Building Technology for Microelectronics Clean Room Design

Clean rooms require especially tight environmental controls. Technological advances in air particle control and cooperative design and construction management are key concerns.

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FORTY YEARS AGO, a team of engineers at Bell Telephone Laboratories developed the world's first electronic digital computer, designated as the ENIAC (Electronic Integrator and Computer). This 30-ton, 20,000 square foot machine could perform up to 5,000 calculations per second, and required 50 technicians and 18,000 vacuum tubes to keep it operating.

Development of the integrated circuit as a replacement for the vacuum tube was the first step toward the miniaturization of computer components and the creation of the pocket calculator, microprocessor-controlled home electronics and personal computers. Today's microcomputers can fit on a desktop and routinely perform more than 1,000,000 calculations per second, an improvement by a factor of 200 times in less than four decades. Current research has developed experimental microchips from a silicon material capable of more than a million calculations per second — all in an area no larger than a baby's fingernail (see Figure 1).

Silicon integrated circuits are made up of elements called electronic switches or gates. These gates are individual line elements that can be as small as 0.1 micron (10^{-8} μ), with typical elements being one micron or about 1/100 the diameter of a human hair (see Figure 2). Working at this scale, a particle no larger than a human cell, residing on the photo negative used to print circuits, can create chips with blocked circuits. A particle this size on the printed chip can cause a short. Table 1 lists the gases, chemicals and metals commonly used in semiconductor manufacturing, as well as impurity sources during the production process and major production source compounds.

The facilities used to research, develop and manufacture these chips demand the strictest environmental controls and pose a complex challenge to today's technical building designer. Providing adequate air particulate and vibration/noise control, water treat-

TABLE 1

Production Materials & Impurity Sources

Gases Used During Production

Phosphine (PH_3)	1% in N_2
Hydrogen (H_2)	—
Nitrogen (N_2)	—
Helium (He)	—
Argon (Ar)	—
Oxygen (O_2)	—
Diborane (B_2H_6)	—
Arsine (AsH_3)	1% in N_2
Ammonia (NH_3)	99%
Silane (SiH_4)	15% in N_2
Hydrogen Chloride (HCl)	99%

Chemicals Used During Production

Sulphuric Acid (H_2SO_4)
Hydrofluoric Acid (HF)
Nitric Acid (HNO_3)
Hydrochloric Acid (HCl)
Acetic Acid (CH_3COOH)
Ammonium Fluoride
Phosphoric Acid (H_3PO_4)
Acetone
Methyl Alcohol
Xylene
N-butyl Acetate
1-1-1 Trichloroethane
Hydrogen Peroxide (H_2O_2)
Silver Nitrate
Potassium Hydroxide
Methylene Chloride
Dimethyl Sulfoxide
Chromic Trioxide
Cyclohexanol
Cyclohexalene

Metals Used During Production

Aluminum (Al)
Antimony (Sb)
Arsenic (As)
Barium (Ba)
Beryllium (Be)
Boron (B)
Boron (B_4C)
Carbide
Chromium (Cr)
Nichrome (NiCr)
Copper (Cu)
Gold (Au)
Indium (In)
Iridium (Ir)
Molybdenum (Mo)
Nickel (Ni)
Permalloy (Ni/Fe)
Supermalloy (Ni/Fe/Mo)
Pallaium (Pd)
Platinum (Pt)
Rhodium (Rh)
Silver (Ag)
Tantalum (Ta)
Tin (Sn)
Tin Oxide (SnO_2)
Titantium (Ti)
Titanium Oxide (TiO_2)
Tungsten (W)
Tungsten Oxide (WO_2)
Zinc (Zn)

Production Impurity Sources

Impurity Source	*Room Temp. State*
Phosphorus Pentoxide (P_2O_5)	Solid
Phosphorus Oxychloride ($POCl_3$)	Liquid
Phosphorus Tribromide (PBr_3)	Liquid
Phosphine (PH_3)	Gas
Phosphorus Spin-on; *i.e.,* Phosphosilica Film*	Liquid
Boron Tribromide (BBr_3)	Liquid
Boron Trichloride (BCl_3)	Gas
Diborane (B_2H_6)	Gas
Boron Spin-on; *i.e.,* Borosilica Film*	Liquid
Boron Nitride (BN)	Solid
Arsine (AsH_3)	Gas
Arsenic Trioxide (As_2O_3)	Solid
Arsenic Spin-on; *i.e.,* Arsenosilica Film*	Liquid

*Emulsitone

Source Compounds Used For Production

Silicon Tetrachloride ($SiCl_4$)
Trichlorosilane ($SiHCl_3$)
Dichlorosilane (SiH_2Cl_2)

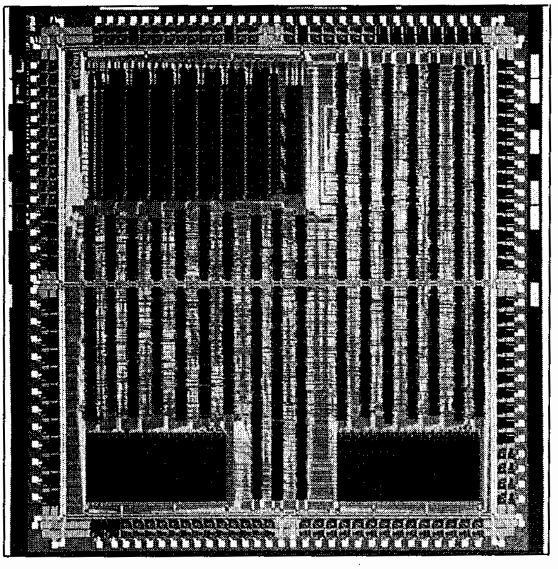

FIGURE 1. A typical integrated circuit.

ment for production rinsing of chips and waste removal systems are major considerations in clean room design.

Contamination Control

In the past decade, miniaturization has become a key concept in the semiconductor industry. Making electronic components as small as possible means faster operation of a greater number of circuits in a given space, resulting in the capacity to manufacture far more powerful and compact computers. At present, the technology for the control of particulate contamination in the research, development and production environment has raced beyond actual microelectronics needs. The industry is at a critical juncture, however, and this situation will soon reverse. Future circuit miniaturization will require further advances in contamination control technology.

Until recently, the state-of-the-art in integrated circuit line geometries was 2 micron line widths called Large Scale Integration (LSI) technology. Today, due to the market demand for one million transistors per chip, the development of Very Large Scale Integration (VLSI) technology is well under way. With line widths for these miniature integrated circuits typically as small as 0.1 micron, this new scale is also referred to as "submicron."

A mechanically controlled environment that regulates the quality of air is necessary for the production of these submicron components. In fact, the level of air purity is used to define the hierarchy of clean room design classifications. The standards for air cleanliness are outlined in Federal Standard 209B that specifies acceptable limits for airborne particle contamination, temperature and relative humidity ranges, differential pressure requirements and acceptable noise and vibration levels. Clean rooms are classified by their specific particle count definition. With five different classes — Class 10,000, Class 1000, Class 100, Class 10 and Class 1, the number of airborne particles 0.5 microns or larger in each cubic foot of air must not exceed the room class number. Particle count, particle size and sampling rate are the three classification parameters. Once the sampling rate has been fixed, the counts and the size constitute the clean room class (see Figure 3).

The issue of statistical error in classifying rooms as Class 10 or Class 1, the level required for future submicron work, has sparked a controversy over the validity of measuring 10

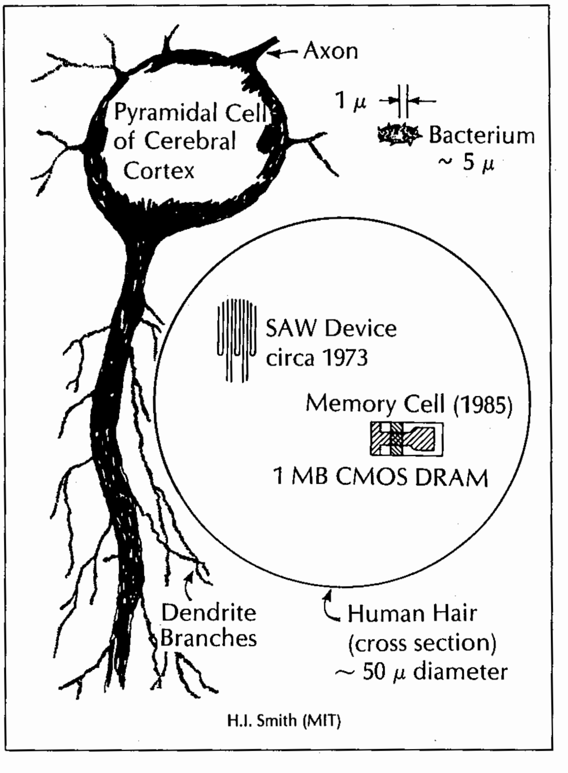

FIGURE 2. Relative size comparisons.

Definition of Terms

At Rest All production equipment in operation with no personnel present.

Chip (Microchip) A square of primarily silicon that is processed to ultimately be an integrated circuit.

Clean Room A clean room is an enclosed area employing control over the particulate matter in air with temperature, humidity, air flow patterns, air motion, pressure control and lighting as required. Clean rooms must not exceed the particulate count specified in the air cleanliness class.

Design Conditions The environmental conditions for which the clean space is designed.

Gate A circuit that has an electrical output dependent on its input.

High Efficiency Particulate Air Filter (HEPA) A filter with an efficiency in excess of 99.97% for 0.3 micron particles as determined by dioctyle phithalate (DOP) test.

High Efficiency Particulate Air Filter (VLSI) A filter with an efficiency in excess of 99.9995% for 0.12 micron particles.

Integrated Circuit (IC) An electronic device that performs the functions of many thousands of transistors.

Laminar Flow Air flow in which the entire body of air within a confined area moves within a uniform vertical air pattern along parallel flow lines.

Laminar Flow Room A clean room with a laminar flow requirement.

Large Scale Integration (LSI) Microelectronics manufacturing technology for integrated circuits with line geometries of 2-micron widths.

Line Width The width of a gate, or line, of a circuit in a microelectronic device.

Micron A unit of measurement equal to one-millionth of a meter (0.000039″). Twenty-five microns equal 0.001″.

Noise Criteria (NC) Curves These curves are a family of curves used to describe ambient noise levels in buildings using frequencies at dB levels. These curves have been developed from experimental data where each spectrum level represents approximate perceived equal loudness. The human ear is most sensitive at the 1,000-2,000 Hz level and is less sensitive at lower frequency levels.

Non-Laminar Flow Room A clean room that does not require a laminar flow pattern.

Normal Operating Conditions All production equipment, exhaust fans and air conditioning systems in operation with personnel present.

Particle Size The maximum linear dimension of the diameter of a particle usually measured in microns.

Unoccupied A bare room before production equipment has been installed with the clean room air handling equipment in operation, following the initial clean down period with no personnel present.

Very Large Scale Integration (VLSI) Microelectronics manufacturing technology for integrated circuits with line geometries as small as 0.1-micron widths.

Wafer A thin, flat circular disk of primarily silicon that is masked, oxide-coated, doped and processed for separation into numerous electronic devices or for packaging as an integrated circuit.

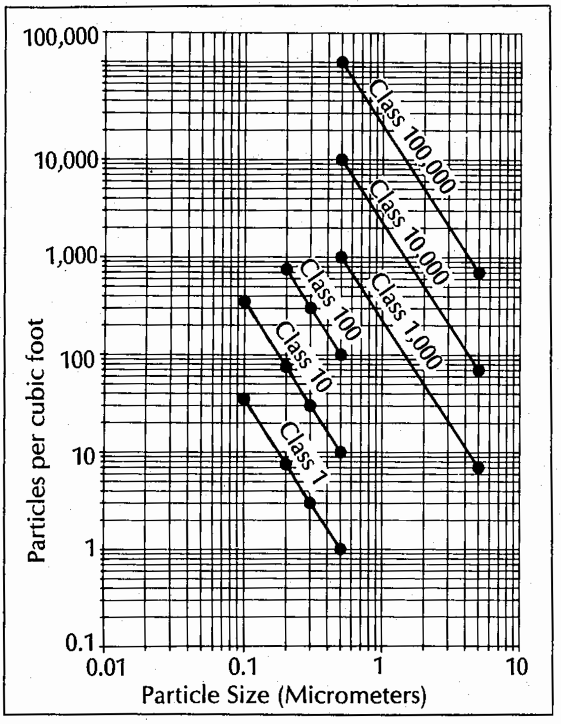

FIGURE 3. Proposed class limits in particles/ cubic ft. (from revision to Federal Standard 209B).

or 1 particles in a cubic foot of air. Although these minimum particle conditions can almost certainly be created, they cannot be effectively measured. The current challenge to the contamination control industry is the development of technology and methodology that will produce accurate testing data for Class 10 and Class 1 clean rooms.

Environmental Characterization

Five major environmental characteristics determine the criteria for the clean spaces that will accommodate integrated circuit development. These are air flow velocity, particle size and number, temperature, relative humidity and differential pressure. Federal Standard 209B states that air flow velocity through a horizontal cross section of a laminar flow space must be maintained at 90 (±18) feet per minute throughout an undisturbed room. These measurements are typically taken at the ceiling just below the High Efficiency Particulate Air (HEPA) filter. Measurements may also be taken at table height (42″) and at the level of any air return grilles or perforated floor panels where the air leaves the clean room. These velocities will vary depending on the type of air return system utilized, *i.e.,* sidewall return or raised floor.

The actual number of airborne particles of certain sizes in a 1 cubic foot volume will characterize the class of the clean room space. There should be a definite correlation between air velocity and airborne particle counts. Typically, field testing has shown that air flow velocities as low as 75 feet per minute will effectively remove particles in the room. At air flow velocities of above 110 feet per minute, testing has shown that any improvement in particle control appears insignificant. The choice of the final operating velocity should represent a balance between the energy consumption for the overall facility and standards for room cleanliness. The typical electrical costs for fan energy for an average clean room that changes its air 600 times per hour (filtering it through a number of fine glass mats) are approximately $20/square foot each year.

Temperature ranges are established as demanded by the product and the personnel occupying the area. In a VLSI clean room, the desired temperature tolerance may be 68° (± 1°) F. Specific areas may be controlled to even closer tolerances of 0.18° F in order to minimize expansion/contraction effects on the manufacturing process.

Typical relative humidity requirements in a VLSI clean room are 37.5 (±2.5) percent. If the relative humidity in some clean room areas is higher or lower than the recommended values, a decrease in the success rate or yield of the final product may result.

A differential pressure requirement of 0.05 psi is recommended with respect to any surrounding atmosphere of the clean room area in order to impede the flow of contaminated air into the room.

These environmental characterizations of VLSI clean rooms are used to qualify the facility for manufacturing or research/development, and to assist the end user in implementing the necessary environmental monitoring programs. Proper clean room characterization enables the user to produce high density devices and to successfully predict

TABLE 2

RP-006-84T Test Areas

Uniformity
Filter Leak
Parallelism
Recovery
Particle Count
Particle Fall-Out
Induction
Pressurization
Air Supply Capacity
Lighting Level
Noise Level
Temperature
Humidity
Vibration

product yield.

Clean Room Design & Testing Standards

During the past two decades, the criteria for the certification of clean rooms have followed the recommendation of Federal Standard 209 and its subsequent revisions, designated as 209A and 209B. Specific details for performance testing have never been included in Federal Standard 209 or its updated versions — resulting in widely divergent test procedures. In 1970, the American Association for Contamination Control, now merged with the Institute of Environmental Sciences (IES), issued a Tentative Standard CS-6T that contained greatly expanded methods for the testing of clean room particle counts as well as for other environmental factors. CS-6T has not been distributed as widely as Federal Standard 209, and thus had not the same impact on the clean room industry.

In the meantime, Federal Standard 209B is soon to be republished as Federal Standard 209C in order to respond to the certification needs of Class 10 and Class 1 rooms. Tentative standard CS-6T will also be revised as RP-006-84T, introducing the methodology for 14 tests to review laminar flow and non-laminar flow clean rooms. Table 2 lists these 14 test areas.

Feasibility Studies

Successful microelectronics facilities are the result of well defined programming and intensive facility planning efforts that begin during the early design phases. In many cases, a feasibility study prior to the initial design is appropriate to determine proper site selection, overall facility size and function (see Figures 4 and 5). Since many facilities require extensive capital expenditures on the part of the owner, the initial step of preparing a well defined feasibility-programming document allows for a more accurate assessment of facility needs. Established site conditions, and design/construction schedules will then generate more accurate preliminary cost models.

Facility Considerations

Site selection is a critical factor and must be studied in detail to assess the stability of the external environment and the reliability and quantity of available resources. The most critical initial decision is the selection of a site with well documented vibration characteristics. Although many internal isolation systems can mitigate vibration, a greater degree of control can be exercised over an isolated site where vehicular traffic, railroad routes, high pedestrian activity and vibration-transmitting soil types are at a minimum. A relatively isolated site will also supply open air spaces into which emissions from scrubbed exhausts may be rapidly dispersed and diluted. This factor is particularly important for production facilities using high concentrations of arsine and phosphine. A concentrated use of solvents in the production process could lead to ambient odors unfamiliar to the surrounding community. Odor absorption equipment is available, but costly.

The availability and reliability of water, electrical power and clean outside air are significant factors in site selection. On-site water is used to feed the sophisticated deionized high purity water systems necessary to rinse process components. The initial purity of this local water source can affect the ultimate cost of these sophisticated water polishing systems. A reliable source of local

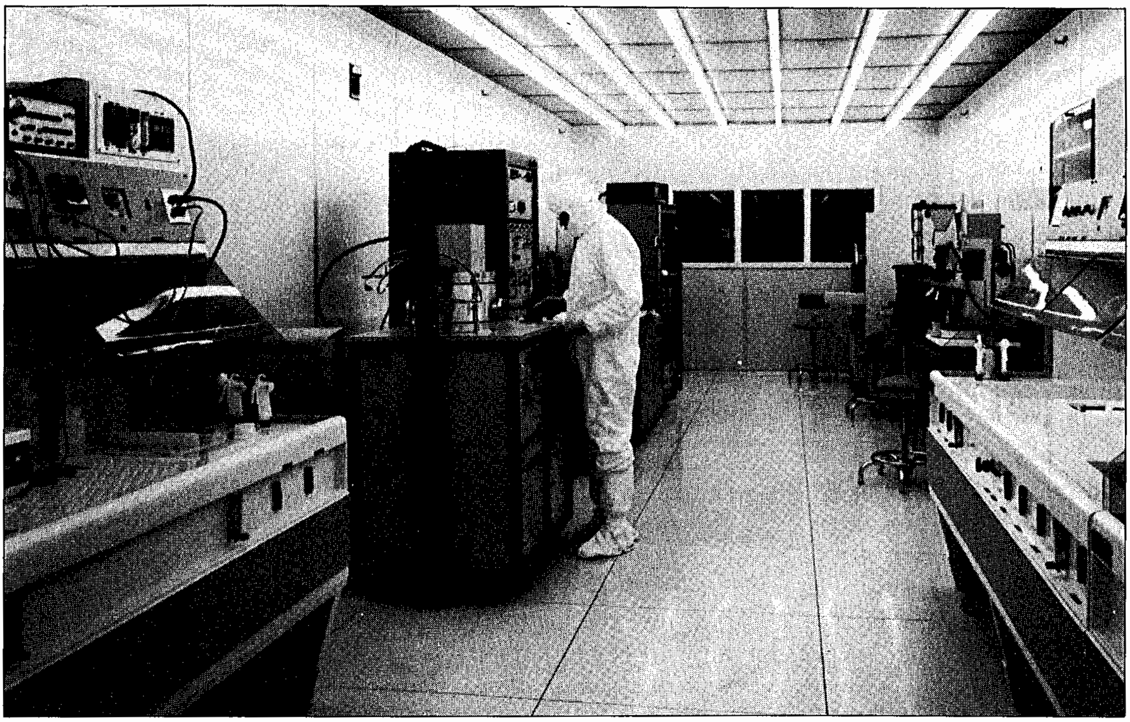

FIGURE 4. A typical clean room.

electrical power is necessary to sustain critical semiconductor operations without equipment or product loss. Back-up emergency generators are an expensive safety measure and areas subject to frequent power outages should be considered questionable sites. Large quantities of outdoor air will provide ample replenishment for the extensive exhaust systems supporting wet stations, fume hoods and equipment. Since wafer fabrication areas require the rigid control of humidity, temperature and outside air contamination, the air conditioning equipment must be designed to handle the "worst case" environmental conditions of outside air. As a result, sites in regions with wide climatic variations will require more expensive heating, ventilation and air conditioning (HVAC) support systems. During the feasibility study phase, the size, location and cost implications of the air-handling systems must be reviewed.

Mechanical, electrical and other manufac-

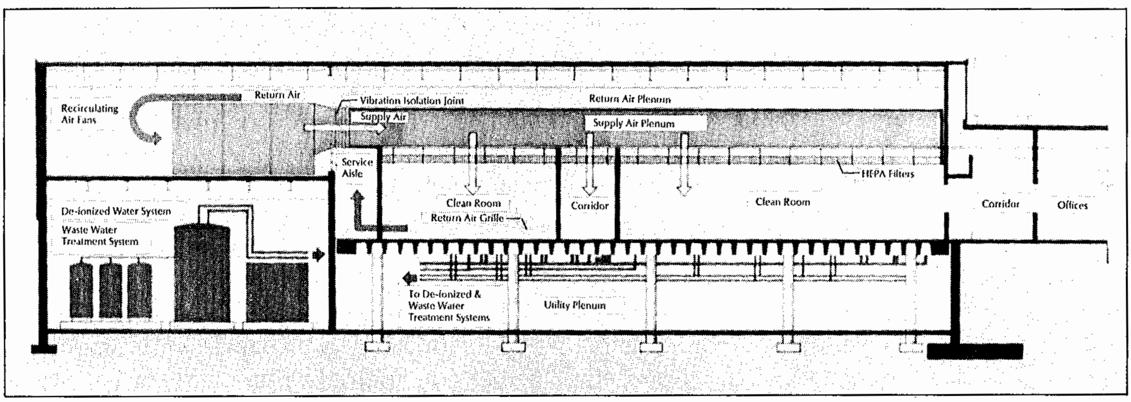

FIGURE 5. A building section from a typical microelectronics facility.

turing process portions of the project should be conceptualized at these initial stages. These systems costs can ultimately represent a range of 50 to 60 percent of the total base building construction cost and will account for a significant amount of the space allocations. Systems supporting temperature stability, relative humidity, air purity and air changes (up to 10 to 12 space air changes per minute in Class 10 and Class 100 rooms) as well as equipment-related process cooling water, process gases and electrical power must be identified early to determine the cost impact on the overall project.

Large semiconductor plants use substantial quantities of gases in the manufacturing process. Bulk storage of liquid oxygen, hydrogen and nitrogen, as well as bottled chemicals and specialty process gases, must be evaluated to determine impact on the building site and the surrounding environment. Even though a thorough review of these considerations may favor a specific location, it is important to review the environmental impact of the project and local community sentiment. Changing attitudes toward the environment may prevent future expansion of the facility. A thorough knowledge of the applicable laws and regulations will assist in moving the project ahead.

The well-developed feasibility study can generate a set of guidelines that will determine a well-structured project cost model. By addressing location, conceptual layout, image, clean room classification and area, construction schedule and available budget, a reasonable cost projection can be made. Cost models should include as many individual line items as possible and be flexible enough to allow for constant readjustment as the scope of the project develops more clearly. Microelectronics facility spaces can vary in cost from $125/sq. ft. for Class 100,000 to $750/sq. ft. for Class 10.

Regulations

Codes, permits and certifications covering microelectronic facilities have yet to be specifically formalized. The Semiconductor Industry Association has published their proposed revisions to the Uniform Building Code, which have been designated as H-6. These revisions attempt to formulate the requirements specific to the construction of microelectronics buildings, including smoke exhaust systems, process gas distribution and storage areas, ventilation of chemical storage areas and unique alarm requirements.

The insurance industry, particularly Industrial Risk Insurers and Factory Mutual, has also taken a leading role in defining safe construction standards. Basic design requirements have been continuously revised by this industry to provide better protection in the case of an emergency. For instance, fiber reinforced plastic ductwork is now internally sprinklered to protect the duct system from fires triggered by the use of silane gas and the presence of condensed materials. Instead of common return air plenums, recirculating air is now compartmentalized with segregated supply and return air, thus minimizing the spread of smoke and fire into other areas through the mechanical system.

Design Guidelines: Flexibility & Cleanliness

Vibration and noise control, particle control and facility flexibility are the major determinants of the design program for microelectronics facilities. Each determinant implies a net of conditions that influence architectural and engineering decisions.

The use of modular, factory-assembled room systems utilizing carefully manufactured high-quality components of non-shedding materials is making an impact on the industry. Still, the field-assembled room consisting of several prefabricated components integrated into a design persists as the most common approach. Many advanced projects of this type are constructed by specialty contractors, experts in this type of construction. The basic components of clean room construction can be summarized as follows:

- A laminar flow filter system at the ceiling with integral lighting
- Unistrut-type wall framing
- Prefabricated wall panels with smooth, baked enamel, porcelain or plastic laminate finishes
- Welded chemical-resistant conductive

flooring

- A perforated raised floor system (if required) appropriate for clean room use, or sidewall return grilles
- Coved flooring bases for ease of cleaning
- Appropriate glazing for outside awareness, visitor observation or safety
- Sidewall grilles with dampers, or dampers in the raised floor for room balancing
- Epoxy-coated walls in service aisle areas for ease of maintenance
- The use of appropriate entry configurations (air lock or component air shower)

The clean room design solution must respond to the need for non-disruptive change (flexibility), easy maintenance or cleaning on a periodic basis, non-shedding construction materials, and ease in coring services for equipment through walls and contamination control.

Vibration & Noise

A completely vibration-free environment is an unrealistic design objective for any sophisticated advanced technology facility. Generally, facility vibration criteria are projected from research compiled by manufacturers and specialty vibration consultants with regard to the manufacturing process' anticipated sensitivity to vibration. These criteria consist of various limits of vertical velocity amplitude *vs.* frequency (see Figure 6).

In this figure, the vibration-sensitive manufacturing equipment corresponds to lines A, B, C and D that are defined as follows:

A. Optical balances, bench microscopes

B. Aligners, steppers, etc., for 5 micron or larger line widths

C. Aligners, steppers, etc., for 1 micron or larger line widths

D. E-Beam and other 1 micron or submicron equipment; scanning electron microscopes

The common criterion for the submicron microelectronics facilities of today is the Sensitive Equipment D line. It is interesting to note that the working magnification level for this equipment is approximately 28 times lower than human perception threshold limits.

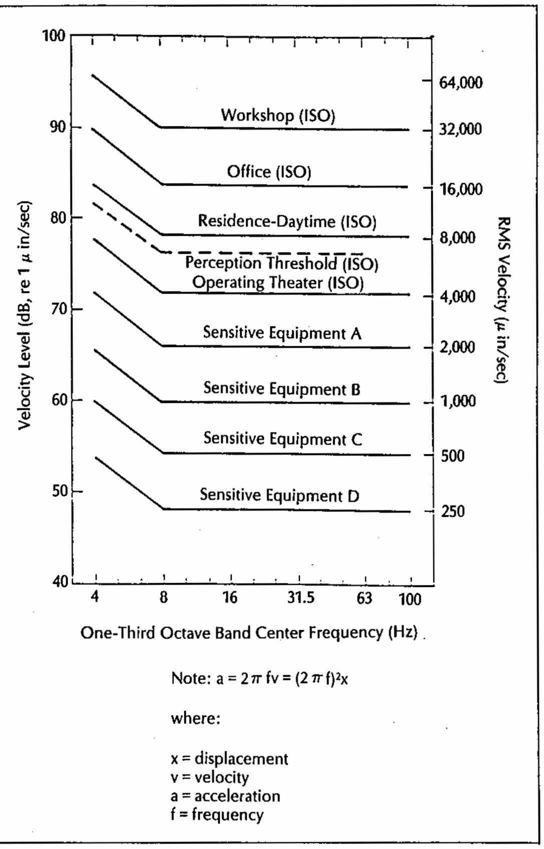

FIGURE 6. Vibration criteria for sensitive equipment in buildings (courtesy of BBN Laboratories, Cambridge, MA).

Levels of vibration are controlled by utilizing structural designs with stiffness and mass. The most common system used today is the concrete waffle slab. The use of this system maximizes the stiffness requirement with its ribbed construction while also using more concrete in volume than structural slabs, thus creating significant background mass. The inside dome areas of 4- to 6-in. thick concrete allow enough flexibility for the penetration of the various support piping and ducts related to the clean room. The use of a waffle slab also offers the end user the added benefit of a 350 to 400 lb./sq. ft. load, the structural requirement for such heavy process equipment as E-beam and ion implantation equipment.

Pedestrian traffic (footfall) within the

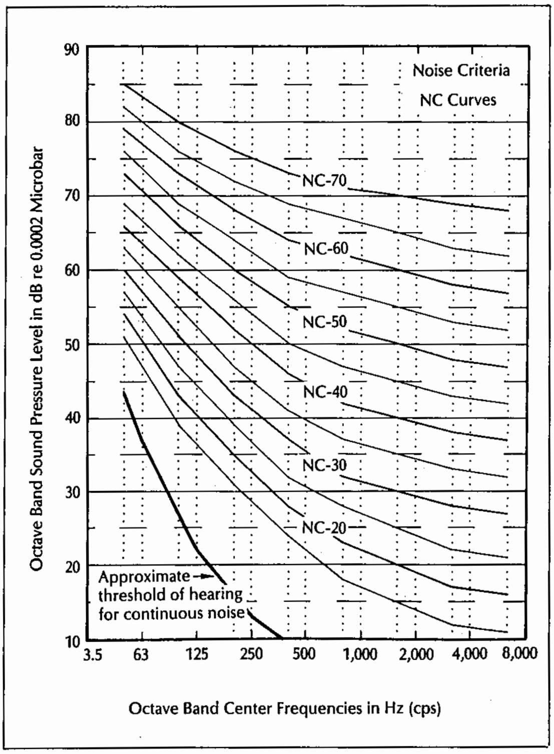

FIGURE 7. The criteria for mechanical system noise (courtesy of BBN Laboratories, Cambridge, MA).

facility is one of the most important vibration sources to consider. The most reliable solutions (other than administrative controls) are the structural separation of high traffic areas, or the use of heavier structural components to bring footfall-induced vibrations within acceptable limits.

Mechanical equipment vibration is usually mitigated by the use of spring isolators, inertia blocks, flexible connections on ductwork or conduit, and equipment selected for its rotating rather than its reciprocating components.

Noise is always a difficult problem in mechanically-intensive facilities, and microelectronic facilities are no exception. Since some noise is vibration related, the vibration features of a building assist in mitigating sound transmissions. However, air-handling systems, fume hoods, exhaust systems and equipment areas (chillers, boilers, pumps, etc.) must be carefully located and appropriate silencers or architecturally-related sound-absorbing elements (walls or casings) must be used to attain a relative sound level indicative of the potential uses of the spaces.

Figure 7 shows the Noise Criteria (NC) Curves that indicate sound levels in dB *vs.* frequencies. The NC-55 noise criteria curve is the generally acceptable clean room area design limit for noise within these spaces. Figure 8 identifies several problem areas that are associated with vibration and noise. A well planned facility will have design components that mitigate the typical issues shown.

High Purity Water

A critical element in the integrated circuit manufacturing process is the ultrapure rinse water used to wash the product at various stages of development. Water for microelectronics use may be purified by distillation, ion exchange, reverse osmosis, ultrafiltration, electrodialysis or a combination of these methods (see Figure 9).

A typical water purification or de-ionized (DI) water system consists of the following:

- Pretreatment/Make-up
- Final Purification
- Storage/Distribution
- Polishing Station

The pretreatment portion of the purification system treats the raw make-up water so that it is suitable to enter the final purification system. Included in this process is the filtration of suspended solids, removal of organics, pH adjustment to minimize scaling, UV sterilization and chemical treatment to prevent the fouling of the reverse osmosis membranes, pre-heating to 70° and reverse-osmosis. Pretreatment removes the majority of the dissolved salts, organics and bacteria. At this point, the treated water should have a resistivity of 1 to 10 megohms and be free of organics and bacteria.

Storage/distribution consists of one or a series of storage reservoirs used to handle peak flow conditions. The stored water is constantly pumped through the polishing loop and returned to the distribution pumps. Final purification consists of ion-exchange and resin traps, prior to final filtration in the polishing

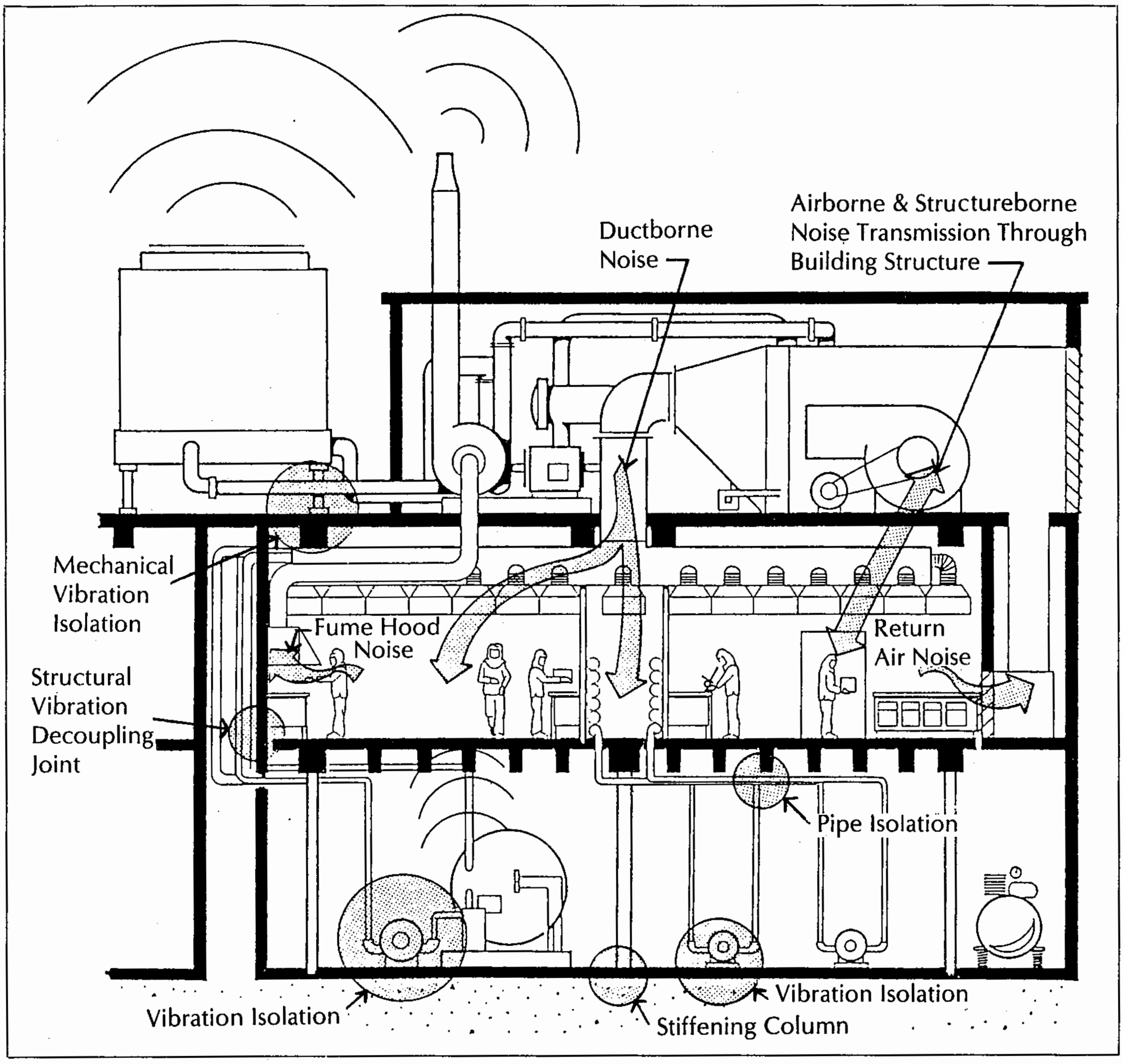

FIGURE 8. Vibration/noise problem areas within a microelectronics facility.

loop.

The polishing loop is composed of UV sterilizers that destroy over 99 percent of the remaining bacteria, polishing de-ionizers that raise the resistivity to 18 megohms, and final filters (for the sub-micron range). The filters prevent resin debris and dead bacteria from contaminating the distribution loop. The water is now considered "Electronic Grade E-1" with a resistivity of 18.3 megohms and can be used for process rinsing.

The state-of-the-art in piping material used to distribute DI water is polyvinylidene fluoride (PVDF). This material has replaced PVC, which was formerly popular due to its low cost and durability, after it was discovered that additives in PVC can migrate into the ultra-pure water.

Waste Water Treatment

Most waste water from the integrated circuit manufacturing process requires only neutralization prior to being discharged to local sewage systems. This process equalizes the strength of strong acids and bases in an equalization tank that overflows by gravity into a treatment tank. Caustic (sodium hydroxide) and acid (sulfuric) solutions are pumped into the treatment tank under the control of a pH probe via metering pumps.

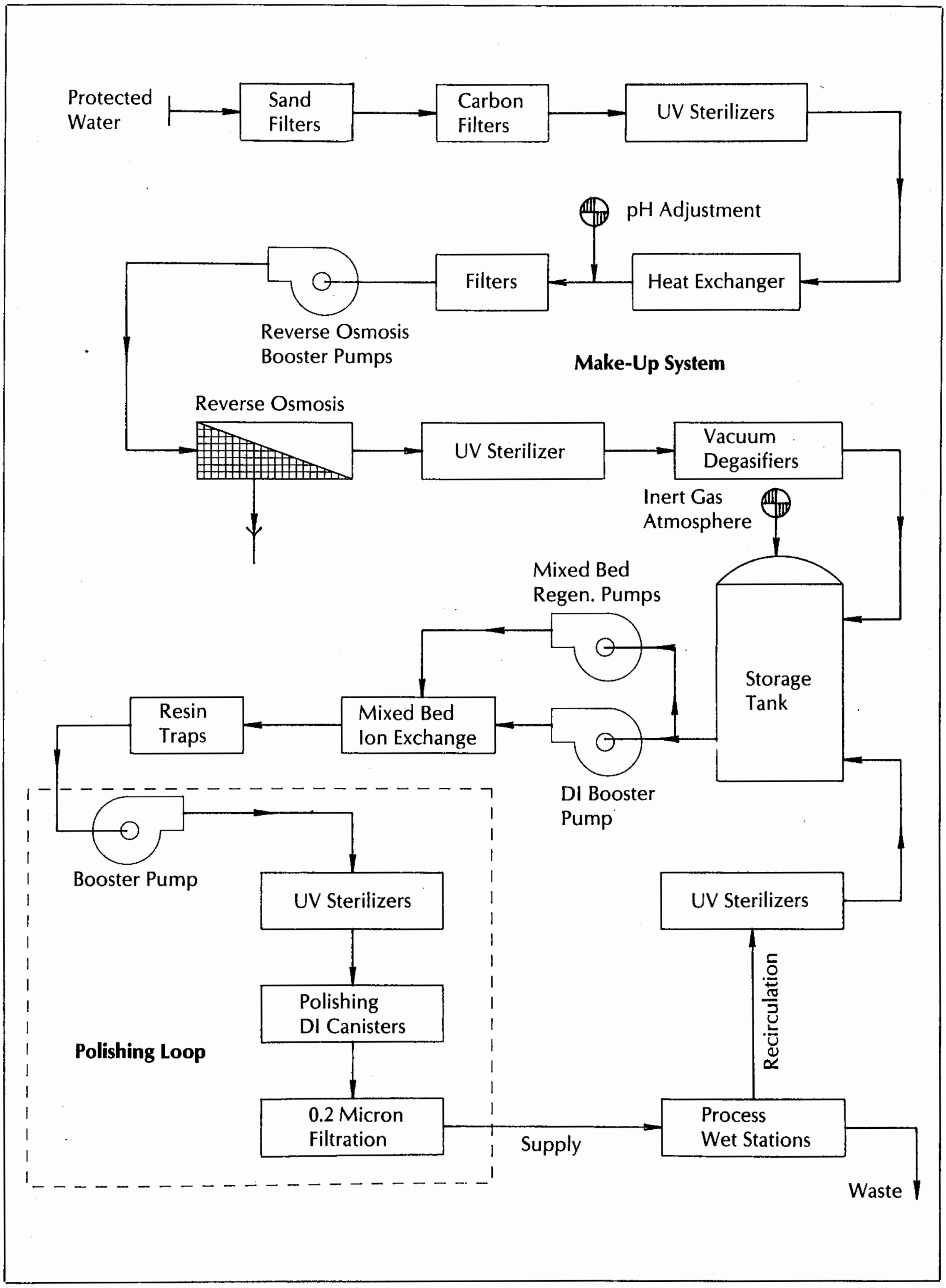

FIGURE 9. A schematic of a typical microelectronics facility high purity water treatment system.

This process is automatic and continuous (see Figure 10).

The overflow from the treatment tank flows by gravity to a wet well and is then pumped to the building sewer. The effluent pH is continuously monitored and recorded along with effluent flow. If the pH deviates from the set pH range (6.5 to 9.0), an alarm alerts the facility monitoring system.

Other liquid chemical wastes such as hydrofluoric acid (HF) effluent and solvents are normally collected in dedicated waste piping systems to on-site storage vessels for off-site disposal.

Contractor Prequalification

Microelectronics projects are among the world's most complex building types. Clean room construction demands exacting room installation tolerances, precise HVAC air-balancing, delicate HEPA filter placement, unusually low internal supply ductwork and process piping cleanliness specifications, room pressurization testing, clean construction sites and the total cooperation of owner, architect, engineer and contractor.

Prequalification of subcontractors by the building design team must be based on past experience and performance with microelectronics projects. This type of bidding approach requires that the owner and design team research and evaluate past subcontractural performance. Despite the great amount of effort this involves, such planning pays higher dividends in decreased risk and greater efficiency. A typical prequalification procedure follows:

- Identify potential qualifiers
- Assess past performance
- Evaluate the ability of potential qualifiers to complete the particular project scope

The prequalification of mechanical/process and clean room subcontractors should be a minimum requirement. Other subcontractors who could also be prequalified include electrical, fire protection and roofing.

Construction Procedures

A finely-tuned construction control procedure is integral to a successful working facility. Clean rooms must be totally sealed throughout construction to prevent the entrainment of large particles into the protected space through areas other than the HEPA filter supply systems. The proper balancing of the unusually high supply air requirements to maintain positive pressurized clean room spaces with respect to contiguous "dirtier" spaces is critical. Interior surfaces of supply air ductwork as well as the interior building spaces through which this air circulates (both supply and return sides) must be cleaned throughout and at the end of the construction period.

Shop Drawings

Because microelectronics facilities are mechanically and electrically intensive, ⅜″ = 1′ scale composite drawings and sections should be submitted as formal coordination shop drawings by the contractor to the architect/engineer. This requirement often reveals "value engineering" layout options that may not be fully apparent at the scale of the original documents. The most obvious benefit of these planning documents is the reduction of "after the fact" change order costs resulting from poorly coordinated or installed systems. The time spent in this preplanned coordination will help to prevent significant delays in construction time caused by poor construction field coordination. Many contractors even designate their own mechanical/electrical coordinator on site to orchestrate this intricate coordination of subcontractors.

Facility Start-Up

The final keys to any successful clean room are a well-planned clean room certification period and a systems start-up, or shakedown, period. The certification should be conducted by an experienced clean room testing agency qualified under nationally acceptable standards and preferably independent of any clean room subcontractor. Typically, three certifications are performed:

- The room unoccupied, with no equipment.
- The room unoccupied, with process

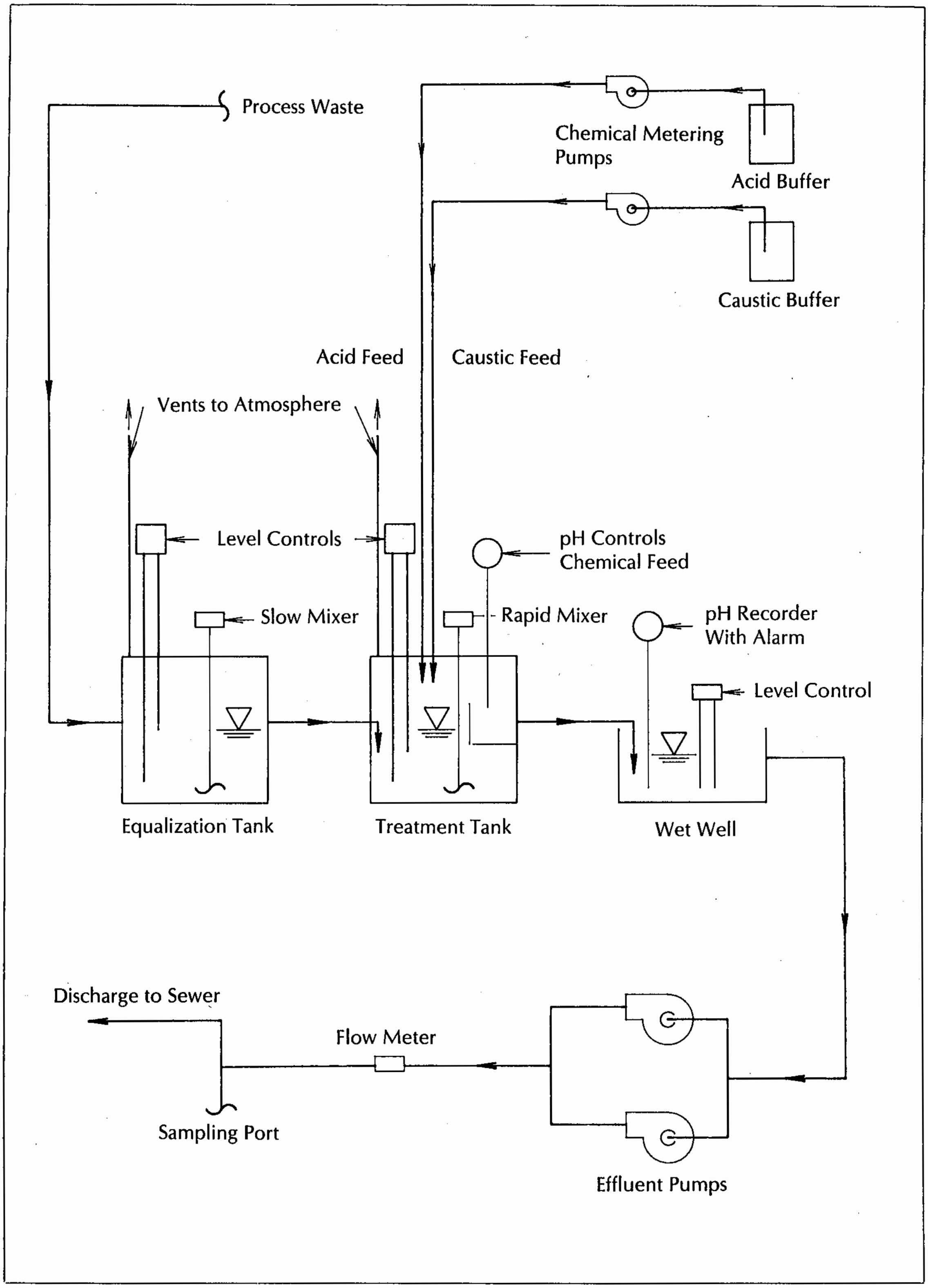

FIGURE 10. A schematic of a typical microelectronics facility waste water treatment system.

equipment in place (at-rest condition).
- The room occupied under normal operating conditions.

Clean room temperature, relative humidity and airflow, as well as other characteristics, will change as equipment and people are introduced into the empty clean room space. Each certification, in its turn, attempts to customize the room's air and control systems, primarily by adjusting supply or return air dampers for balancing air, and by accounting for the various equipment characteristics (for example, added heat load or vibration).

The testing of automatic temperature control systems is also critical at facility start-up. Although state-of-the-art direct digital controls (DDC) are standard equipment, their software can be faulty. Other systems such as process chilled water, high purity water treatment and distribution, process gas distribution, fire alarm, security and fire protection (HALON or wet sprinkler) require similar operational testing. The architect/engineer, owner and contractor must act in concert as a quality control team in order to correctly assess the proper function and operation of all these final systems.

Project Management Issues

In recent years, the planning, design and construction of clean room facilities has evolved to its present advanced state requiring a highly integrated owner, designer and contractor team approach. No single area of the design and construction phases can be overlooked since each phase has critical influence on the final success of the project. However, in the early phases of architect/engineer selection and contractor selection, programming and planning are the key elements.

A multitude of approaches can be used to select an architect/engineer team. As with subcontractors, the most popular method consists of developing prequalified lists of architectural/engineering firms that have had experience in microelectronic facility design and construction. Once this list has been finalized, proposals can be solicited that will identify each firm's approach, unique qualifications, key personnel and any other special considerations. A qualified firm can then be selected and a fee negotiated on the basis of the initial proposal document.

For larger and more complex facility projects, it has become common to include a construction manager as part of the project team. The construction manager is often brought aboard during the early design phases as an active participant in the budgetary analyses and scheduling of the project. Depending on the success of the early project decision-making process, the possibility of issuing early site, foundation and structural steel subcontracts may result in significant time savings. Again, care should be taken to make sure that construction management firms are carefully screened and selected only from qualified firms that are active in the high technology construction market. This selection may be based on proposals received from various construction management firms that identify their approach, team members, qualifications and, if requested, fees for doing both design consultation (generally a lump sum) and construction phase management (generally a percentage of the construction costs). As a rule, the architect/engineer and owner team should be jointly involved in this process.

The final project team is composed of the following typical elements:

- An owner/end user representative
- An owner/facilities representative
- The architectural/engineering design team
- The construction team (construction manager or general contractor, subcontractors)
- Specialty design consultants (process and vibration/acoustical)
- Post-construction owner representatives — clean room and plant managers

A communications system that integrates each of these functional team members is critical for complete project control. In the early programming and planning stages, the professional team will be working closely with user and facility owner groups to incorporate information from client input. It is up to the professional team to indicate the feasibility of any "wish list" items in light of budget/project goals, and include them in the construction program if possible.

The design and construction phases of the project require constant value engineering and a review/approval process at the end of the various traditional project phases (feasibility/programming, schematic, design development and construction documents). Ongoing reviews of the cost model and schedule must also be performed in order to monitor the status of the target budget and to uncover any schedule constraints.

The development of the final construction cost is the result of competitively bid packages assembled via the contract delivery process. The evaluation and procurement of the various subcontract components of the work should have the involvement of the owner, designer and contractor. This involvement is typical of the construction management process and is not usually part of the traditional general contractor competitive bidding process. Regardless of the ultimate construction delivery process selected, the architect/engineer, owner and contractor must coordinate their efforts during the construction period to accommodate any necessary changes under the requirements of the contract. Unlike a normal building project, changes to microelectronics facilities are frequently the result of unexpected state-of-the-art changes in semiconductor technology, particularly in such sensitive areas as microcontamination control and process equipment advances.

After the design and construction are completed, the critical building system start-up or shakedown process begins. Only through the intensive testing of the building's critical systems — particularly automatic temperature controls, certification of clean room environments, certification testing of process and ultra-pure water piping systems, and HVAC system balancing — can the successful operation of the project's process can be assured. Typical issues of concern to the project team during the design and construction phases from assessment and project scope to identification of documents and project cost modeling are summarized in Table 3.

Particle Control: Operator Discipline

The best operating clean room design can be nullified by operator negligence. Contamination control requires the facility staff to follow disciplined operating procedures. In Japan, sophisticated contamination control management procedures have substantially reduced the degree of outside contaminants entering clean room facilities on the clothing or bodies of the operators. Figure 11 illustrates the control typical in these Japanese facilities from the time the worker arrives at the plant to the time that he or she enters the clean room environment. Such an approach is ultra conservative, yet there is no argument that the disciplined pattern, as well as worker understanding of contamination control, result in higher production success. Clean room managers estimate the percentages of product loss to be as high as 50 percent for some processes due to inadequate environmental management of workers. Inattention to correct clean room entry procedure, even wearing make-up or aftershave, can affect the quality of the day's production or lead to its loss.

Future Trends

The pending revisions to Federal Standard 209B, which will be designated Federal Standard 209C, will attempt to respond to state-of-the-art changes in clean room designs for today and into the future. The major recommended changes in 209B will be the addition and definition of Class 1 and Class 10 clean rooms. The number of sampling points will be specified differently, and a distinction will be drawn between unidirectional and non-unidirectional flow rather than laminar and turbulent flow. Minimum sampling volumes will be set based on the amount of anticipated errors in sample testing. Verification requiring particle sampling will be performed both initially and periodically, and all particle counting instruments will require periodic calibration.

This forthcoming revision of 209B was proposed by the current RP-50 Committee of the Institute of Environmental Sciences (IES), and breaks new ground by including particle sizes smaller than 0.5 microns as well as

TABLE 3

Design Decisions For Determining Project Cost & Success

1. Assess Existing Conditions
   - Geotechnical
   - Environmental (if applicable)
   - Master Planning Impact
   - Permit & Approval Procedures (Macro/Micro)
   - Pedestrian & Vehicular Access
   - Site Sensitivity

2. Agree on Scope of Project
   - Resolution of Facility Square Footage
   - Research & Development Area Requirements
   - Support Area Location & Requirements
   - Establishment of Design Criteria by Specific Spaces
   - A Reliable Utility & Equipment Matrix
   - Agreement on Facility Design Image

3. Prepare a Detailed Design Task Schedule
   - GANTT Chart
   - Critical Path Method Diagram
     - Identify Design Tasks & Approach Milestones
     - Allow for Coordination & Review Times by Architect/Engineer & the Owner
     - Constantly Test & Revise the Schedule as Necessary
     - Check That Each Task Noted Is Within Definable Scope of Work

4. Establish Project Control
   - Perform Budget Testing
   - Develop Accurate & Timely Communications
   - Plan Reliable Reporting Procedures
   - Designate Monthly Corporate-Level Meetings
   - Establish Design Sign-Off Procedures
   - Set Agenda & Other Meeting Standards

5. Identify the "Undeliverable" Documents at Each Phase
   - Agree on the Extent of Written Materials, Particularly Specifications
   - Prepare Mock-Up Drawings at the Start of Each Design Phase
     - Establish schedules & Cost Estimate Formats
     - Allow Formal Presentations of Each Major Submittal
     - Keep Project Team Comments on One Master Set

6. Initiate & Maintain a Project Cost Model
   - Establish a Preliminary Project Cost Model of as Many Components as Practical
   - Develop Timely Comprehensive Estimates to Test the Original Cost Model
   - Make Cost Estimating Important to the Project Function
   - Understand Your Value Design Options That May Not Affect the Actual Program
   - Carefully Assess Contingency Percentages to Be Used
   - Evaluate Local Labor & Tax Conditions & Potential Impacts on the Cost Model of Productivity in the Geotechnical Project Area

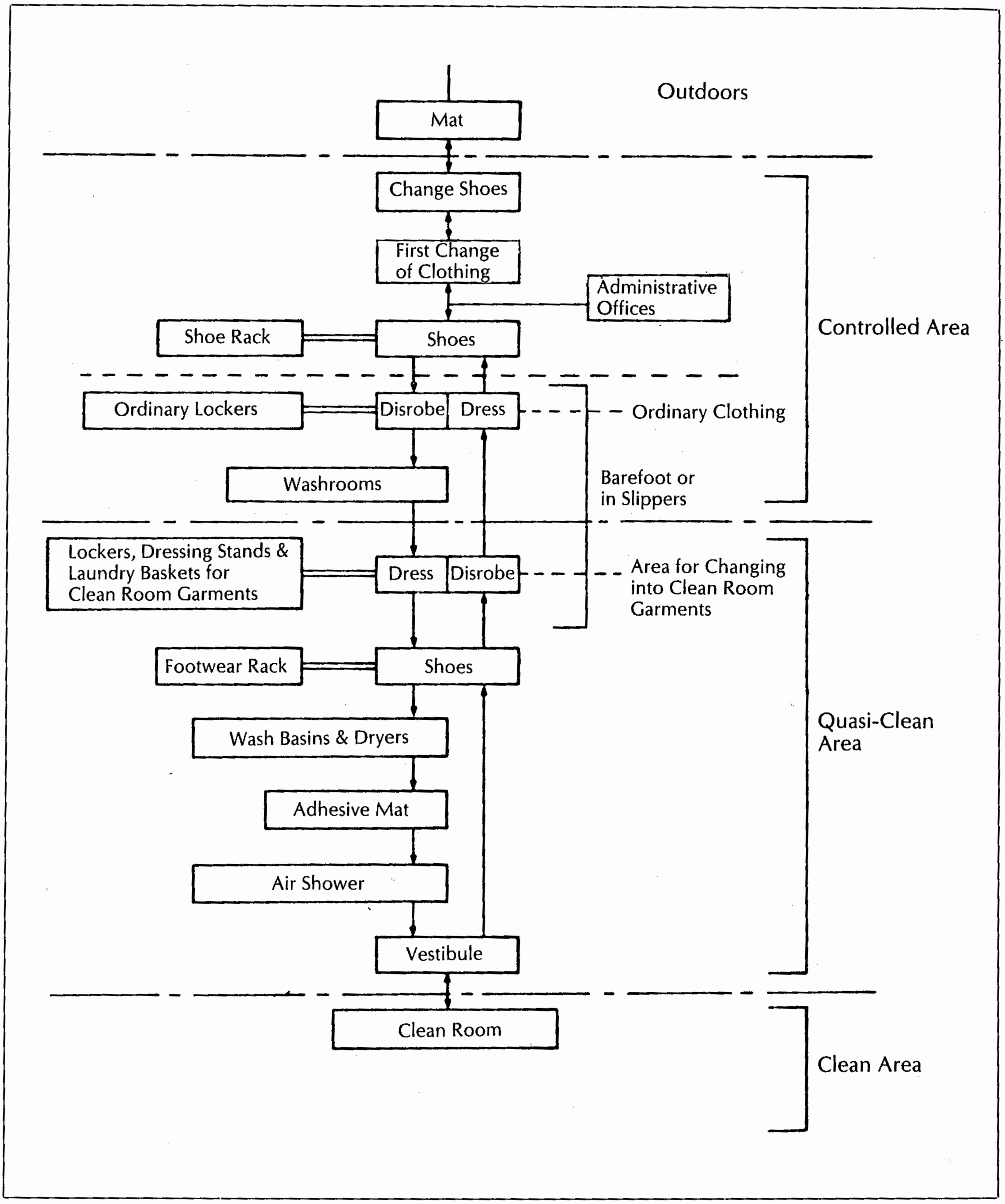

FIGURE 11. A clean room entry diagram.

including Classes 1 and 10. The revision represents the contributions of scores of specialists in the contamination control field who hope that it will improve statistical measurement practices.

These proposed changes will begin to satisfy the needs of the microelectronics industry for cleaner air classes and smaller particle sizes. However, there will continue to be a disparity between the desire for more accurate clean space characterization and the willingness to bear the costs for such characterization.

The physical characterization of clean rooms is also changing. The recent trend has been the prepackaging of the clean room envelope, specifically the use of modular clean room components to construct clean room spaces. This trend is particularly important in light of the rapidly changing semiconductor manufacturing technology that dictates the need for enormous flexibility within these process spaces. The manufacturers of these prepackaged clean rooms point to the exact tolerances achieved during factory assembly. In fact, many of these modular clean rooms are initially assembled at the factory, then disassembled, delivered to the job site and reassembled at the construction site. Such systems are expensive in terms of first capital cost, yet they they do have such advantages as short knock-down capability and short installation time.

Beyond prefabricated systems comes the concept of flexible components such as unistrut assemblies and finished laminated walls that can actually create a reusable field-assembled clean room space. This concept meets the need for flexibility since components of the walls can be taken apart, moved or retrofitted to accommodate equipment changes.

Because sophisticated clean room prices can run between $350 to $750 per square foot in terms of net space cost, the future trends in clean room design will primarily center on the use of automated cassette-to-cassette wafer transfer clean tunnels as a potential replacement for human-occupied clean rooms. These facilities will eliminate the human and equipment contamination factors with robotic process lines that have only critical portions of equipment left in the clean spaces, thereby reducing clean room size. Without the need for wide clean room tunnels on the order of 12 to 14 ft. wide, the first cost in terms of capital installation will be reduced as will the extremely high energy costs per year for air recirculation since these spaces will be smaller and less air will be required. The basic reason for applying these robotic systems is the lessening of both capital and operating costs of tomorrow's clean rooms while providing even cleaner spaces through the elimination of human particle contributions. Laminar flow protective wafer transfer systems will significantly improve the microcontamination control that protects the wafer's surface, thereby increasing production yields at sub-micron geometry levels.

Conclusion

Since the clean rooms of today generally have an effective operating life of three to five years without technological change, future facilities will require unique flexibility requirements to accommodate anticipated changes in equipment and processes. The elements of design and construction described here represent the types of planning that will allow tomorrow's researchers to make the same type of technology gains in the twenty-first century as we have witnessed in the last four decades.

It is interesting to note that as integrated circuits have become increasingly more miniaturized, so has the production environment, further cutting back the overall cost of this elaborate manufacturing process. The amount of space for these process clean spaces will decrease yet more as the need for smaller, faster and unique microelectronics grows. The success of these facilities will still depend, however, on the carefully planned human element of programmed spaces and proper design.

ACKNOWLEDGEMENT — *The authors wish to thank Stephanie C. Hodal, Director of Communications for Symmes, Maini & McKee Associates, for her assistance in preparing and editing this article.*

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