.3.1 *Temperature*—Certified accuracy of ±1°C to ±1.5°C (±2°F to ±3°F) in the range of 16 to 27°C (60 to 80°F).

7.13.3.2 *Relative Humidity*—±5 % in the range of 25 to 75 %. Dew point measurements may be required for some applications.

7.13.3.3 *Pressure Differential*—Differential pressures between adjacent areas such as the cleanroom, changing rooms, airlocks, and outside air. The measurement of pressure drops across filters should also be considered.

7.13.3.4 *Airborne Particles*—Airborne particle concentrations should be measured at locations suitable for facility and operational needs. At least two particle size ranges should be measured. Equal to and greater than 0.5 µm and equal to and greater than 5 µm are typical for general cleanroom monitoring of ISO Classes 6 (FS209E Class 1 000) and higher. When measuring air at lower Classes, sizes 0.3 µm and larger and 0.5 µm and larger should be used in order to count enough particles to get a good statistical sample. For example, the 0.3 µm range would be required for the measurement of particle concentrations immediately downstream of a HEPA filter. Several commercially available laser particle counters have been found to be satisfactory.

7.13.4 The following additional measurements should be considered for some applications:

7.13.4.1 Indications of door openings and closing,

7.13.4.2 Molecular contaminant deposition using surface acoustic wave (SAW) and temperature controlled quartz crystal microbalances (TQCMs), and

7.13.4.3 Particle deposition using surface particle counters or light scatter sensors.

7.14 *Cleanroom Equipment and Furniture*—All equipment and furniture to be used in a cleanroom shall be purchased new, if possible. Inherently corrosion-resistant materials and finishes, such as stainless steel, anodized aluminum, or hard plastics, are preferred over painted steel or wood. Non-metallic equipment shall be constructed of non-shedding, low-outgassing, and highly cleanable materials.

NOTE 3—Materials and equipment specified for use in cleanrooms are sometimes described as compatible with or meeting the requirements of a particular class of cleanroom air per ISO 14644-1 or FED-STD-209. These documents only apply to concentrations of airborne particles and do not contain any requirements for materials and equipment.

7.14.1 *Stands and Ladders*—Stands and ladders used to access flight hardware will require frequent cleaning. The need for smooth, cleanable configurations must be balanced with safety requirements for non-skid surfaces. Waffle grid and expanded metal are very difficult to maintain clean and should be avoided when possible. Since these items are likely to be subjected to physical wear and impact, inherently corrosion resistant, unpainted surfaces are recommended.

7.14.2 Equipment containing blowers, such as fume hoods, laminar flow benches, electronic equipment racks with cooling fans, and processing equipment, must be carefully selected and strategically placed within the cleanroom to avoid blowing contaminants from dirtier areas, such as floors, onto critical hardware. Exhaust requirements for fume hoods and processing equipment must be considered in the initial sizing and balancing of the HVAC system.

7.14.3 *Lifting and Handling Equipment*:

7.14.3.1 *Overhead Cranes*—Overhead cranes can be a significant source of contamination in cleanrooms, but are unavoidable in many aerospace facilities. The specification for a crane to be installed in a cleanroom must include drip pans for all potential oil leakage areas and a debris shield (“umbrella”) at the hook to prevent contaminants from dropping onto the hardware from the crane. The specification must require that bumpers, chains, control cables and tracks be made of corrosion resistant, non-shedding materials, and be unpainted. The specification must also require that the crane be protected from corrosion and the elements during assembly, shipment, and storage prior to installation in the cleanroom. Cranes are

generally not recommended when hardware requires environments cleaner than ISO Class 7 (FC209 Class 10 000). However, cranes can be designed, operated, and maintained to achieve the desired air cleanliness in the room. In addition, sensitive hardware can be protected with covers during crane operations.

7.14.3.2 *Air Pallets*—Where air pallets are to be used to transport hardware in a cleanroom, the cleanroom floor must be specified to be level and uniform compatible with the specifications of the air pallet. Compressed air provided for air pallet operation must be filtered to the same cleanliness as the entering cleanroom air.

7.14.3.3 *Portable Lifting Equipment*—Portable lifting equipment commonly used in aerospace cleanrooms include forklifts, cherry pickers, scissors lifts, and portable cranes. These items must be electrically driven. Internal combustion engines are not permitted. Pneumatics or hydraulics must be of high quality and low maintenance. Scheduled maintenance must include inspections for leaks. In highly NVR sensitive cleanrooms, hydraulics should be avoided. Non-marking tires are preferred.

7.15 *Static Control in Cleanrooms*—Most aerospace cleanrooms will house electrostatic discharge sensitive (ESDS) hardware. Provisions must be made to protect this hardware from ESD hazards in the cleanroom. Many ESD protective products and supplies are incompatible with the molecular contamination limits of spacecraft hardware. IEST-RP-CC0022 provides information on ESD controls and their implementation.

7.15.1 *Materials Selection for ESD Control*—Materials used in cleanrooms for electrostatic control must be low outgassing and non-particle shedding. Inherently conductive or static dissipative materials such as stainless steel and carbon or metal fiber filled hard plastics are recommended. Plasticized films (such as “pink poly”) and poly-vinyl chlorides that outgas and transfer films through contact are unacceptable. Topical antistatic treatments are generally unacceptable since they create molecular films that are readily transferred to hardware.

7.15.2 *Grounding Schemes*—Aerospace cleanrooms that will contain ESDS hardware must include provisions for connecting personnel and hardware ground straps to earth ground. A copper ground bar along the perimeter of the cleanroom, at a 1 m (3 ft) height, is a typical solution. Floor ground connections, distributed around a large cleanroom, will minimize electrical cables on the floor.

8. Facility Certification

8.1 ISO 14644-1, ISO 14644-2, and IEST-RP-CC006 provide guidelines for facility certification. ISO 14644-3 describes various methods of testing cleanrooms. These methods are in the informative annexes of the ISO 14644-3. References to the above documents should include tailoring of the requirements and procedures to meet the needs of the particular designs and operations. The certification of large, high bay aerospace cleanrooms can be expensive if the number of measurement sampling locations recommended in ISO 14644-1, FED-STD-209E, and IEST RP-CC006 are used. The users of these types of cleanrooms should determine if the cost of the required number of samples is required. Alternative approaches are to measure in critical areas based on the potential for contamination of hardware and sources of contaminants.

8.2 Requirements for certification of the cleanroom in the as-built condition should be a part of the construction contract. Certification levels for the as-built condition must contain substantial reserve to support the required performance and certification of the cleanroom in the operational condition.

8.3 Certification should consider the following measurements as agreed upon by the parties involved:

8.3.1 *Airborne Particle Concentrations*—Well designed and constructed cleanrooms in the as-built and at-rest conditions

TABLE 2 Comparison of ISO 14644-1 and FED-STD-209E

ISO Class N Nominal FS209E Class	Particle Concentrations Max Number of Particles per m^3(ft^3) of Air for Particle Sizes Equal to or Greater than the Stated Size					
	0.1 µm	0.2 µm	0.3 µm	0.5 µm	1 µm	5 µm
ISO Class 1	10	2	. . .	. . .	. . .	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .
ISO Class 2	100	24	10	4	. . .	. . .
FS209E Class 0.1	3	1	. . .	. . .	. . .	. . .
ISO Class 3	1 000	237	102	35	8	. . .
FS209E Class 1	28	7	3	1	. . .	. . .
ISO Class 4	10 000	2 370	1 020	352	83	. . .
FS209E Class 10	283	67	29	10	2	. . .
ISO Class 5	100 000	23 700	10 200	3 520	832	29
FS209 Class 100	2 832	670	288	100	24	. . .
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
FS209E Class 1 000	28 300	6 700	2 880	996	236	8
ISO Class 6.7	. . .	. . .	. . .	176 000	41 700	1 470
FS209E Class 5 000	. . .	. . .	. . .	5 000	1 180	42
ISO Class 7	. . .	. . .	. . .	352 000	83 200	2 930
FS209E Class 10 000	. . .	. . .	. . .	9 960	2 360	83
ISO Class 8	. . .	. . .	. . .	3 520 000	832 000	29 251
FS209E Class 100 000	. . .	. . .	. . .	99 600	23 600	828
ISO Class 8.5	. . .	. . .	. . .	11 100 000	2 630 000	92 500
FS209E Class 300 000	. . .	. . .	. . .	315 000	74 500	2 620
ISO Class 9	. . .	. . .	. . .	35 200 000	8 320 000	293 000
FS209E Class 1 000 000	. . .	. . .	. . .	996 000	236 000	8 280

can be expected to have airborne particle concentrations that approach the concentrations of the incoming HEPA or ULPA filtered air. This would result in concentrations approaching ISO Class 5 (FC209 Class 100) and lower. Particle concentrations are given per ISO 14644–1 in Table 2, with the equivalent particle classes per FED-STD-209E for reference. Practice F 50 should be used for airborne particles in size ranges up to 5 µm and larger. Test Method F 25 should be used for airborne particles of greater than 5 µm.

8.3.2 *Particle Deposition*—IEST-STD-CC1246 should be used as a guide for measuring and specifying particles on surfaces. Practices F 24, E 1216, and E 2088 may be used for the measurement of particles on surfaces. Methods of specifying and measuring particles on surfaces should be agreed upon by the parties involved in the design, construction, and acceptance process.

8.3.3 *Molecular Contaminant Deposition*—IEST-STD-CC1246 should be used as a guide for measuring and specifying molecular contaminants on surfaces. Methods of specifying and measuring molecular contaminants on surfaces should be agreed upon by the parties involved in the design, construction, and acceptance process. Facility molecular deposition performance can be monitored and verified by sampling and testing NVR in accordance with Practice E 1234 and Methods E 1235.

8.3.4 HVAC airflow, temperature, and humidity performance must be tested and verified periodically.

8.3.5 Room air temperature control normally is verified by constantly measuring it and recording the results on a strip chart recorder or graph.

8.3.6 Room air humidity control normally is verified by constantly measuring it and recording the results on a strip chart recorder or graph.

8.3.7 *HEPA or ULPA Filter Installation Leakage*—This test is critical following installation of the filters because leakage through the filter media or seals may limit the lower limit on airborne particle concentrations. IEST-RP-CC006, IEST-RP-CC0034, and Annex B6 of ISO 14644-3 describe test methods. Test aerosols introduced upstream to challenge the filters, if used, should not be liquids. Acceptable solid aerosols may be used. Ambient (outside) air challenge may be used, but the upstream particle concentrations may be too low to achieve a satisfactory sensitivity for the scan. The user should evaluate the tradeoffs between the benefits of a more sensitive scan against the potential problems with a test aerosol.

8.3.8 *Cleanroom Leakage*—This test is difficult to perform. The user should evaluate possible leaks by measuring filter face velocity per 7.1.1.2 and positive pressure per 7.1.2.1. Any decrease in positive pressure without a reduction in airflow velocity suggests that there is a cleanroom leakage and should be evaluated further.

8.3.9 The ability to maintain required pressures in the cleanroom at the appropriate airflow and makeup airflow rates must be verified. Measure the pressure in the cleanroom and compare it with the pressure in the anteroom and external areas to verify that the positive pressure per 7.1.2.1 is present.

8.3.10 *Room Recovery Time or Time Constant*—This test is appropriate for nonunidirectional cleanrooms. The method in ISO 14644-3, Annex B 13 is not recommended. This requires increasing the airborne particle concentrations in the room with a test aerosol or outside air. A test method using the difference in airborne particle concentrations between the operational mode and the at-rest condition is recommended. This method will not affect operations within the cleanroom. Regular monitoring of the time constant of this change is indicative of HVAC and cleanroom performance.

8.3.11 *Room Airflow Visualization and Direction*—Tracers and other methods are used to show the airflow. Tracers may be test aerosols. Only water aerosols are recommended. Aerosols containing other chemicals may result in permanent contamination of the cleanroom. Strips of thin metallized films or threads may also be used to determine the directions of flowing air. Other techniques are in use and may be suitable.

9. Keywords

9.1 cleanroom; construction; design; spacecraft; test