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CLEAN ROOM TECHNOLOGY

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FOREWORD

The emphasis on improving component reliability in the United States Space Program has generated an expanding number of facilities throughout NASA and its supporting contractors to control contamination. NASA has reported many hardware failures attributable to contamination. Although the clean room is only one of several elements in a contamination control plan, it is a vital part. Developing the techniques for contamination control requires an increasing number of trained technicians each year. The literature related to clean rooms abounds in information from a wide variety of sources and diverse technical publications, but a comprehensive compilation for use in training clean room technicians is not easily found.

This publication evolved from lectures presented to acquaint technicians and their supervisors with the characteristics and operation of a clean room. The material has been gathered not only from published data, but also from discussions with clean room operators and recognized authorities in contamination control technology. This is one of a series of publications issued to make technological information of potential value to many industries generally available.

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BACKGROUND INFORMATION

Advances in the field of mechanical science have established the need for the clean rooms of today. As more sophisticated mechanical devices are produced using very precise tolerances, the requirement to prevent contamination becomes more important. The clean room provides the environment necessary to manufacture and assemble these devices. Controlling the contamination of a product has not only resulted in highly complex clean rooms, it has also produced a whole new technology. It is characteristic of contamination control technology that the technical demands are compounding with time and that a once simple concept now requires highly skilled personnel. They must have experience in the basic sciences to operate the devices and equipment required for a clean room as well as to manage such a facility. The information contained herein certainly is not a compilation of all that is known in clean room technology, but it does provide an insight into this rapidly expanding technology.

Historical Background

The first recognition of a need to control the environment during a work operation was in medicine. During the latter part of the 19th century, physicians learned that microorganisms were responsible for transmission of infection. A great number of these carriers is present in an infected patient. Hospitals were also recognized as a primary source of further infection. "Operating rooms" were established in which an effort was made to control the spread of infection. The emphasis in the operating room was on sterile conditions or control of biological contamination.

The modern operating room is constructed and operated to minimize the chances of infection to the patient. Control of both airborne and transfer contamination is a major function in an operating room. This is evidenced by the meticulous preparation taken by the surgeon and his staff prior to an operation.

The operating room environment is controlled by three procedures. The instruments and equipment taken into the room are cleaned and sterilized. They are then packaged to maintain sterility. The surgeon and his staff of assistants and nurses all scrub thoroughly and are clothed in aseptic garments. Finally, the patient is cleaned and prepared for the operation.

Several areas of operation of a hospital operating room are common to a clean room. The equipment used in an operating room as well as in a clean room is reserved for use in that area only. In each, the personnel are clothed

in special garments that are similar. Each room is subjected to extensive cleaning procedures prior to use and at regular intervals. In spite of these similarities, there are some basic differences between clean room and operating rooms. In certain respects, the cleanliness level of a clean room that handles space-age equipment must exceed that of even the most modern operating room. In the clean room, the emphasis is on control of dust or particulate matter. Particulate matter is of little concern in an operating room provided it is sterile. On the other hand, clean rooms have had little difficulty with bacteriological growth. There is little on which bacteria can feed in a clean room. Also, the low humidity in a clean room is not conducive to bacterial growth.

Just as most of the advances in operating room techniques have been an outgrowth of World War I, the birth and development of clean rooms is tied to World War II. The aircraft and navigation devices of World War II required many small components with close tolerances. Dusty atmospheres and the general uncleanliness of a machine shop were soon recognized as a source of much difficulty in quality control and reliability assurance. As a result, controlled assembly areas were constructed, and some semblance of cleanliness established. Today's clean rooms are several orders of magnitude better than these first work areas of 1940. The originals should more properly be called "white rooms" as distinguished from clean rooms.

Generally speaking, a clean room controls three types of contamination transfer. The first of these is *airborne contamination.* The contamination can be of any size, shape, or nature and is transferred by conduction air currents or by the trajectory of a particle during a work operation. The next method of contamination transfer results from particulate matter carried from one subject to another by *direct contact.* This method of contaminating is prevalent and should be given as much attention as airborne particulate transfer. The third type of contamination transfer comes from *fluids.* This occurs with cleaning solutions as well as lubricants and propellants.

Contamination control was first effected by good housekeeping practices, by segregating the work area from other operations, and by providing a filtered air supply. Better filtration systems, the wide-spread use of air conditioning, and room pressurization techniques have done much to advance the state of the art. Personnel protective clothing, air showers, and shoe cleaning equipment have been the latest additions to contamination control. Improved methods of component cleaning and better personnel work procedures are adding to these advances.

Within military organizations, clean rooms have been used to overhaul and maintain precision instruments and equipment such as navigational devices and bombsights. Many of these items require periodic overhaul after a fixed number of hours of use. Others are sent through maintenance shops when they fail to perform. In either case, a large workload exists requiring controlled environment facilities. The military services also use clean rooms

for photographic reproduction work. This type of activity requires a high degree of control of airborne particulate matter.

In fact, the earliest clean rooms in the United States were Air Force facilities. Olmsted Air Force Base in Pennsylvania had the largest area of clean room space in the world. Recently, this installation was deactivated and the operation transferred to Wright-Patterson Air Force Base in Ohio. Smaller units exist throughout the Strategic Air Command for use by photographic reproduction units. The Navy operates a clean room facility at North Island Naval Air Station, California. The National Bureau of Standards, the U.S. Public Health Service as well as the Atomic Energy Commission in Sandia, New Mexico, have been influential in developing clean room facilities. However, the sophisticated equipment used by NASA has made the space industry the primary user of clean room technology. NASA is in the process of establishing standards for the space industry, and the program outlined in the NASA Handbook for Contamination Control of the Apollo Program will soon be a part of many NASA contracts.

The Air Force was influential in establishing the first written standards for clean room operation. Air Force Technical Order 00–25–203 entitled "Standard Functional Criteria for the Design and Operation of Clean Rooms and Clean Work Stations" was published in 1961. After extensive study, it was redefined and reissued in July 1963.

In April 1963, the Atomic Energy Commission conducted a conference at Sandia, New Mexico, to review the standards in use by clean room operators. Approximately 200 clean room practitioners were present and took part in this program. As a result, a group was established to write a standard for clean rooms. By the end of 1963, Federal Standard 209 was published. It is now the basis for all clean room operations. It also established three classes of clean rooms: Class 100,000, Class 10,000 and Class 100. The Class 100,000 corresponds to the previous Air Force "standard" clean room. Federal Standard 209 also established a size distribution relation of particulate matter in each of the classes to be used in evaluation of facilities. This is discussed in detail in the section Air Cleanliness Classes and Standards.

Need for Clean Rooms

Experience in the space program has shown that an entire mission can fail because of contamination. For example, the function of a valve in the propellant system of an attitude control device with 10-micron clearances could be impaired by very small particles of contamination. If contamination were to cause the valve to stick partly open, creating a continuing loss of propellant, the attitude control propellant would soon be dissipated, and control of the vehicle would be impossible. The entire mission would fail. Contamination of this sort is caused by any foreign matter from very small accumulations

of practically invisible dust to gross chunks of solder, lubricants, and other debris from the fabrication process.

During World War II, the first clean rooms were used in the development of the Norden bombsight and the first navigational gyroscopes. The clearances in these devices were such that if particles in the range of 20 to 50 microns were introduced their function would be impaired. In 1956, the Navy procured an inertial guidance system (ASN–28) containing two floating gyros. The flotation was in a highly viscous fluid that provided virtually friction-free suspension. The reliability and efficiency of the system depended ultimately on the cleanliness of the fluid and the gyro components. It was demonstrated that contamination one-third the size of the particles in cigarette smoke could compromise the system.

The manufacture and processing of photographic film has long required a dust-free environment to prevent the deposition of dust on the film. However, recent advances in enlargement techniques have accentuated the problem. Five- to 10-micron-size dust particles cause spots on the film that will be increased in diameter many times during the enlarging process.

Today's highly sophisticated electronic, hydraulic, electromechanical, and electro-optical systems require such extreme precision that the presence of microscopic particles of dust cannot be tolerated.

In many cases the need for a clean room is obvious. Holes result in thin-film components of solid-state devices if dust particles are present on the original at the time of photographing or processing. When very close spacing between moving parts must be maintained, particles can jam into these spacings. Hard, sharp particles in bearings cause wear. However, when improved reliability or precision is the aim of using a clean room, the evidence of the advantages to be gained is often circumstantial or nonexistent. Few data are available to indicate the degree of cleanliness required to achieve the desired results. Very little is known regarding the importance of particle size or the harm caused by particular levels of particle concentration. It is difficult to give an answer to the question, "How clean must the

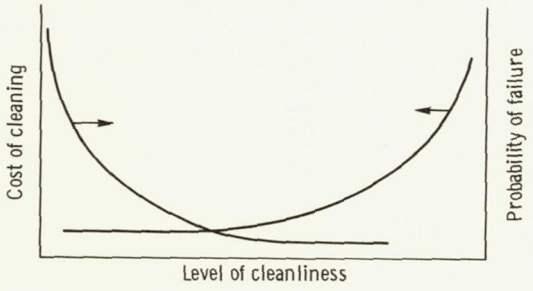

FIGURE 1.—Probability of component failure and cost of cleaning related to required level of cleanliness.

piece be"? Usually a compromise is made between the cost of the cleaning process required and the probability of failure of the component. Figure 1 demonstrates this trade-off. Of course, getting sufficient reliable data to construct such a figure for a particular application is difficult.

Nature and Origin of Contamination

We live in a dirty world. Absolute purity seldom, if ever, is achieved. There is some contamination on every object we handle, but it may not be significantly harmful. Thus, it is important to consider the desirability of controlling the degree or level of contamination *only* to a point where it will not constitute a hazard or degrade the function of the product.

Contamination may be classified in four general categories:

(1) Particulate: dust, chips, fibers, etc.
(2) Chemical: gases, liquids, oily films, etc.
(3) Biological: bacteria, virus, fungi, spores, etc.
(4) Energy or changes of state: light will contaminate film, magnetic fields contaminate iron or nickel, radiation affects living cells and plastics, heat degrades, etc.

Some of these contaminants are the result of production or processing of an item, while others result from external sources. For the present, contamination from external sources will be considered. The most common sources of industrial contamination are shown in table I. This table refers only to particle size. A micron is one-millionth of a meter or 0.000039 inch. Particle concentrations, however, will vary widely with location and season. For example, in rural areas under normal atmospheric conditions, concentrations up to 40 000 particles per cubic foot are not unusual. However, in metropolitan areas counts up to 1.5 million particles per cubic foot (larger than 0.5 μ) are normal. The general industrial atmosphere has concentrations up to 1 million particles above 1.0 micron with a normal range of distribution up to 600 microns. Much larger particles can be expected to occur frequently in such a distribution, since increased sizes and concentrations are a positive function of industrial operations.

Internal sources of contamination are as important as the external ones, especially since they originate in the vicinity of the product involved. Internal contamination results from machining and forming operations, processing, and from general handling such as maintenance, packaging, shipping, and storage. The main problems with internally generated contaminants are caused by their migration in the factory air handling and ventilation systems, personnel and personnel traffic, and production process and equipment. For a better understanding of the nature and influence of the contaminants, additional knowledge of their behavior and source is necessary.

Operating personnel performing their normal work activities will generate

TABLE I.—SOURCES OF INDUSTRIAL CONTAMINATION

Source	Particle size range, μ
Combustion products:	
Power generating plants	0.5 to 50
Refineries	0.5 to 50
Commercial transportation (including private autos)	0.1 to 10
Heating plants	0.1 to 1200
Exhaust from chemical processing plants	2 to 10
Construction:	
Erection of new buildings	1 to 50
Demolition of buildings	1 to 100
Construction and repair of streets and roads	1 to 100
General:	
Mining and quarries	1 to 500
Cement plants, foundries, steel mills	0.5 to 1000
Domestic coal smoke	0.01 to 5

particles. In general, these will have a greater specific gravity and be of larger size than those present in the ambient air. In addition, these particles will have a considerably higher originating velocity than those produced from the bodies and clothing of the personnel involved. Typical sources of the particles resulting from ordinary activities are shown in table II. Many functions and operations performed by personnel in clean rooms increase the ambient level of the particles in the environment. Typical personnel functions are shown in table III.

TABLE II.—TYPICAL SOURCES OF PARTICLES

Activity	Particle size, μ
Rubbing ordinary painted surface	90
Sliding metal surfaces (nonlubricated)	75
Crumpling or folding paper	65
Rubbing an epoxy painted surface	40
Seating screws	30
Belt drive	30
Writing with ballpoint pen on ordinary paper	20
Handling passivated metals such as fastening materials	10
Vinyl fitting abraded by a wrench	8
Rubbing the skin	4

TABLE III.—INCREASE OF CONTAMINATION LEVELS BY PERSONNEL

Activity	Times increase over ambient levels (particles, 0.2 to 50 μ)
Personnel movement:	
Gathering together 4 to 5 people at one location	1.5 to 3
Normal walking	1.2 to 2
Sitting quietly	1 to 1.2
Laminar flow work station with hands inside	1.01
Laminar flow work station—no activity	None
Personnel protective clothing (synthetic fibers):	
Brushing sleeve of uniform	1.5 to 3
Stamping on floor without shoe covering	10 to 50
Stamping on floor with shoe covering	1.5 to 3
Removing handkerchief from pocket	3 to 10
Personnel *per se*:	
Normal breath	None
Breath of smoker up to 20 min after smoking	2 to 5
Sneezing	5 to 20
Rubbing skin on hands and face	1 to 2

Not only are the size and distribution of contaminants important, but their relative energy level is also a significant factor. The relative energy level between a particle and a point of deposition controls the rate at which the particle will be collected and retained. The type of energy gradients of importance in particulate deposition are electrical, kinetic, and thermal.

Electrical gradients cause electrostatic precipitation capable of affecting collection in almost any size range. Once the particles are charged, they will be strongly attracted to grounded or oppositely charged surfaces. After deposition, the effects of the initial electrification may alter the adhesive forces, but quantitative data regarding this are difficult to compile. Normal aerosols are composed of particles with a charge distribution that depends on chemical composition. Particles pick up their charge during the generation process by exposure to ionizing radiation and by contact with other charged particles. The variation in the electrical field surrounding a component surface is highly dependent on the conductivity of the material.

Kinetic energy gradients cause accumulation of particles because of velocity differences between the contaminant particles and the component surface. These forces are usually referred to as inertial. Direct gravitational or impaction effects are included.

Impaction effects are not considered separately whether they arise from

motion of particles (as wind carried) or motion of the component (as on a fan blade). The controlling parameters of device, particle size, and airflow determine whether the particle will deposit on a surface or will follow the air streamlines around the surface.

Thermal energy gradients cause precipitation to take place when the substrate is at a lower temperature than the surrounding air. When this occurs, submicron particles will be deposited. They may aggregate to sizes large enough to cause difficulty.

CLEAN ROOMS

Controlling Contamination with a Clean Room

Clean room contamination is controlled by six major means:

(1) Facility design
(2) Equipment used in the room
(3) Procedures employed
(4) Personnel activity
(5) Environment control
(6) Maintenance

Usually the design, equipment, and environmental control of a clean room are features that the technician cannot change. He is presented with a particular facility and must make it operate or suggest modifications. However, he is directly involved in the procedures used in the room, his own and his colleagues' activity, and the daily and periodic maintenance of the facility. His performance in these areas will greatly influence the cleanliness level achieved in the facility.

Air Cleanliness Classes and Standards

In general, precision mechanical devices which have clearances in a range from 100 to 1000 millionths inch are affected by particle sizes from 2.5 to 25 microns. These items will require contamination control both during manufacture and overhaul. Clearances less than 100 millionths inch (2.5 μ) will require the use of a higher quality clean room (probably Class 100) or a clean work station. The need for several levels of clean work areas has been recognized, and Federal Standard 209 established three classes of air cleanliness. The levels of these classes are based on statistical distribution for average particle sizes. They depend on particle concentrations with a maximum allowable number of particles per unit volume of air of 0.5 micron and larger, or 5.0 microns and larger. For statistical purposes, the particle counts are taken during normal work activity periods and at locations where the air approaches the work area. The clean room classes defined in Federal Standard 209 are

Class 100—Particle count per cubic foot of air not to exceed 100 particles

0.5 micron and larger, and not more than 1 particle 4.0 microns or larger

Class 10,000—Particle count per cubic foot of air not to exceed 10 000 particles 0.5 micron and larger, 65 particles 5.0 microns and larger, and not more than 1 particle 35 microns and larger

Class 100,000—Particle count per cubic foot of air not to exceed 100 000 particles 0.5 micron and larger, 700 particles 5.0 microns and larger, and not more than 1 particle 100 microns and larger

Figure 2 shows the particle concentration as a function of particle size for each of the three clean room classes. Counts below 10 particles per cubic foot are indicated as dashed lines because they are unreliable except when a large number of samplings is taken. Class 100,000 conditions cannot be met by natural air at any locations over the continents and other land masses with the possible exceptions of Antarctica and Greenland.

The Class 100,000 or poorest cleanliness level clean room is equivalent to the previously designated "Standard Air Force Clean Room". This term as well as the numbered classes such as Class 1, Class 2, etc., are now obsolete, having been replaced by Class 100, etc.

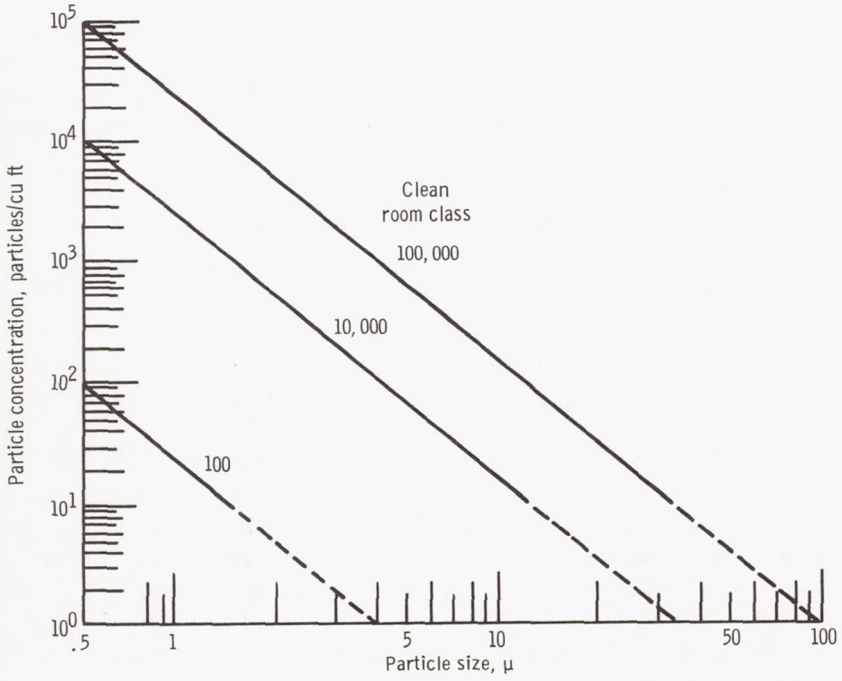

FIGURE 2.—Statistical particle size distribution in clean rooms.

Conventional Flow Clean Rooms

Two design concepts for clean rooms are in current use. The older type is referred to as a conventional flow clean room. This type uses standard, but filtered, air handling and distribution systems. The air normally enters from the ceiling and takes a random flow pattern exiting near the floor. A typical conventional flow system is shown in figure 3. The majority of the clean rooms in operation today are of this type. The advantages and disadvantages of the conventional airflow clean room are discussed in the next section.

Laminar Flow Clean Rooms

A more recent design uses the laminar flow principle. Laminar flow merely means that the airflow is in one direction and that parallel elements of flow remain parallel in one plane. In this type of facility, one wall is made up of a bank of high efficiency particulate air (HEPA) filters and the opposite wall is the exhaust grill. A typical laminar flow room design is shown in figure 4. Theoretically the air, after being forced through the HEPA filters, will move directly to the exhaust grill across the room in a straight line. The airstream makes only a single pass through the clean room before being returned to the filters for recirculation. This reduces the problem of deposition and resuspension of light particulate matter.

Laminar flow clean rooms can be from wall to wall with the flow being horizontal or from ceiling to floor where the flow is vertical. Laminar flow, however, exists in such a room only when it is unoccupied. Furniture, equipment, personnel, and any movement in the room will destroy the laminar flow. Because the air streamlines must divert around these objects, eddy currents are created that destroy the laminar flow. The chief advantage of a laminar flow room is that a large mass of moving air entrains and sweeps particles of contamination downstream as they are generated and are made airborne. This is essential when high levels of cleanliness must be achieved. The laminar flow clean room is the only type that can achieve Class 100.

Comparison of Clean Room Types

Conventional flow clean rooms have the following advantages and disadvantages:

Advantages:

(1) Production line work-flow patterns are not critical and are simple to lay out.
(2) Design is flexible. Several areas can operate off the same air handling system.
(3) Filters and air handling are less complex and easy to maintain.

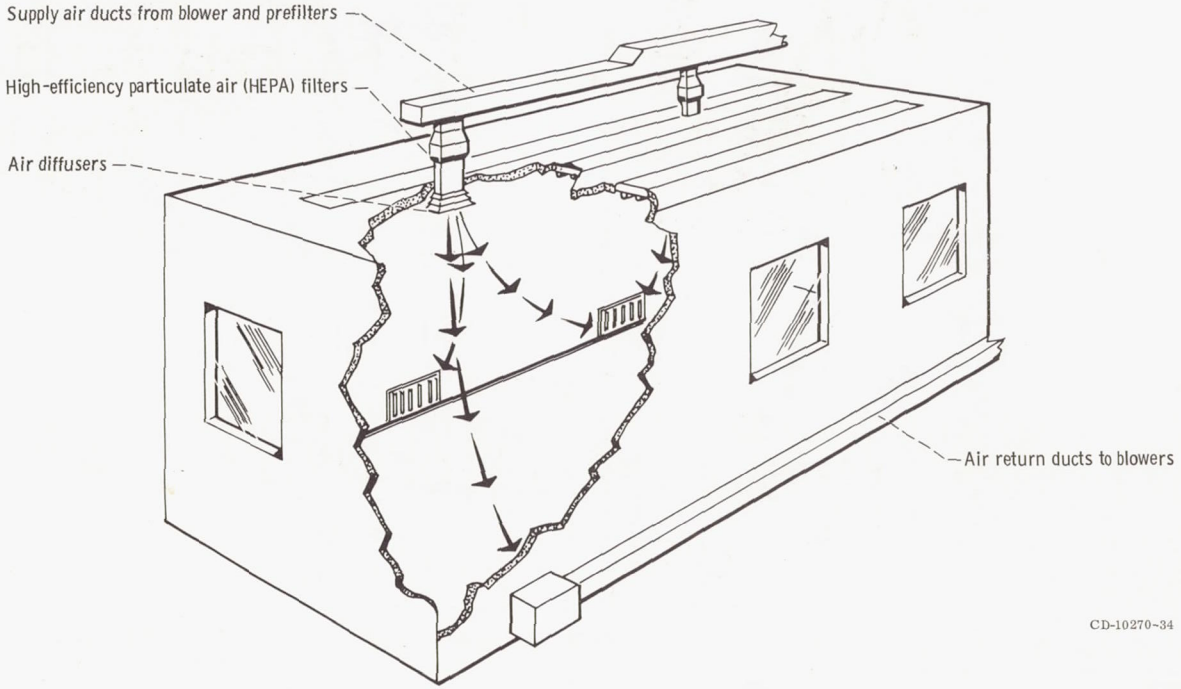

FIGURE 3.—Conventional flow clean room.

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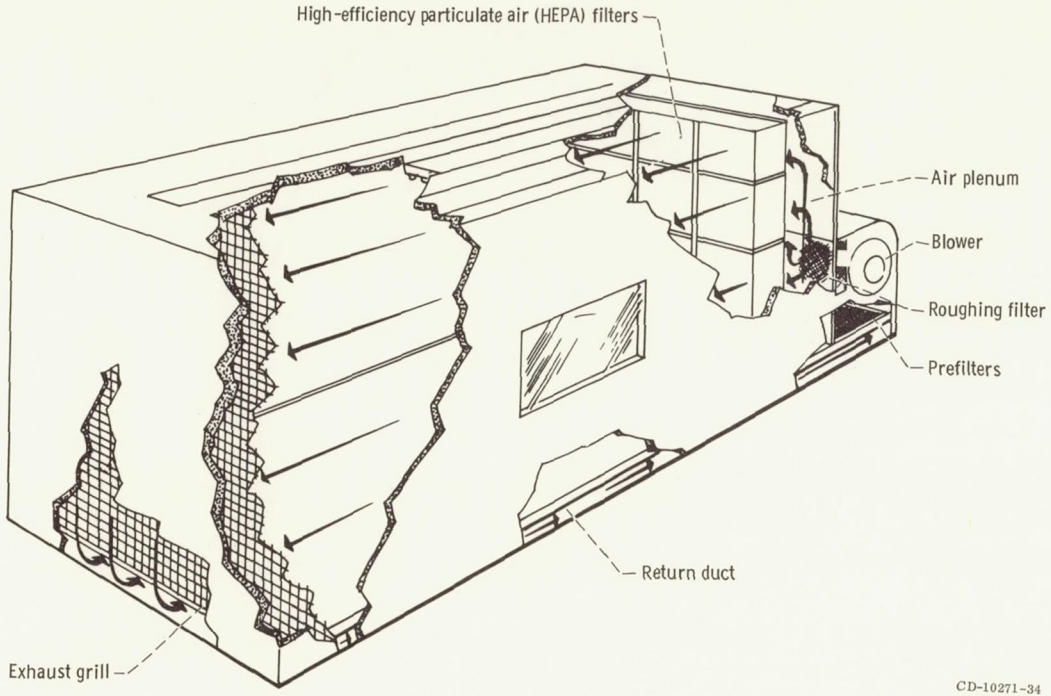


FIGURE 4.—Laminar flow clean room.

(4) Size is more flexible and easy to expand.
(5) Construction and operation are the least expensive.

Disadvantages:

(1) Recovery from a contaminated condition is slow.
(2) Personnel capacity is limited.
(3) Changes of air are few (20 to 25 per hr).
(4) Frequent janitorial service is required.

Laminar crossflow clean rooms have the following advantages and disadvantages:

Advantages:

(1) Deposition and resuspension of particles is minimal.
(2) The facility can be secured for several days without compromise of cleanliness. (The facility must be started at least 1 hr prior to start of the work shift.)
(3) Air changes per hour are frequent.
(4) Recovery from a contaminated condition is rapid.

Disadvantages:

(1) Failure of a single filter module requires shutdown and reconditioning.
(2) Uniform velocity profiles are difficult to attain with personnel, furniture, equipment, and movement in the room.
(3) Efficient work-flow patterns are difficult to achieve. Downstream work is always subject to upstream activity.
(4) Size is less flexible with limited expansion capabilities.
(5) Cost per square foot is considerably higher than conventional flow types.

When the advantages of a single pass of air moving horizontally through a room are considered, a limiting factor becomes obvious. Particles larger than 10 microns are not assured of removal. These large particles tend to fall out within the room. In addition, the initial velocity of particles generated during a work operation is not affected by the airstream. The airstream moves at approximately 1 mile per hour. Particles released by mechanical operations such as tightening screws will be moving at about 25 miles per hour. In most cases, these operations will not be in the main airstream because it is convenient to place work benches near the walls away from the center of the room. Once particles have fallen out or have become attached to a surface, the moving laminar airstream will not reentrain them.

Using the laminar flow principle in a vertical direction rather than in the horizontal direction has an added advantage. Vertical flow systems have the

entire ceiling as the filtered air entry and the floor as the exit grill. This design takes advantage of gravity as well as the moving airstream to remove particles. Consequently, large particles are eliminated, and a greater efficiency is achieved. Such a facility will accommodate more people, and efficient work-flow patterns can be designed. The primary disadvantage of the vertical flow system is the difficulty of construction. An expansion limitation is imposed by the ceiling, and the flexibility is impaired. Operating difficulties are caused by a floor of grill construction. Small objects are easily dropped through the floor.

In general, because of the high cost of construction and operation, the vertical laminar flow room will prove practical only in unusual situations requiring extremely high cleanliness levels.

Laminar Flow Work Stations

The laminar flow work station is used to provide a small working space of particularly clean environment when this is more economical than providing a complete clean room of that standard. Work stations are often used in a clean room or a white area. For example, the laminar flow work station shown in figure 5 provides an assembly area of Class 100 level in a Class 10,000 clean room. Work stations are classed similarly to clean rooms and are included in Federal Standard 209.

A laminar flow work station is a modular unit that usually accommodates one or two operators. It provides a working area of a higher cleanliness environment than the clean room that contains it. The cleanliness of the work station is provided by self-contained high-efficiency particulate air (HEPA) filters that make up the back of the station.

HEPA filters use a medium of pleated fiberglass sheets. Some types have corrugated craft paper separators between the pleats. Others use plastic or corrugated aluminum foil. The frames are made either of wood or metal. The most economical type uses plywood frames and paper separators. HEPA filters are 99.97 percent efficient by volume in filtering particles larger than 0.3 micron.

All air entering the work station must pass through the filter as any leaks around the filter or through cracks in the elements would contaminate the work area. Frequent monitoring of the pressure drop and air velocity through the filter elements is necessary to maintain a high level of cleanliness.

In a laminar flow work station, the air across the work area must have a velocity of 90 ± 20 feet per minute. This velocity is maintained up to 1 inch from the containment surfaces and the forward edge. The velocity is measured from back to front, as differences will occur from side to side because of variations in the porosity of the filter elements. Lateral movement of the dust particles is not affected by variation in flow rate across the station surface. As the filter elements collect more contaminant, the velocity will decrease. In

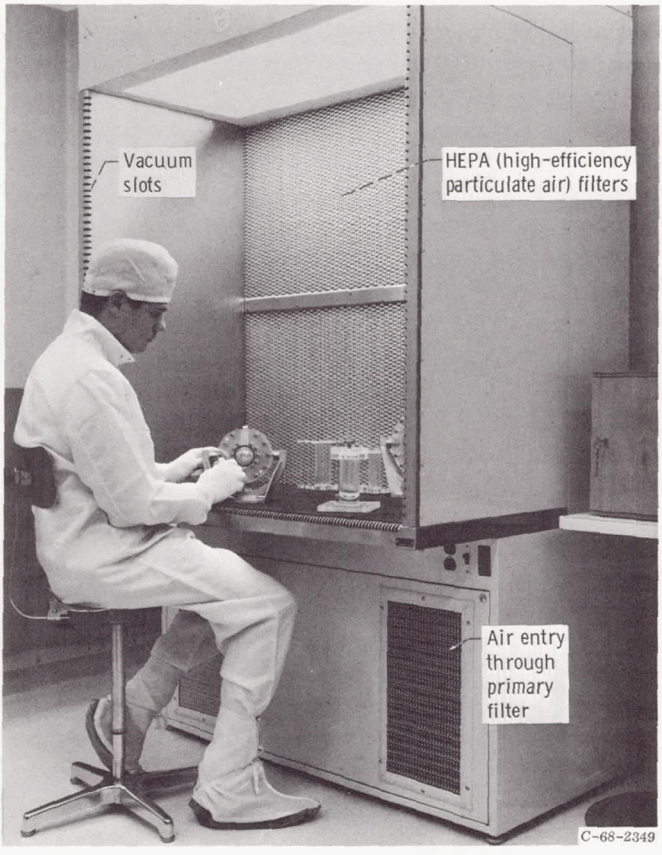


FIGURE 5.—Technician assembling test tanks in laminar flow work station. Class 100.

general, the efficiency of the filter will increase with use. However, the settling of dust particles will be influenced if the rate of flow drops below 50 feet per minute. The frequency of servicing the filter elements must be determined by experience. Velocity measurements must be made at regular intervals, and accurate records are important. Usually, these records will include a particulate count. The importance of keeping regularly reported records cannot be stressed too highly in establishing when the filter elements should be changed.

The previous discussion regarding laminar flow clean rooms also applies to work stations. Laminar flow exists only until some object is introduced into the airstream. It is known that, when an object is introduced into a moving stream of air, a higher pressure exists on the upstream side than on the down-

stream side. This pressure gradient around an object creates turbulence. In a work station, objects near the front of the work area will create turbulence near the outer edge. Thus, turbulent air can pull contaminated air from the room into the work area, and the contamination level in the work station will be compromised. This condition can be eased by keeping all the work well back into the station. Of course, the operator's arms will cause some disturbance in the airflow regardless of where the work is performed. To counter this disadvantage one manufacturer has introduced suction near the outer edge of the work station (see fig. 5). The outer edge of the station has a series of vacuum slots that provides an air sink at a lower pressure than the moving airstream. This straightens the airflow after it passes over an object. Turbulence and backwash behind the object still exist but to a lesser degree. The barrier created by the moving airstream and the air sink eliminates entering contamination except that carried in by the operator. The manufacturer also claims that this technique extends the filter life by 50 percent.

CLEAN ROOM ENVIRONMENT

Clean Room Monitoring

Regular analysis of detailed clean room records over a long period of time is the key to recognizing deficiencies in contamination control. Good records will pinpoint and assist in solving the contamination problems as they arise. These records should include continuous measurement of the pressure differentials, temperature, humidity, particulate distribution, and frequency of personnel entry into the room. An understanding of the factors influencing the clean room environment is necessary to minimize the problems of monitoring.

Contamination levels will vary throughout the clean room at any particular time because of several factors. Filtered air enters at one or more locations in the room. Contamination is generated in varying amounts throughout the room. Contaminated air exits the room from one or more locations and the highest level of contamination is not necessarily at the air exit point. Air from a highly contaminated area may be diluted with filtered air prior to exiting the room. Large, heavy particles are usually separated out by gravity. Higher and lower concentrations of contamination can thus exist within a given room, and these concentrations are constantly changing.

The areas of most concern are those where the work is performed. It is not practical to monitor all work areas continuously. However, the area that exhibits the most contamination can be determined by statistically sampling the room. Representative areas can be monitored continuously. Other work areas should be checked several times a month. However, the exact requirement for monitoring must be determined on an individual clean room basis.

Pressure Monitoring

A positive pressure differential must be maintained throughout the clean room and its entryways. Pressure should increase linearly from one compartment to the next, with the anteroom or entrance having the lowest pressure. The clean room proper should have the highest pressure. A minimum positive pressure of 0.3 inch of water should be maintained. A differential of 0.1 inch of water should exist between the clean room and each successive entryway or room.

Pressure monitoring is usually a simple task. A U-tube manometer with each opening set to measure the pressure differential between the clean room and the outside or the anteroom is all that is required. An ordinary pressure differential gage capable of measuring several inches of water may be substituted for the manometer. The chief disadvantage of this equipment is that recordings must be made manually and are not continuous. If the pressure differentials are fed to a transducer, the signal can be recorded on a simple recorder such as that shown in figure 6. Frequently such systems are equipped with an alarm device that is activated when a preset minimum positive pressure is reached. If the pressure in the room falls below an acceptable value, the operator is made aware of the situation. The advantage of a continuous recording of the pressure differentials is that any gradual decay due to increasing leakage or decreasing inflow would become readily discernible.

Temperature Distribution

The temperature within a room varies from point to point even with a good air distribution system. This temperature variance is referred to as a temperature gradient within the clean room. Temperature gradients can produce aggregation of particulate matter. Since cool air is entering the room from the air conditioner and heat is being liberated from the people and equipment in the room, different levels of temperature are to be expected. Temperature monitoring can be done with conventional measuring devices. The simplest of these is the thermometer. However, again this provides only instantaneous readings. Automated devices with thermocouples may be used as a supplement to the thermometer but they should be calibrated regularly.

If the items being worked on are extremely sensitive to the rate of change of the temperature, it may be necessary to equip the automated device with an alarm system to warn of rapid deviations. In the standard clean room, the temperature distribution should be surveyed manually in the normally operating room and compared with the automated device indicating the temperature at a given station. If the variation is less than $\pm 2°$ F, the automated reading can be used for record. In making the survey, at least eight locations should be used in the room. Readings are taken at each station and at the automated device every hour for at least 6 hours. Once this survey

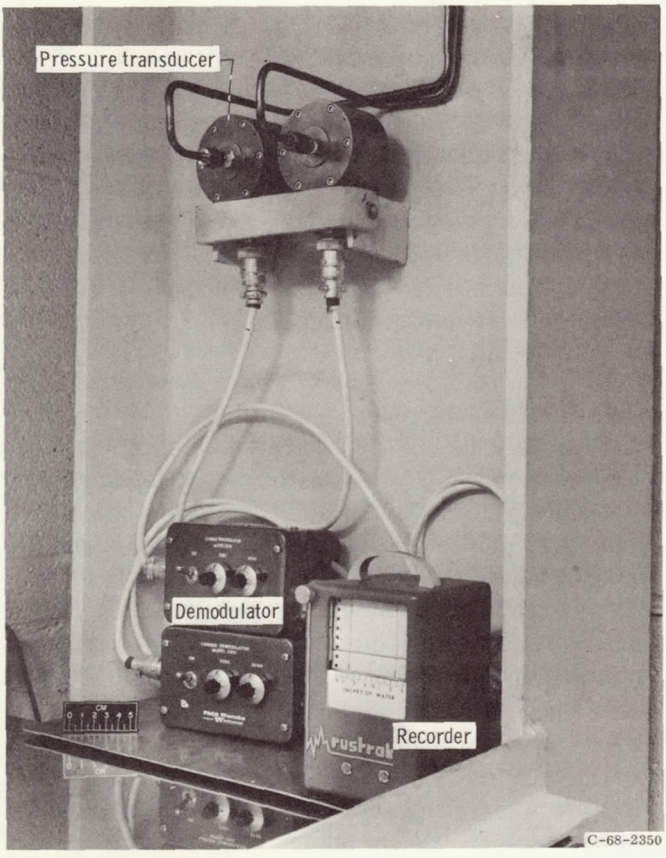


FIGURE 6.—System for continuous monitoring of clean room pressure differentials.

has been established and compared with the reading provided on the automated device, only the automated values need to be taken continuously.

Humidity Measurements

Humidity in the clean room can be a problem. If it is allowed to reach a low level, static charges are generated by movement of the clean room personnel. If the humidity is too high, metallic oxidation (rusting) results. Generally speaking, a humidity level of no less than 30 and no more than 60 percent is desired. Relatively few products are extremely humidity sensitive. The primary reason for this control is reduction of the static charge. Humidity monitoring may be done with a wet and dry bulb thermometer used in conjunction with a psychometric chart. Fully automated hygrometers may be used as a supplement to the wet and dry bulb thermometer. Such devices

should be calibrated at least once a month. The humidity level can be as flexible as that used for temperature. Many clean rooms are operating at relative humidities less than 30 percent because of the dry ambient air such as exists in Arizona or Southern California. In general, however, where the ambient conditions are not limiting, the relative humidity should be maintained at 45 ± 10 percent.

Particulate Monitoring

Contamination monitoring is the most difficult monitoring problem of the clean room operation. Many clean rooms have been temporarily shut down because indicated contamination levels were greater than was acceptable. In many cases, such shutdowns could have been avoided if proper contamination monitoring equipment and techniques had been employed.

Logic must be used in ordering a room shutdown. An occasional peaking for a few minutes of the contamination level within the room is permissible. Continual peaking indicates improper exhaust of the contamination producing operations or excessive movement in a dirty clean room. Both conditions are unacceptable and must be corrected. Contaminant levels that are continually above operational standard limits are not to be tolerated. This condition may indicate a faulty air filter system, a negative room pressure, or a continuous particle generation within the room. A qualitative identification of airborne contaminants should be made when room contamination levels remain above operational standards. The source of contamination can then be traced and eliminated. A visual identification of airborne particulates may be made using a polarizing microscope in conjunction with a filter sampling technique. If visual identification of particulate matter is not possible, qualitative chemical analysis should be performed.

Monitoring of the particulate content in a clean room can be done either by using manual or automated techniques. Both techniques are discussed. A comparison of the advantages and disadvantages is made following the explanation of each system.

Selection of Sample

It is important that a good statistical sample be taken of the clean room air under survey regardless of the monitoring technique. The standard sample quantity is 10 cubic feet (283 liters). However, the sample size may be adjusted for specific conditions such as very clean levels in a Class 100 area. For a Class 10,000 clean room, where the contamination level is reasonably constant, a 10-liter sample is usually taken to conserve time. However, this sample should be calibrated with a standard sample periodically to ensure accuracy. Samples should be taken at waist level (36 to 40 in. from the floor) or at bench level unless the area is limited. General sampling points are as

350-354 O—69——4

designated in figure 7. The number of samples collected is a function of the floor area of the space being sampled. Sample at 1 for cabinet size units, sample at 2 and 3 for areas less than 150 square feet, sample at 1, 4, 5, 6, and 7 for areas up to 1000 square feet. For areas larger than 1000 square feet, increase sampling by 4 locations per 1000 square feet. If desired, for an average count, a single sample may be taken for 5½ minutes at each of the five designated sampling points. Operating conditions may make it necessary to increase the number and location of samples. Each critical work position within a clean room should be monitored. Past experience has shown that these work positions should be checked daily and during periods of most activity.

Manual Counting Technique

This procedure uses the Millipore kit for counting particulate matter. The kit includes a filter holder, a metering orifice, filter elements, a vacuum pump, and tubing to connect the various parts. Prior to sampling, dirt and dust must be removed from the filter holder by washing with a free-rinsing detergent, ketone-free isopropyl alcohol, and reagent grade petroleum ether. The laboratory equipment and the area used for counting the airborne particulate must be maintained in a condition of cleanliness equal or superior to that of the area being sampled.

A rigid, transparent microscope hood has proved satisfactory as a cover device. Microscope slides and Petri dishes used in counting should be cleaned and prepared for holding the filter elements. Lens tissue, properly used, is satisfactory for this operation.

All filters will contain some particulates no matter how well they have been packaged or how carefully they have been handled. About four filter papers per box of 100 should be given a background count. This is used as a standard. If the background count approaches 10 percent of the sample count, each filter should be given a background count. If the background count is estimated to be greater than 10 percent of the total count from a 10-cubic-foot specimen, a larger sample (15 to 20 cu ft volume) should be used. Acceptable filters should be placed in clean Petri dishes, identified for test tube use, and covered.

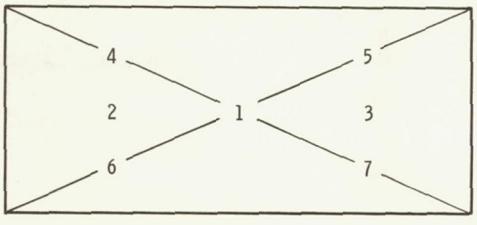


FIGURE 7.—Sampling floor plan.

Sampling procedure.—Connect the filter train to the vacuum pump with laboratory tubing. The filter train includes the filter holder, a 10-liter-per-minute limiting orifice or flowmeter, and the membrane filter. Vent the vacuum pump outside the area being studied. A typical installation is shown in figure 8. In the sampling area, the filter should be held about 36 to 40 inches from the floor with the filter element pointed upward. The predetermined sample quantity is then collected. Remove the filter element with forceps and place it in a clean, covered Petri dish.

Preparation of microscope.—A high-magnification, scientific microscope is a prime requirement in particulate analysis using the manual technique. A typical manual counting operation is shown in figure 9. A magnification of approximately 100 will be required for counting particles 5 microns and larger. Greater magnification ($\times 1000$) would be required for counting particles down to the half-micron size. The greater magnification will also be useful in particle identification. The following procedure is used in preparing the microscope for particle analysis:

(1) Place the ocular micrometer in one eyepiece. Using a stage micrometer, calibrate the measuring eyepiece (ocular micrometer) for each magnification to be used.

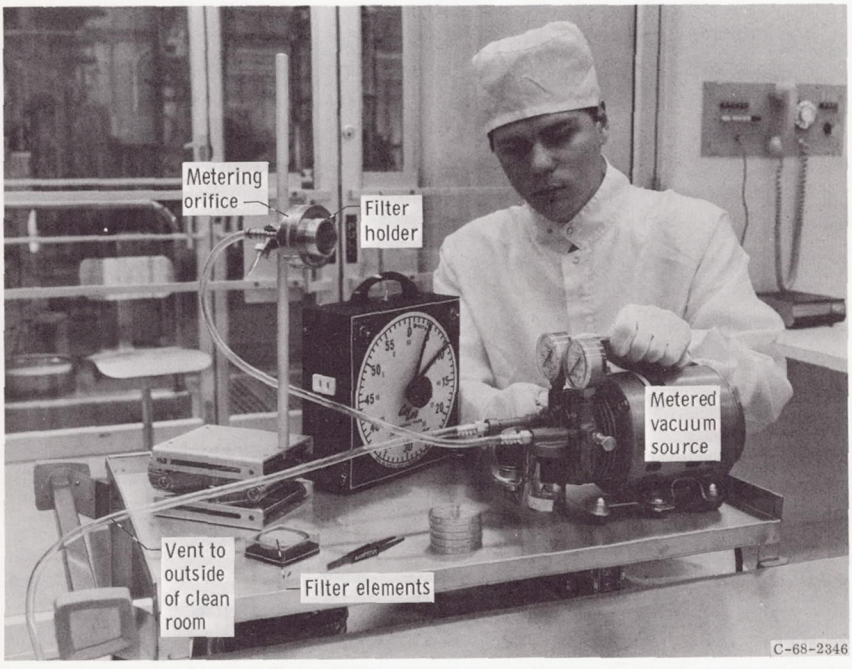


FIGURE 8.—Typical installation for manual collection of particulate sample.

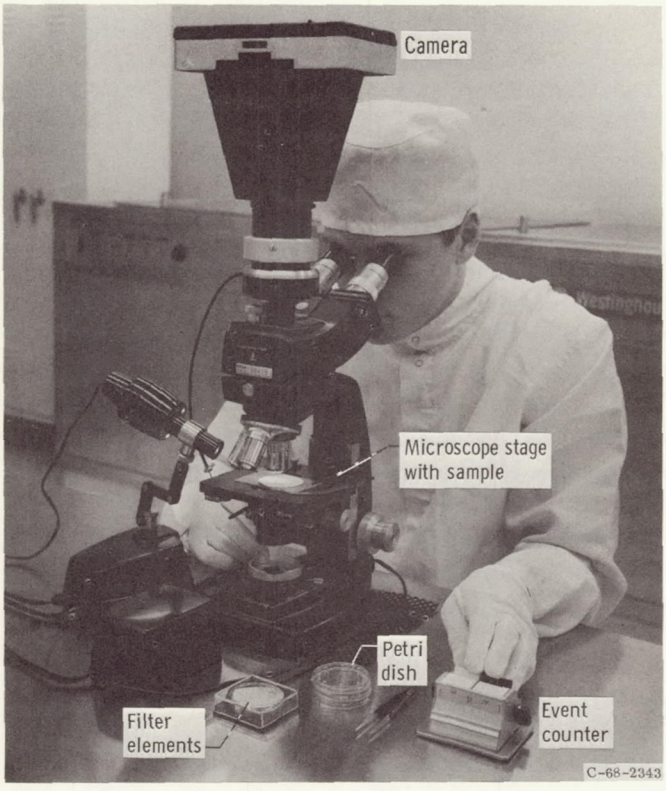


FIGURE 9.—Use of microscope for manual counting of particulate sample. Microscope is also equipped for photographing filter element.

(2) Place the Petri dish containing the specimen under the microscope. The cover must be removed.

(3) Adjust the microscope lamp intensity and direct it onto the specimen from an oblique position to obtain maximum definition for sizing and counting. High intensity illumination is a critical requirement. The angle of the light beam is significant for defining different types of contamination.

(4) Knowing the subdivisions of the stage micrometer, size the divisions of the measuring eyepiece.

(5) Particles should be counted and tabulated in three size ranges; all particles between 5 and 15 microns, all particles between 15 and 25 microns, all particles greater than 25 microns. The size of the particle is determined by its greatest projected dimension. Particles smaller than 5 microns are not usually counted by this method. Fibers are not counted as particles but are listed separately.

Counting particles.—The following procedure is useful in counting particles with a microscope:

(1) Adjust the microscope focus and lamp position so that maximum clarity of the filter surface and particle definition is obtained.

(2) Use the largest projected dimension of a particle to determine the size category.

(3) Count 10 grid squares (printed on the filter elements) or unit areas within different grid squares.

(4) After counting 10 squares or unit areas, if the total number of particles in each size range does not equal or exceed 50, count additional squares until the following statistical parameter requirement is met: $F_n N_t = 500$, where F_n is the number of grid squares and N_t is the total number of particles counted in F_n squares. If this requirement is not met for all size ranges after 50 areas have been counted or 50 percent of the total effective filtering area, it will be necessary to increase the volume of the sample.

(5) To obtain the number of particles, count 10 or more grid squares on a filter disk. From this count, calculate the number of particles that would be present on the total effective filtration area.

(6) Select unit areas for counting so that the average total number of particles in a unit area does not exceed 50 to 60 particles. If a particle lies on the upper or left boundary line of a square, count this particle as if it were in the square.

(7) Start and finish a selected grid square by sizing and counting from the left edge of the grid line, scanning exactly 1 grid square width as the operation continues from left to right.

(8) Scan the unit area for particles by manipulating the stage so that particles to be counted pass under the ocular micrometer scale. Only the maximum dimensions of the particle are significant. For particles improperly oriented for the ocular micrometer scale, estimate the maximum dimension. The eyepiece containing the micrometer should not be rotated to size specific particles. Using an event counter, count all particles in the selected area. Record the number of particles in each size range. A sample work sheet is shown in figure 10.

Calculations.—Calculate the total number of particles in a given size range on the filter using the following equation

$$P_t = N_t \frac{A_e A_f}{n}$$

P_t total number of particles of a size range on filter
N_t total number of particles counted in n grid squares
A_e effective total filter area, sq mm
A_f field area, sq mm
n number of fields

CLEAN ROOM PARTICLE COUNT DATA

Source	Volume	Filter type	Time	Day	Month	Year	Collected by	Counted by

Magnification	Particle size, μ	Area per field, A_f, mm^2	Particles counted in selected field										Number of fields, n	Total number of particles counted in n grid squares, N_t	Effective total filter area times area per field divided by number of fields, $\frac{A_e A_f}{n}$	Total particles, $P_t = N_t \frac{A_e A_f}{n}$	Background	Particle concentration (total particles minus background), particles/cu ft
			1	2	3	4	5	6	7	8	9	10						

FIGURE 10.—Sample work sheet for particulate counting

The background count for the filter should be subtracted from the total number of particles. Results are expressed for each size range in particles per cubic foot of sample by dividing the P_t by the sample size (10 cu ft standard).

Precision and accuracy.—The accuracy of this method can be no higher than that of each of the variables. In order to minimize variables attributable to the operator, a trained microscope technician is required. Variables due to equipment will be recognized by an experienced technician. A periodic check should be made of the microscope with a check slide. This is a commercially available slide with a known particle size and concentration distribution. Figure 11 gives the range of sizes that is typical for airborne contaminants.

The limits of particle size measuring devices and techniques are shown in figure 12. A good research microscope is capable of detecting particles as small as about 0.5 micron. More powerful specialized microscopes can detect particles 1 order of magnitude smaller.

Automatic Counting Techniques

The lengthy procedure outlined points out the need for an automated system for measuring and sizing particulate matter in a clean room. In addition, automatic particle counting should be performed when manual techniques are inaccurate, inadequate, inefficient, or costly, and when greater reliability, repeatability, and accuracy are needed. Automatic counters are necessary in areas where the transient contamination level must be known. Generally speaking, areas that permit few large size particles, that is, particles greater than 5 microns, require automatic counting. Automatic monitoring devices have application in other areas also. These include areas where smaller particles will affect the operation and where particles cannot be effectively monitored by manual techniques. For example, in the production of color television components, airborne contaminants can greatly affect the three dot color deposition operation. The automatic monitoring device will provide rapid feedback of information on the airborne contaminant level and permit adjustment of the production assembly line. It also provides a record of the contamination level during continuing periods of time. The chief disadvantage is the high initial cost.

Light transmission method.—One of the less expensive devices for automated monitoring of a clean room depends on light transmission sampling. This device costs about $500. Its main disadvantages are that it must be calibrated against a manual counting technique at regular intervals and that the composition of the particulate must be reasonably constant. The light transmission device collects a measured sample on a filter tape. The filter tape is made transparent with an oil with a refractive index of 1.515, and the particles are counted. A background count of the tape must also be made. The sampling device can be used to make periodic samplings of a clean room and

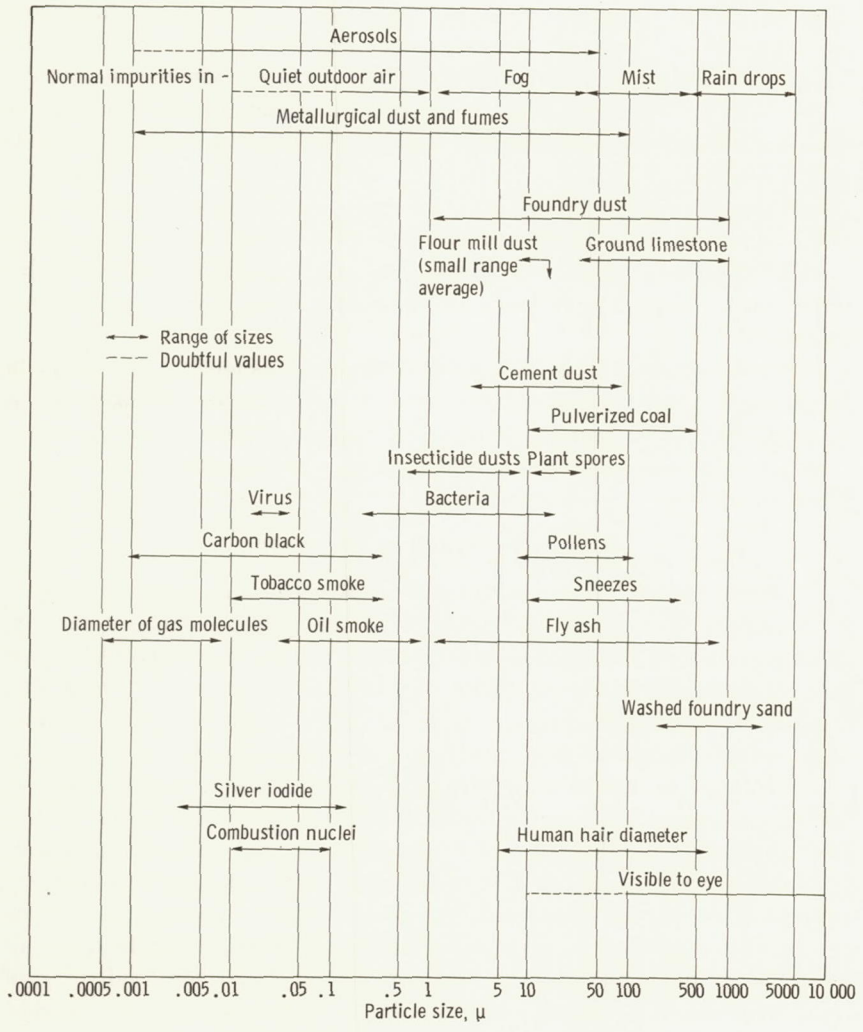


FIGURE 11.—Typical water distillation system for clean room use.

the light transmission factor recorded. From a graph of the light transmission factor as a function of the actual particle count, a good estimate of the airborne contamination can be made. The obvious failing arises when the airborne contaminants in the area change widely in composition or distribution from the samples used to calibrate the light transmission factor.

Electrical aerosol method.—An electrical particle counter and size analyzer has been designed to measure sizes from 0.015 to 1.2 microns. It has application where very small size particulate is considered. The principle of this method of sizing and classification is to charge the aerosol electrically. The

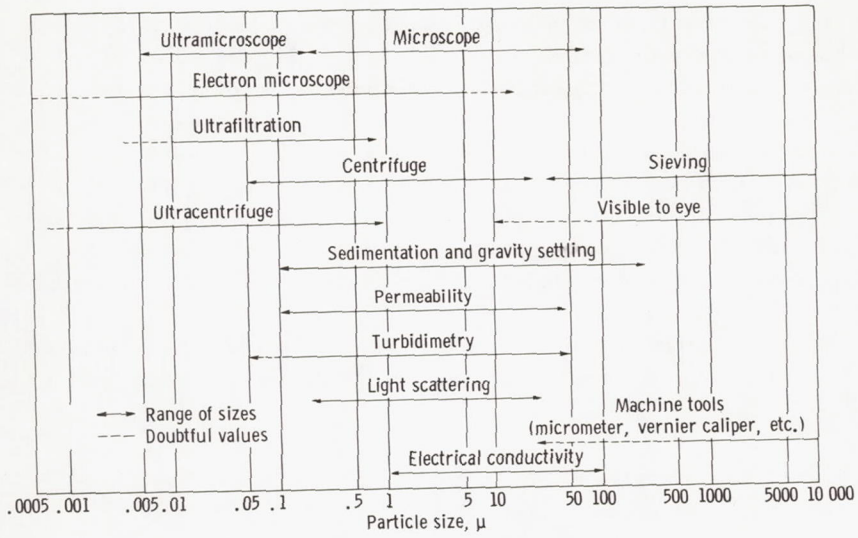


FIGURE 12.—Limits of particle size measuring techniques.

charge carried by the different size particles is of such magnitude that the electrical mobility of the particle is directly proportional to its size. A direct measurement is made of the particle mobility. To date, this instrument is only semiautomatic, although a completely automated version is entirely practical. This device used together with an optical counter, described in the next section, would permit continuous monitoring over the size range from 0.01 to 25 microns.

Light scattering method.—The most sensitive automatic contaminant monitoring device for the 1.5- to 25-micron range uses a light scattering technique. This device costs about $7,500 and is easily portable. The airborne sample is passed through an optical system that is highly illuminated by a beam of white light. The suspended particles scatter a portion of the light, a fraction of which is picked up at 90° to the axis of the beam by a lens system and proceeds to a photomultiplier tube. The light pulses from the individual particles are transformed to electrical impulses. These are amplified and sent to discriminators for counting. This method assumes that the intensity of scattered light from an individual particle is proportional to its size. Light scattering theory specifies that for a given wavelength of incident light, angle of scatter, and refractive index, the scatter intensity is a function of the particle radius to some power. The value of the power varies according to the particle size. For particles from 0.4 to 1 micron, the power value is about 2, and for particles larger than 1 micron the power value is 1. Since both particle size and refractive index may vary in atmospheric dust, some error will be present.

In a practical system, a number of things happen that also alter the amount of light scattering. For example, the light source darkens with use, and the lens becomes dirty. Such changes are slow, however, and some devices have light compensating arrangements that use a calibrated light source. The elimination of stray light and electronic noise has plagued manufacturers. The obvious requirement of electronic maintenance at regular intervals adds to the operating cost of this device. Figure 13 shows a complete system for automatically sampling the particulate content of a clean room with this type device. Continuous temperature and humidity measurements are also taken.

Operating cost comparison.—The technology in the field of particle size and distribution analysis is advancing rapidly. Only a few years ago, only one

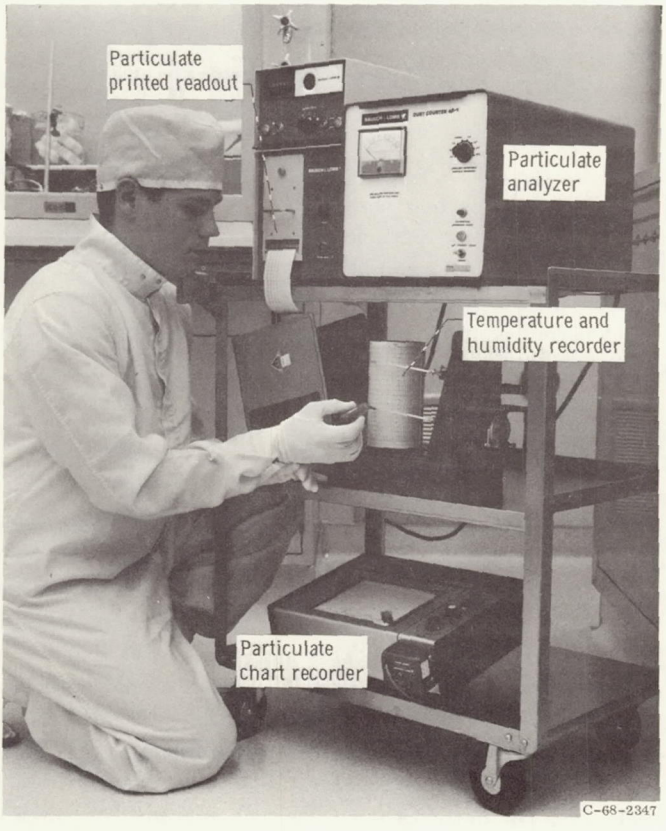


FIGURE 13.—Complete system for particulate sampling in clean room. Center shelf also has device for continuous recording of temperature and relative humidity.

system of automated equipment was available and it cost more than $40,000. The equipment occupied a space about 6 feet high by 5 feet wide by 4 feet deep. In contrast to this, the NASA Electronics Research Center has produced a small self-contained miniaturized aerosol particle analyzer for launch in sounding rockets. It measures aerosol particle concentrations and size distributions from 0.5 to 10 microns. A direct readout of the particle concentration and size is provided. The instrument cycles every 2 minutes. A self-contained battery supplies the instrument for at least 100 cycles. The instrument measures 7.5 by 5.5 by 3.5 inches and weighs 5.5 pounds. The cost of this device is estimated at several hundred dollars. This particle analyzer was devised for a specific mission and is not applicable to continuous clean room monitoring. However, it appears practical to develop the device into a more conventional particle analyzer for clean room application.

As recently as 1965 when automated particle counting equipment had a cost of $40,000 to $50,000, it was necessary to justify this high initial expenditure. A cost comparison was made by the Autonetics Co. in which they studied the use of a manually counted microscope operation and a completely automated light scattering device. The study lasted for 2 years and required monitoring at four separate locations. The cost per sample for a manual operation was $2.65 for the first 2 years based on the following information:

Four technicians at $2.45 per hour	$44, 512
Filters and equipment	$8, 692
Total number of samples taken	20 800

The cost of monitoring for 2 years with automated equipment was $2.29 per sample. The central control unit with four separate sensing heads cost $46,000. One technician was required to operate the unit at a cost of $11,128 for 2 years. During that time, 48 samples were taken per shift for a total of 24 690 samples.

The big saving was realized after the first 2 years. The cost of manual samples dropped to $2.23 per sample, while the cost of the automated operation dropped to $0.44 per sample. Autonetics estimated that they saved $47,174 per year using the automated device after the initial investment. Now that the cost of automated particle sizing and measuring devices has dropped by an order of magnitude, the saving over a manually monitored system is much more significant. Also, the advantage of having continuous monitoring over a 24-hour period cannot be weighed with the cost.

Effect of Static Charge

Normally, static charge accumulation is associated with plastics or nonconductive materials. But, in fact, any material can take on a charge. For example,

a person walking across the vinyl floor of a clean room, wearing nylon coveralls and plastic boots, picks up a piece of copper wire from a formica surface work table. At that instant, the piece of copper wire takes the same static charge as the person. This may be as much as 20 000 electrostatic volts. The wire and the person are now a precipitator or a magnet for particulate in the air. The smaller the particle, the more efficient is the precipitation.

Rubbing any two dissimilar materials together produces a charge. Of course, some materials produce greater charges than others. Nonconducting materials, for example, are more prone to accumulate large charges. Because the clean room has many nonconductive surfaces, it is particularly prone to production and accumulation of static electricity.

The most common method of controlling static electricity is to maintain a high relative humidity. A high absolute moisture content in the air, in grains of moisture per pound of dry air, has little or no effect on static generation or dissipation. A high relative humidity creates a film of moisture on the surface of materials which acts as a conductor draining off the static charge. The higher the relative humidity, the faster the rate of static removal.

Clean rooms usually do not have a high humidity (above 60 percent) because of the effect of the moisture on small components. Effective grounding and other means of controlling the accumulation of static electricity is not practical where personnel must move about. Air ionization devices that use either radioactive or electrical sources can be used to control static charges. Equipment of this nature is available, but of limited usefulness. This is an area of clean room technology that has not yet been fully developed.

Liquid-Borne Contaminants

The study of the contamination content of liquids is useful in two separate areas. First, there is an interest in the particulate content of a liquid being used as a reagent. Second, the fluids used in cleaning are analyzed for their contaminant content as a measure of the cleanliness achieved. The methods of analyzing particles in liquids are the same as those for measuring particles in gases. Where filtration techniques are involved, care must be taken to ensure against the monitoring liquid dissolving the filter. Also, care must be taken to prevent the liquid lines to the sampler becoming a source of particulate matter. This can happen when they contain valves, fittings, etc. Care is required in system application, sampling, data collection, and interpretation. These are all sources of error.

A unique problem exists in analyzing liquids caused by the presence of soluble contaminants. In solvent systems, it is necessary to ensure that a maximum concentration of dissolved contaminants is never exceeded. The techniques for examining nonvolatile residue (NVR) fall into three categories. The first is a manual process involving gravimetric analysis of the residue after careful evaporation. The second is an analog method wherein

the solvent is allowed to evaporate from a test substrate surface. Observation of the resulting surface is used to indicate the NVR in the solvent. A go, no-go method of observation (the water break test) uses a water spray to indicate the presence of organic matter by observing the contact angle of the water with the surface. In a more quantitative test (tracer desorption) the test fluid is placed on a substrate, and variations of its vaporization rate are measured as a function of the NVR concentration. The third category uses a method developed by NASA Marshall Space Flight Center in which the solvent is sprayed into excess air. If the solvent is clean, the spray will vaporize completely. If NVR is present, droplets of solvent-NVR mixture will remain. By scanning the stream with a sensitive photometer a few parts per million of NVR can be detected.

When analysis time is not a factor, the gravimetric system is the best method to study fluid contaminants. In this method a grid-marked filter is cleaned, prepared, and placed in a filter holder. The filter holder is placed between a lock funnel and a vacuum filter flask. The fluid is poured into the funnel and the vacuum applied to the flask. When filtration is about half complete, the vacuum is removed. While some fluid still remains in the funnel, the funnel wall is washed with this fluid to gather any residue that might be collected on the wall. The vacuum is applied again and the remainder of the fluid is pulled through the filter. Neither the filter nor the funnel should be rinsed because the particle distribution may be disturbed. The filter holder should be opened and the filter element removed with forceps to a Petri dish. The particulate count is made in the same manner as in airborne sampling.

Monitoring Questionnaire

The following clean room monitoring questionnaire prepared by the Sandia Corporation will provide a useful tool to those operating or inspecting a clean room. The answers to these questions will indicate whether the facility is really intended to be a clean room or just one in name.

General:

(1) How does the user classify the clean room?
(2) Has a dust monitoring program been established?
(3) Is the program a well established procedure or a hit-and-miss operation?
(4) Who is responsible for the monitoring program?
(5) To whom and how are the results reported? (Graphs, data sheets, verbal)
(6) How are the results fed back into the control of the room?
(7) Have maximum limits been set to indicate an out of control condition?
(8) What plans have been established for action on the data obtained?

Instrumentation and Procedure:

(9) Is a single method or instrument used or a combination of more than one method?

(10) Do the results obtained refer strictly to particle number or concentration or is an attempt made to identify the particle source?

(11) Is a commercial instrument used?

(a) Is it continuously operating? In what form are the data read out?

(b) Is it a periodic sampling device? How are the data read out?

(c) How often is a sample taken?

(d) Is the sample taken in a single location or several places?

(e) What is the range of particles counted?

(f) How and how often is the method calibrated?

(12) Is the monitoring method a sampling plan using microscopic analysis?

(a) How are samples obtained? (filtration, settling, impaction)

(b) What is the sampling period?

(c) How does the sampling schedule correlate with the work and cleaning schedule?

(d) What is the sample test?

(e) How often are samples taken?

(f) How many samples are taken at a time?

(g) What is the location in the room of the samples?

(h) What type of microscope is used? What power?

(i) What type of personnel are used?

(j) What is the range of particles counted?

(k) How are data reported?

Recorder:

(13) Are permanent records kept?

(14) What use is made of them?

(15) What degree of confidence does the user place in the results of the monitoring program?

(16) What is the average particle count in the room?

CLEAN ROOM OPERATION

Factors Affecting Clean Room Operation

Individual clean rooms will have specific factors that greatly influence their particular operation. However, in general, clean rooms are influenced by the design, equipment, procedures, personnel, and maintenance. Various clean room designs have already been discussed to some extent. However, there is need for further consideration of the clean room design from another

point of view. In selecting the design for a specific clean room, three considerations must be made. The first of these is *function;* that is, consideration must be given to the environment and other specific controls that are required in the specific clean room. For example, some clean rooms are used solely to clean components. Others are used as assembly areas. Still others are used for both types of activity. The second consideration is *operation.* This includes consideration of the work-flow patterns and procedures required to produce the desired product control. The third consideration is ease of *maintenance.* A careful study of the equipment and materials available for a clean room will aid in the economical and effective maintenance of the area. Often this is overlooked in the original design concept. The maintenance factor should properly have a great influence on the design.

Facility Design Criteria

Detailed design procedures are outside the scope of this particular discussion. However, clean room operators must be familiar with some of the basic design considerations. For example, in the air handling system, filtering is accomplished through three stages. In the first stage, the air is filtered through a roughing filter with an inexpensive felt cloth, glass wool, or similar medium. This stage will filter out the massive contaminants, usually larger than 10 microns. The second stage is usually a fiberglass or electrostatic filter with efficiency ratings from 35 to 85 percent for particles above 0.3 micron. The percentage efficiencies are arrived at by using the DOP (dioctyl phthalate, a chemical smoke) test developed by the Army Chemical Warfare Service. The final stage (HEPA) filters have the highest efficiency (99.97 percent of all particles above 0.3 μ) and are normally located just before the diffuser or air inlet to the clean room. A fourth filtering stage is sometimes used to remove hydrocarbon contamination. These filters are activated charcoal and will absorb up to 50 percent of their own weight of such contaminants. One cubic foot of charcoal has 2 million square feet of absorbent surface.

Positive pressures are established and maintained in the clean room through a series of dampers or shutters located in both the supply and return ducts. As much of the return air as possible is reclaimed since it is relatively clean air and near the desired temperature and humidity. Usually about 25 percent makeup air is required.

The following considerations are typical of those that should be made in designing a clean room:

(1) Machines such as pumps, blowers, motors, etc., should be located outside the clean room.

(2) Service quarters should be provided around the facility with access to the service process equipment.

(3) Cooling air and air from pneumatic devices should be exhausted outside the room.

(4) Noncorrosive, nonsloughing materials should be used in the air handling system.

(5) Nonsloughing, nonabrading materials should be used for the floor, walls, and ceiling. These should be readily cleanable and rounded corners should be used.

(6) Easily cleaned and maintained lighting system should be used.

(7) Close attention should be given to door hinges and hardware because of heavy duty service against positive pressures.

(8) Interlocks, either mechanical or electrical, should be placed on the airlocks or pass-through windows.

(9) Instrumentation should be located outside the room when possible.

(10) Maintainability of power and service utilities should be such that it does not require entrance to the clean area.

(11) Communications devices should be used to minimize the need for personnel entry.

Selection of Clean Room Equipment

The furniture and equipment selected for the clean room should be chosen to minimize maintenance and cleaning. A large variety of clean room furniture is being marketed today. In general, there should be a minimum of sharp edges and corners. Ledges and horizontal cracks should be avoided. Finishes should be tough, nonflaking, and abrasive resistant. Work surfaces should be of laminated plastic that is resistant to heat, moisture, and abrasion. Stainless steel can also be used, but the surface should be be treated to reduce reflections and glare. The stainless steel should also be passivated to reduce stains. Comfort of the operator should not be overlooked. For example, the chairs in the clean room should be adjustable to various heights and should be of comfortable design. Fabric covered chairs or cushions should be avoided. In summary, the furniture should be simple in design and have a minimum of areas to entrap contaminants.

The tools selected for a clean room should be chosen to minimize the generation of particulate matter during their use. They should be good quality, chromium-plated tools. Tools with rough surfaces such as vises should be painted with epoxy or urethane paints. Tools should be inspected regularly to prevent contamination from wear. Permanent pneumatic or vacuum connections should be made of stainless steel. All exhaust air should be dumped outside the clean room. Hoses should be of polyvinyl or Teflon to reduce abrasion. Moving parts should be shrouded with a vinyl boot or other device to contain excessive contamination. Cabinets, consoles, and similar equip-

ment should be enclosed. Crinkle or similar rough decorative finishes should be avoided.

Friction points other than power driven ones should be equipped with Teflon, nylon, or other self-lubricating bearings. Stainless-steel ball-bearing hinges should be used for the doors and openings. Continuous or piano hinges should be avoided. Casters, where required for portable equipment, should be provided with a vinyl or rubber bumper guard. Stainless-steel cables or nylon-covered wire should be used when lifting devices are required. All edges and corners should be rounded. The contact surface of equipment that rests on the floor should be large enough to minimize indentation of the floor.

The design of the clean room must include provisions for service and personnel use. Entrance vestibules, air showers, shoe cleaners, tacky mats, and similar devices are normally needed. A typical entryway is shown in figure 14. In addition, large clean rooms will require a change area, an eating area, rest rooms, etc. These functions can usually be served by existing facilities requiring only a plan for their controlled and effective use. Careful planning of the location of the clean room facilities within an existing plant will usually provide access to personnel areas. When this is not practicable, the clean room will require these added features and provisions for control.

Additional clean room features which have proved useful include intercom systems, telephones, windows that allow visitors to see into the clean room, the use of pastel colors to reduce glare, a central vacuum cleaning system, and a pass-through for introducing material and equipment to the room. A typical communications system, viewing window, and an equipment pass-through are shown in figure 15.

A factor of importance is the illumination level in the various parts of the clean room. For laboratories, a minimum of 100 foot-candles at the work bench is required for close work. There is a tendency to overlight these areas with as much as 500 foot-candles. A level of 400 to 500 foot-candles throughout an installation certainly meets the minimum specifications, but usually results in eye fatigue from glare and reflections. Personnel may object to working in a room without really knowing the reason. When such a situation arises, primary consideration should be given to the illumination. The heat generated by high levels of illumination can cause cooling problems. However, the current use of fluorescent lighting has reduced this problem.

Clean Room Personnel Garments

Clean room operators are usually the greatest single source of contamination in the clean area. Not only do they bring contaminants into the room on their person, but their normal functions continue to generate contaminants. Those people who enter the area must be clothed to minimize this contribution to contamination. Apparel worn in the clean room is the ma-

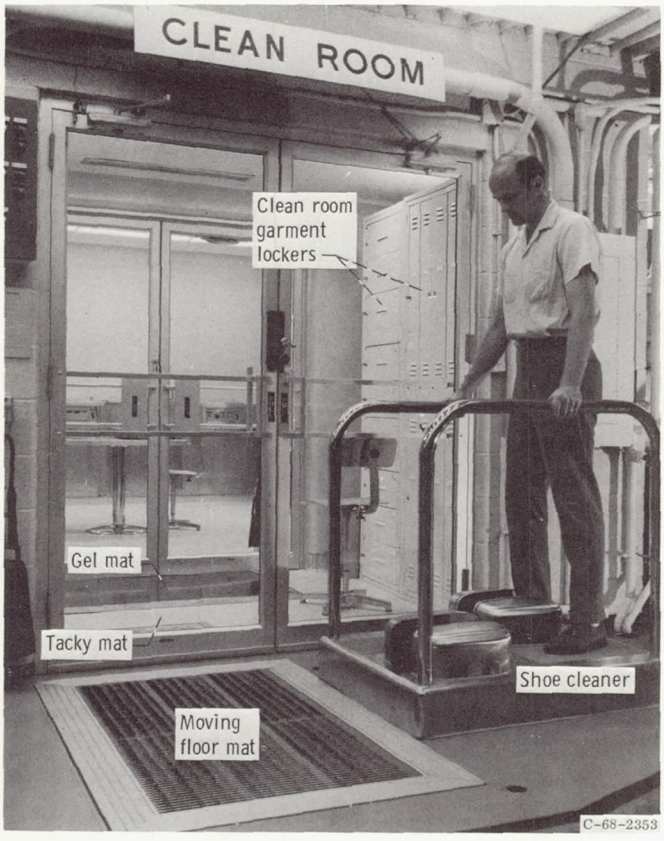


FIGURE 14.—Clean room operator using shoe cleaner prior to entering area for donning clean room garments.

terial that will come in most frequent contact with the work pieces and surfaces in the clean room. Therefore, clean room clothing must be chosen to minimize the ability of the garment to carry contaminants and to act as a source of contamination.

Clean room apparel has been developed to a high degree. Most of the materials used are synthetics and are relatively lint free. The most common materials are dacron and nylon. Dacron is more favorable because of its low retention of static charge and resistance to yellowing with age. One of the most significant characteristics of clean room garments is the weave. Both a herringbone and taffeta weave are in current use. Each has specific properties which influences its use. The herringbone weave is more durable because of its heavy weight and density. Body contaminants that originate

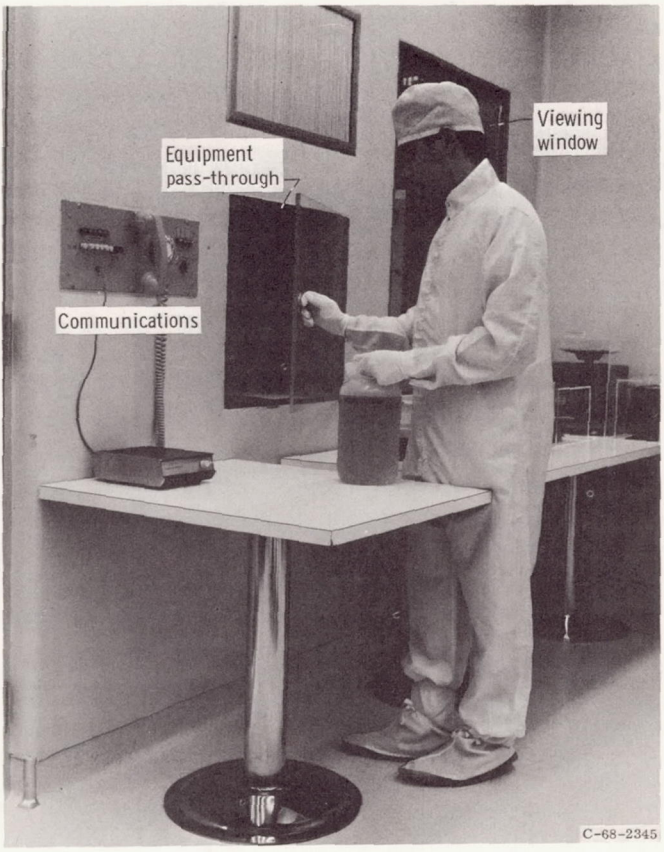


FIGURE 15.—Clean room technician at equipment pass-through.

with the wearer do not migrate through the material readily. Of course, this same characteristic makes the garment more difficult to clean. On the other hand, the taffeta weave can be laundered to a low particulate count easily, but its light weight results in short life. Such garments are used for very meticulous operations that justify frequent changing of apparel.

The clean room uniform (see fig. 15) usually consists of coveralls without pockets, caps that fit snugly around the head, gloves that must be lint free and yet maintain a delicate feel, and boots that are worn over the shoes. Touch sensitive gloves are also available in either rubber or vinyl. Such synthetic gloves are used by surgeons. However, these require special preparation before they are suitable for clean room use. Surgical gloves are powdered by the manufacturer for ease of handling and donning. Before such gloves are taken into the clean room they must be cleaned to remove the powder.

The boots are also a major problem in current clean room apparel. They are dust traps and in almost every case are loose and ill-fitting. The result is that dust from street shoes migrates through the covers. A sneaker-type shoe with vinyl soles and dacron uppers that can be laundered makes a better shoe, and then the boots can be eliminated.

Clean room apparel must be laundered under extremely clean conditions and double packaged to prevent contamination. Garments used in a Class 10,000 room should be laundered and packaged under Class 100 conditions. Such laundry facilities are extremely rare particularly in the eastern part of the United States. Some garment laundries provide air express service each week to remote areas. With each cleaning, each garment should undergo a visual inspection for evidence of wear. A particulate inspection should be made of a representative sample of the garments. The procedure for this inspection is enumerated in Air Force Tech Order 00–25–203.

Associated with the clean room apparel are the wiping cloths used in the clean room. Normal wiping cloth material, such as cotton, has a high lint content and is unsuitable for use in a clean room. Fabrics, such as dacron and nylon, are relatively lint free but have poor absorption characteristics. This dilemma has been solved to some extent by fabricating a laminated wiping cloth. A highly absorbent cotton wiping cloth is enclosed on both sides with a dacron cover that has been completely sewn around the edges. Cross-stitching has been added to retain its flatness. This type of wiping cloth provides a fair amount of absorption without introducing the problem of high lint content.

Clean Room Maintenance

The maintenance of a clean room facility requires two distinct types of operation. These are *preventive maintenance* performed by the clean room personnel and *janitorial maintenance* which may or may not be performed by the clean room personnel. The distinguishing feature is that preventive maintenance is a continuing effort. It takes place all the time the personnel are in the clean room. Janitorial maintenance is a periodic operation that is usually more comprehensive and requires several hours. It is usually done once or twice a week.

A sound preventive maintenance program will eliminate unscheduled shutdowns and will contribute significantly to the continuous operating economy and integrity of the facility. The following suggestions will assist in establishing a preventive maintenance program. Ensure that adequate spare parts are on hand for replacement and repair of special equipment such as vacuum systems, shoe cleaners, filters, etc. A file should be kept of all the instruments used in the clean room. This file should include the operating instructions, parts list, and addresses of suppliers of spare parts. A periodic check should be made to ensure availability of spare parts. Records should be kept of the repairs and replacement of clean room equipment or instru-

ments. These can be used to indicate the cost of an operation and possible cost reduction procedures. Scheduled inspections should be made periodically to prevent unforeseen deterioration or other malfunction which could lead to a shutdown of the clean room operation. A simple checklist will suffice for most major items especially equipment used for processing. These reports should be accurate and kept for a reasonable length of time as a reference.

Good housekeeping practices are of prime importance in the clean room. Every effort should be made to remove contamination as soon as it is generated. Visible contamination should be cleaned from the work bench by wiping cloths or the vacuum cleaning system as soon as it becomes evident. Aside from the continuous cleaning process, the clean room area will be cleaned at the end of each work day. This will usually be done by the regular clean room workers. It should include vacuuming the floor and all large pieces of equipment in the clean room. All work benches and flat areas should be damp sponged. Occasionally, the work load in the clean room will be such that some of the preventive maintenance will be omitted. This should not be allowed to become a regular procedure, as it will increase the requirement for janitorial services. Even when the clean room is not operating at its full working level, the daily housekeeping maintenance should be performed.

Janitorial cleaning should be done after the normal work day at the end of the week. This will allow the weekend for reestablishment of the clean environment. Janitorial personnel should be under the supervision of the clean room operator until they are aware of the need for special care. Cleaning personnel must wear clean room garments similar to those used in the normal operation. They must use equipment that has been specially selected for clean room cleaning. This cleaning equipment must be stored in the area of, but outside, the clean room. It should not be carried from one clean room to another.

Maintenance equipment must be selected to minimize particle generation and maximize cleaning ability. Nylon mops with metal handles are recommended. Damp cleaning should be done with sponges rather than cloths. The sponges should be of a photographic type. These will shed large particles as they begin to wear. They should be replaced as soon as wear is evident. High grade plastic buckets which are not subject to flaking must be used. Ten quart capacity is the usual size. Stainless-steel buckets may be used, but they are usually more costly. The ladders used in the clean room maintenance should be metal and must have rubber foot pads for the legs to prevent slipping. All water used in the cleaning process must be from the deionized, distilled water supply. The detergent used in the cleaning process should be a low-residue type. A liquid detergent is best, but powders can be used if the solution is prepared outside the clean room.

The janitorial services normally will include damp cleaning with sponges

of the work benches, utility fixtures, walls, covers of the equipment, and the work station. Windows and doors are cleaned with a liquid cleaner and polished with lint-free cloths. Cloths should not be shaken in the clean room and must be placed in plastic bags when not in use. Vacuum cleaner outlets and air entry and exit passages are sponged. The floor should be mopped with detergent water and rinsed with neutral water. All flat surfaces such as tops of cabinets are sponged and dried. After all surfaces are sponged and dried, they should be vacuumed. The entry area and lockers as well as the floor are to be sponged, dried, and vacuumed. Special cleaning procedures for the gel and tacky mats should be observed according to the manufacturer's instructions. The shoe cleaners are to be vacuumed and washed. All traps should be emptied, and the pit of the moving floor mat, vacuumed, washed, and revacuumed.

As a control, an automated particulate count should be made during janitorial cleaning at periodic intervals to measure the efficiency of the cleaning operation. This count should begin before the cleaning, be made at several intervals during the process, and at least at two time intervals immediately following the process. One reading about an hour after the cleaning is completed and another 3 hours later will establish a trend in the reestablishment of the room operating level. Particulate sampling should be taken by the first person to enter the room on Monday morning. This will establish the base of the cleanliness level for the whole week. Cleaning check sheets should be used. Periodic review of these reports will indicate required changes in the janitorial services and procedures.

Clean Room Certification

The growing requirement for controlled environments has provoked a need for standardization of the requirements for clean rooms and has led to certification of clean rooms. NASA Office of Manned Space Flight has established the first procedures for clean room certification. Certification in this case is defined as acknowledgment that the controlled environment facility is capable of achieving the specified conditions and has satisfactorily demonstrated this capability. It does not establish degrees of cleanliness nor environmental levels of humidity, temperature, etc. The degree and level of control is a function of the product requirements as defined by the product specifications. This procedure, however, presents the methods and provisions necessary to assure that the required cleanliness and environment have been achieved and are maintained.

Certification is evidenced by a formal statement that the facility has demonstrated its ability to conduct this procedure. Continuous or repeated demonstration of this procedure will permit continuous certification. NASA's requirements for certification are detailed in "Handbook for Contamination Control of the Apollo Program." The need for continuing documented mon-

itoring of the facility and documentation of demonstrated performance as well as written procedures for sampling, testing, monitoring, etc., is stressed.

At least one commercial certification organization is available. For a fixed fee, this organization will perform a complete study of the clean room environment including contour mapping of the pressure, temperature, and particulate distribution within the facility. A special survey is made of clean work stations within the clean room. The work station is monitored both for airflow velocity and particulate contamination. Continuing certification is available provided that records are maintained and a spot check is made every 6 months.

CLEAN ROOM PERSONNEL

Selection of Clean Room Operators

In selecting personnel for any critical task, the first consideration is to be assured of the ability of the individual to perform the operation. It is obvious that just the ability to perform the operation is not enough as far as the clean room is concerned. The worker must be able to do his work in such a way that the essential cleanliness is not compromised. Compromises of the cleanliness are not always directly visible. An individual may create a violation unknowingly or unintentionally that may result in costly rework or maintenance procedures. Therefore, each person who comes in contact with the clean room must be motivated to achieve and maintain a high level of cleanliness. He must have a knowledge of the contamination control principles and be aware of the consequences of each action or inaction.

Many physical and human characteristics must be considered in the selection of clean room personnel. It has been suggested that the problem of selection should be dealt with by a combination of management, microbiologists, and applied psychologists. Consideration of such items as manual dexterity, visual acuity, patience, concern for detail, attitudes toward repetitive operations, skin conditions, and reaction to rigid discipline that accompanies confinement to a controlled area are all important. Therefore, the attitude of the clean room personnel is important. They must be prepared to meet the challenges of clean room work before they are allowed to enter the area. They must be instructed to consider everything not in their immediate area to be contaminated and to recognize the types of contamination.

Usually it is difficult to find the necessarily highly disciplined personnel for clean room operations. The problem of adapting to a clean room is mostly psychological in origin. Space laboratories have found that three distinct conditions appear to ease adapting to the restrictions of the clean room. These include *competition;* that is, the work performed in the clean room is sufficiently critical to warrant higher wages. This competition for

more compensation reduces complaints. *Status* is also important. An image is created if the clean room workers are selected for their skills. Several relatively unnoticeable features also add to individual status. Longer cleanup periods should be allowed for clean room personnel than for those who work in nonclean areas. A clean room worker may also require longer and more frequent breaks because of the nature of the restrictions in his work. Finally, the *special services* available to accommodate the clean room operator will influence his attitude toward the job. Because he is confined, he will require the cooperation of other shop workers to secure equipment, work items, etc., that are outside his area. He may also require the purchase of special items of equipment that are not ordinarily available to other workers because of the nature of his job.

Psychologists have tried to uncover personality factors of those individuals best suited to clean room work. The Thurstone temperament schedule has been useful in scoring clean room operators. Successful clean room operators have been shown to score as follows:

(1) High in emotionally stable characteristics
(2) Average in active, vigorous, and sociable characteristics
(3) Low in impulsive, dominant, and reflective characteristics

However, these findings should be interpreted cautiously since they may vary with the particular task.

Personnel Control Procedures

Personnel control must begin before the employee enters the clean room area. Items of clothing such as raincoats, overcoats, overshoes, etc., are stored away from the clean area. After disposing of these items, the clean room worker enters the area and begins to prepare his personal apparel. He cleans his shoes with special shoe cleaning equipment. One type cleans the soles and the second type cleans the tops and sides of his shoes. This is an important function and all loose particulate matter must be removed. He then enters the clean room entryway. Here he removes his suit coat or jacket and personal belongings such as cigarettes, notebooks, pencils, etc.

If the facility has an air shower he moves through the air shower taking about 20 seconds to pass through. He raises his arms and rotates his body through 360° in passing through the air shower. He will then don the clean room apparel.

Dressing is usually done in a standing position. Care must be taken to keep the garments away from contaminates. The novice will find it difficult to get into the clean room garment without dragging the sleeves or the legs of the garment on the floor. However, this can be accomplished with some practice. The boots are to be put on last, and then the operator, wearing his boots, will proceed immediately to the gel mat. Each time the operator

enters or leaves the clean room he goes through the same procedure. Each time he leaves the clean room he must don a clean uniform before reentering. In any case, the complete uniform is changed each day. Gloves, however, are changed more frequently and each time that they become soiled.

Probably the one area in a clean room operation that has been most thoroughly exploited is the establishment of rules. Each facility has a varying set of rules, although basically they are similar. It is very important, however, that the individual operators understand the reason for the rules and with this recognition observe them. The following procedures for entering the clean room, leaving the clean room, and the rules for operation within the clean room are typical of those that are in normal practice.

Entering Clean Room:

(1) Use the shoe cleaner and electric mat to clean shoes before entering the air lock. Do not wear overshoes into the air lock.
(2) In the air lock, walk on the tacky mat and bare floor. Avoid the gel mat until the protective booties are put on over the shoes. Never walk on the gel mat with shoes.
(3) Remove all articles from pockets. Remove wrist watch and all jewelry.
(4) Remove outer jacket and store with jewelry in locker provided.
(5) Take a clean garment from the storage cabinet.
(6) Do not tear open the wrappings. Cut with scissors. Discard wrappings in the container provided.
(7) Coveralls go on first. Take care not to drag the garment on the floor.
(8) Garments are to be snapped at ankles, neck, and wrists.
(9) Wear booties over shoes; snap and tie at ankles. Do not step on bare floor with booties. Step on gel mat only.
(10) All hair from head is to be inside the head covering.
(11) Enter clean room and immediately put on gloves of the desired or specified type.

Leaving Clean Room:

(1) Remove clean room garments only after entering air lock.
(2) Do not step on gel mat with shoes. Do not wear booties outside the air lock.
(3) Place used clean room garments in laundry cabinet outside the clean room. Cloth gloves are to be kept separate from garments.
(4) A clean garment should be used with each entry into the clean room. Exceptions to this must be arranged with the clean room operator.

Clean Room Procedures:

(1) Individuals having skin or respiratory ailments are not allowed in the clean room area.
(2) Individuals with a cold or severe sunburn are not permitted to work in the clean room.
(3) No unauthorized personnel are to enter the clean room.
(4) Only test fixtures, tools, jigs, and assembly fixtures needed to perform the task are permitted in the clean room.
(5) No abrasives such as files, crocus cloth, etc., are permitted.
(6) No shredding or masking tapes are permitted.
(7) No parts or components are to be left on work benches.
(8) Only approved clean room garments will be worn.
(9) No smoking or eating is permitted in the clean room.
(10) No person having cosmetics such as, after-shave talc, lip ice, etc., or external medication is allowed in the clean room.
(11) No pencils are allowed in the clean room. Ballpoint pens and lint-free paper are provided.
(12) Movement in the clean room should be slow and rhythmic.
(13) Do not shuffle feet.
(14) Do not swing arms.
(15) No watches or jewelry are to be worn in the clean room.
(16) Do not scratch head, eyebrows, or exposed skin areas.
(17) Coveralls are not to be unzipped in the clean room.
(18) No skin area is to be exposed between the gloved hand and coveralls.
(19) All equipment taken into the clean room must be visibly clean.
(20) No more than four persons are allowed in the clean room at one time.[1]
(21) No more than two persons may work in the laminar flow work station at one time.[1]
(22) Hand tools and instruments are to be stored in cabinets or under covers when not in use.
(23) Exceptions to the preceding rules will be considered after technical consultation and can be granted only by the facility supervisor.

Training and Certification of Operators

Once individuals have been selected as clean room operators, they must be trained for the job. The following important factors should be considered:

(1) Indoctrination must include a thorough acquaintance with clean room rules, regulations, and procedures.

[1] The number of persons permitted in a clean room or work station is a function of the size. Normally a clean room with 500 sq ft of floor space can accommodate four persons.

(2) An explanation of the reasons for these stringent regulations must be given. This aspect is extremely important and, unfortunately, is often overlooked. Workers are more likely to feel responsible for abiding by clean room constraints if they have a clear understanding of the causes of contamination.

(3) It is advisable that both individual and team training be conducted in a simulated clean room. This procedure permits smooth transfer into the actual clean room with a minimum of errors. It also ensures high probability of maintaining the cleanliness level.

It is advisable that this indoctrination and training be extended not only to the immediate level of supervision of the clean room operators but to the next higher level. Thus, the special problems that must be dealt with in connection with clean room operation will be recognized and appreciation will be made of the difficulties encountered in meeting these problems.

NASA has prescribed a minimum course of instruction for all personnel whose activities may bring them in contact with contamination-sensitive articles. This specification spells out the following areas as a minimum for inclusion in this training program:

(1) Definition of terms associated with contamination control
(2) Presentation of the need for contamination control and the consequence of contamination
(3) Discussion of the origin and types of contamination including internal sources created by manufacturing or handling activities, external sources present in prevailing environment, and personnel-created contaminants
(4) Presentation of the devices and techniques used to achieve and control cleanliness including applications and limitations
(5) Discussion of tamper-proof seals on clean closures
(6) Demonstration of methods of measuring and verifying contamination levels
(7) Presentation of the high orders of cleanliness capable of being achieved and necessary for manned space missions

Those personnel selected for assignment to activities within the clean room should have additional training to include the following categories:

(1) Design criteria for clean rooms and clean work stations
(2) Personnel control and occupancy within controlled environment
(3) Considerations in the selection of furniture, fixtures, and tools that are used in clean rooms
(4) Design criteria for garments and special apparel
(5) Maintenance and janitorial considerations for clean rooms

On completion of each course of instruction, the trainee should be tested

with basic questions on each element of instruction. A grade that indicates adequate retention and understanding of the subject must be obtained to qualify for working in contamination-sensitive activities. Provision should be made to award a certificate indicating completion of the prescribed training. This certificate is prepared for each successful trainee by the quality control organization. Annual reindoctrination sessions should be held with the clean room staff to review the procedures currently in use and to consider revisions. As new personnel are added to the clean room, special training sessions should be held.

CLEANING TECHNIQUES

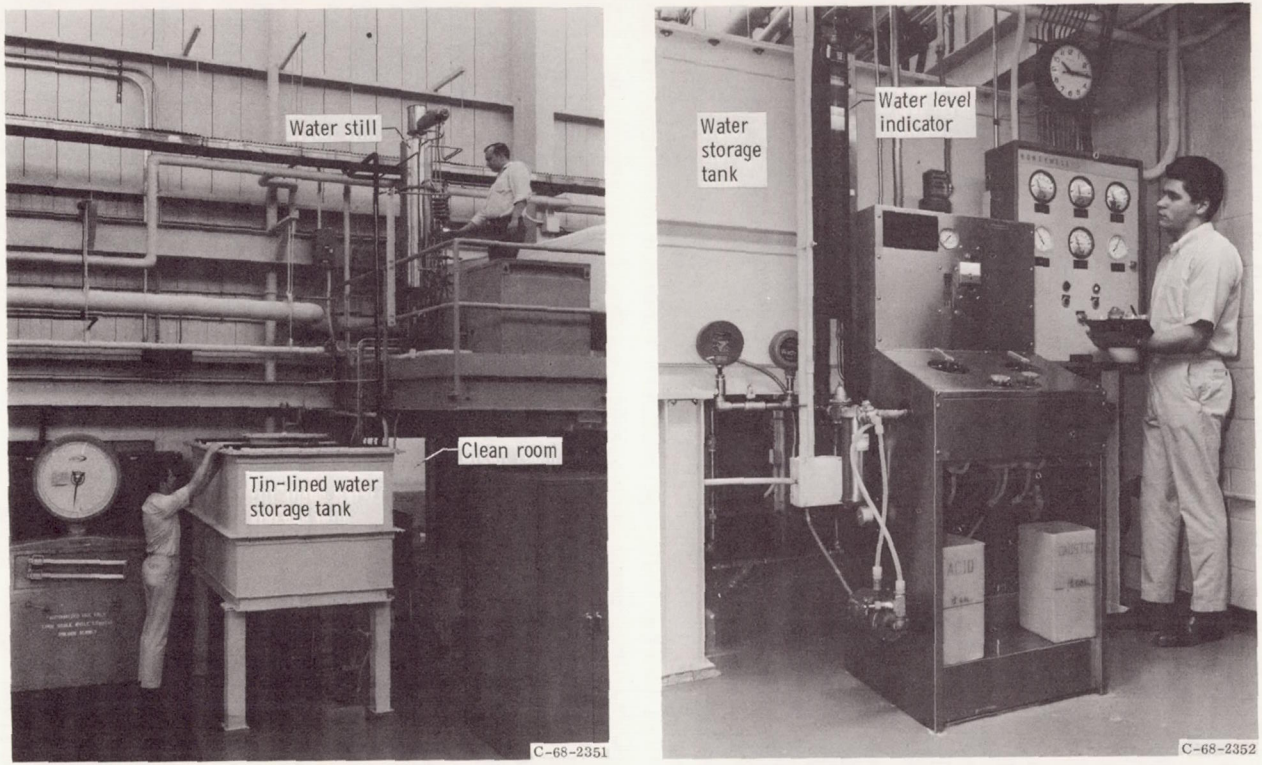
One function that is basic to most clean rooms is the cleaning of precision components. However, it is difficult to generalize on cleaning techniques, as they vary with the component being cleaned and with the type of contamination. In fact, a complete industry of solvents and detergents has arisen to meet the current needs for precision cleaning agents. Cleaning involves removing contaminants either by putting them into suspension or into solution. Differences in cleaning arise with the techniques used to put the contaminant into solution and the various solvents used in the process.

Many methods have been introduced to release the contaminant from the surface to be cleaned. These vary from common scrubbing with brushes to the more sophisticated use of ultrasonic energy to dislodge the contaminants. Placing the contaminant into suspension or solution is difficult and has been the object of much chemical research. Water is the most common solvent used. Detergents are usually added to increase the wettability or lower the surface tension of water to increase its effectiveness. As the contaminants become more complicated and the degree of cleanliness required increases, more complex chemical solvents are needed. These are discussed in the section on Precision Cleaning Methods.

Pure Water

As previously mentioned, water is the most common fluid used in cleaning. Even when more sophisticated solvents are used in the component cleaning process, water is still important in the cleaning of the various parts of the clean room itself. Normal tap water is seldom suitable for clean room use because of its organic and mineral content. As a result, most clean rooms have a system for removing minerals (such as calcium compounds), removing ions, and distilling the water used in the facility. A typical water system is composed of a tin-lined storage tank and distillation apparatus (fig. 16(a)) and the demineralizer and system control panel (fig. 16(b)).

Theoretically, pure water contains no dissolved solids and has a pH of 7.0. However, if pure water is exposed to the atmosphere for even a few



(a) Storage tank and distillation apparatus.

(b) Demineralizer and system control panel.

FIGURE 16.—Typical water distillation system for clean room use.

minutes, it will dissolve enough carbon dioxide to change the pH value to as low as 5.8. The quality of the water changes only by 0.1 part per million. However, the concentration of carbonic acid (H_2CO_3) formed reaches 1.5×10^{-5} moles per liter, while the purity remains high. Thus, acidity and purity cannot be equated. It is evident that there is a need for more than one purity specification as far as water is concerned. Normally, the characteristics of pure water are defined in terms of ion concentration, conductivity, organic content, total solids, microorganisms, and other specifically undesirable contaminants. Each of these is discussed separately in the following paragraphs.

Conductivity, the most common and often the most significant measurement made in purity evaluation, is a function of the residual, ionizable contaminants. Good, reliable, low-cost indicating and recording instruments are available to measure water conductivity. Water-assessing electronic devices measure conductivities from 15 to 0.6 microhms. Some devices convert the conductivity to an equivalent sodium chloride content in parts per million. Water with a concentration of 0.8 part per million is considered pure water.

Organic contamination is generally present only in surface waters. High organic content is more common in the South where rivers often originate in swampy areas. Organic matter is evaluated in the laboratory by determining the amount of sodium permanganate consumed under standard conditions during the organic matter decomposition. These contaminants are ionized either poorly or not at all by the decomposition and are not usually removed by the deionization process. Removal by coagulation, settling, or filtration must be considered. Tests for total solids can be performed only in the laboratory. This test involves controlled evaporation of a water sample and examination of the residual deposits. Good wash water has less than 0.5 part per million of total solids. The technique for determining the quantity of total solids can be considered only for occasional monitoring of the purification process. Twenty-four hours are required to evaporate a sufficient amount of water for accurate weighing of the residues, and the water supply under study will have long since been used during this period.

Microorganic contaminants are present in all natural waters and are generally not harmful because of their low concentrations. However, if the amounts present are permitted to rise sufficiently, they will contaminate the deionizing resins and either limit or stop their action. Microorganisms form slimes in pipes and tanks which will flake off in large pieces and cause bad results in a good cleaning process. Their presence should be evaluated regularly in the laboratory by standard techniques of culture growing.

When pure water has been produced, it must be protected during its storage as most containers will add either ions, organics, or particulate matter to the water. Storage tanks for clean room use are normally lined with high-purity tin. However, with time, the tin lining forms stannic oxide on the

surface. This will shed and go into colloidal suspension. Inserting a 0.3-micron membrane filter in the system will remove these particles. Glass linings, on the other hand, dissolve silicates into the water and affect surface tension measurements by about 1 part per million. Plastic linings are normally not suitable because they contribute complex hydrocarbons to the organic contamination. Resin type (often referred to as glass in the trade) linings will produce an ion exchange that will also contaminate the water with organics. Therefore, a compromise must be made when selecting a tank for storage of pure water based on the eventual use of the water. When highly pure water (such as used in surface chemistry studies) is required, the most suitable way is to produce the water by a triple distillation process and then use it immediately rather than store it for any length of time.

Precision Cleaning Methods

Precision cleaning of components is a more complex subject than might be presumed at first encounter. The size and type of contaminant, as well as the surface being cleaned, can vary widely. Particulate contamination can vary from oxide scale to fine dust particles. Organic contaminants will vary from heavy greases to the oils deposited by fingerprints. Film deposits of either nonvolatile residues or airborne vapors are a special problem in many cleaning operations. These are not normally removed from the air supplied to a clean room by the HEPA filters. An elaborate system of activated charcoal filters is required.

Cleaning involves transferring a high concentration of contaminant from a part to a lower concentration in a fluid or solvent. This implies that the cleaning solution must be at least cleaner than the part to be cleaned. Also, the final rinse solution must be as clean as the surface being prepared.

Cleaning in a clean room must be preceded by gross cleaning in some other area. Gross cleaning removes heavy deposits such as scale, rust, metal chips, shop dirt, and other forms of obvious, unwanted substances. Gross cleaning is usually done by wire brushing, wet or dry shot or vapor blasting, or by grinding. These mechanical cleaning techniques are followed by gross chemical cleaning. This includes acid pickling, alcohol soaking, solvent rinsing, etc. Gross cleaning must be done to a visibly clean condition before a component is taken into the clean room.

Precision cleaning, however, is the type done in the clean room with special solvents. The solvents may be used in baths, vapors, sprays, or flushes. The type and number of solvents used will depend on the contaminant encountered and the surfaces being cleaned. The Atlas Chemical Industries, Inc., for example, publishes a list of over 100 chemical surfacants from which to choose. Each of these is intended to solve a particular cleaning problem. The number of techniques used for cleaning a particular type of material varies almost as widely as the number of persons

doing the cleaning. For example, there are at least three accepted techniques that are used for precision cleaning glass surfaces. These techniques are discussed in detail as an example of the variety of techniques in use.

In the electronics industry, it is important that the glass used for vacuum tubes be cleaned to a high degree. The following technique originated with the General Electric Company:

(1) Scrub in hot tap water containing 0.05-percent Igepal wetting agent
(2) Rinse in hot tap water and then in running deionized water
(3) Boil in 5-percent hydrogen peroxide solution in deionized water for 15 minutes
(4) Rinse in running deionized water and dry in oven at 110° C

The Bell Telephone Company, on the other hand, uses an ultrasonic wash in tap water with a detergent for 5 minutes and then a 3-minute boil in 3-percent hydrogen-peroxide—deionized-water solution. This process is followed by pure water rinsing and drying at 110° C.

NASA uses the following procedure to clean borosilicate glass:

(1) Hand wash with distilled-water—detergent solution
(2) Rinse with benzene
(3) Rinse with acetone
(4) Rinse with distilled water
(5) Cleanse with chromic acid cleaning solution at approximately 80° C for 1 minute
(6) Rinse with distilled water and dry in filtered air

A widely used process for precision cleaning requires ultrasonic energy to impart mechanical action to the cleaning. Figure 17 shows a clean room operator removing small components from an ultrasonic cleaner. This installation includes the cleaner, a rinse tank, and a filtered-air drying tank. Ultrasonic energy is very effective in dislodging tightly adhering particles that are insoluble. The action depends on creating tiny (usually invisible) bubbles in the solution that implode against the particle to produce the mechanical scrubbing. Of course, during the cleaning process, the solvent becomes contaminated. A recently developed system has incorporated distillation and filtration apparatus to supply a clean solution to the bath continuously.

An even further improvement uses vapor degreasing for precision cleaning. Figure 18 is a schematic drawing of a typical vapor degreasing system that includes an ultrasonic cleaner. In this system, the solvent fills the ultrasonic compartment, which is a tank energized by transducers. The parts to be cleaned are immersed in this tank, and the contaminants are removed by solution in the solvent and by the ultrasonic activity. Solvent in the boiling sump is vaporized by heat, and the vapors fill the area above the tank. A vapor blanket is formed over both the boiling and the ultrasonic compart-

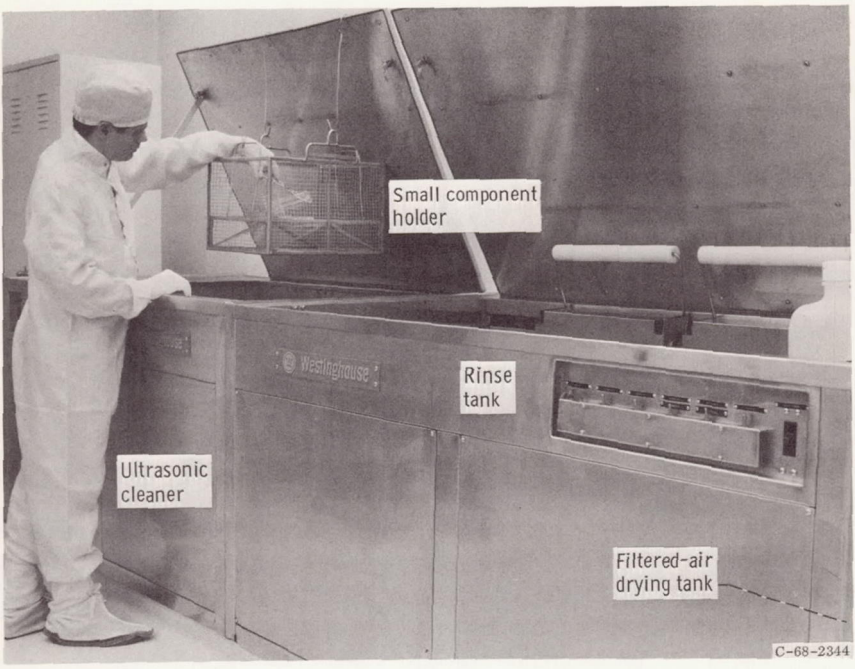


FIGURE 17.—Clean room operator removing small component from holder in ultrasonic cleaner.

ments. After the parts have been cleaned in the ultrasonic compartment, they are withdrawn through the vapor blanket. Pure distilled solvent from the vapor condenses on the parts providing a final rinse. Cooling coils are installed above the tanks to reduce loss of the solvent. The condensed solvent is returned to the ultrasonic compartment and overflows into the boiling compartment. It is then revaporized and the cycle begins again. The most common solvent used in this process is one of the family of Freons. Freon TF is particularly suitable because it is easily vaporized and only a moderately cool trap is required to contain the vapors.

There are two major limitations to using ultrasonic energy for cleaning. First, it does not clean resilient materials such as soft plastics, rubber, or fibrous components. These absorb the energy making the ultrasonic action ineffective. Second, ultrasonics destroy sensitive components. For example, semiconductors (transistors, diodes, etc.) are often damaged by ultrasonic cleaning. Water is the best solution for ultrasonic use from an energy transmission standpoint. Most other solvents attenuate the energy generated more than water. However, the choice of water as a cleaning agent must be compromised with the insolubility of many contaminants in water.

Clean room operators are sometimes embarrassingly surprised by a

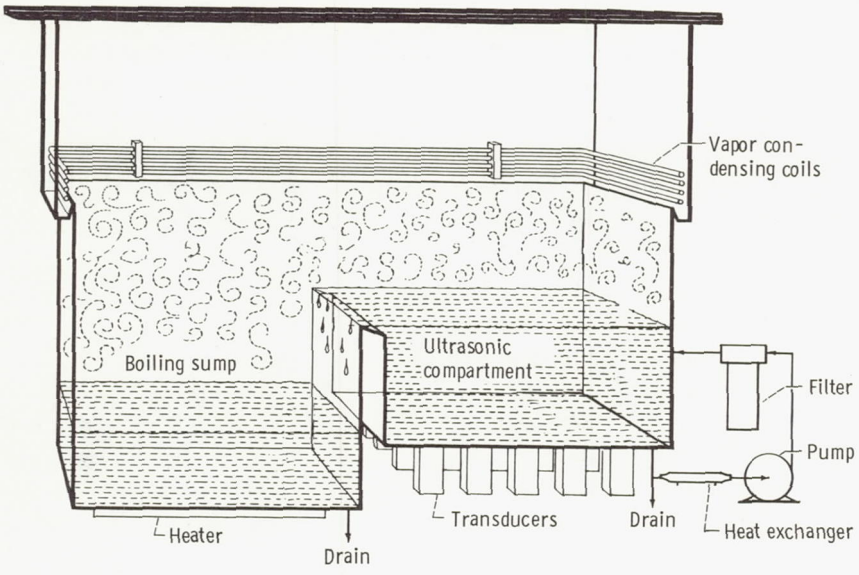


FIGURE 18.—Schematic drawing of vapor degreaser and ultrasonic cleaner.

situation that should be mentioned. It is important that the operator know what materials are involved before cleaning is begun. More than one operator has been astounded to see rust forming on a part as he completes the cleaning and drying process. Some metals, iron in particular, will oxidize extremely rapidly in the normal clean room atmosphere when a thorough cleaning of the surface has been made. The operator should be aware of this and plan accordingly. For iron components, immediate packaging in a dry, inert atmosphere, such as helium or nitrogen, will prevent the oxidation.

In summary, there are no predetermined rules for good cleaning techniques and often these must be developed by experience. It is important that clean solvents or reagents be used and some method be used either to clean the solvent or replenish it as the cleaning process takes place.

Evaluating Cleaning Methods

Effective removal and control of organic contaminants requires availability of suitable detection and evaluation methods. Because the first molecular layers of organic material are the most tightly bound, a detection method must be sufficiently sensitive to indicate when these layers have been removed. It should be possible to perform the test simply and rapidly and with a minimum of expensive equipment.

One technique is to test the final rinse solution. A sample of the final rinse is collected and filtered. The filtrate is studied with a high magnification microscope to determine the particulate content. A determination of the nonvolatile residue (NVR) can be made by a comparative weighing of the residue after evaporation of the used and unused solvent.

A more common practice is to test the cleaned surface with various physical phenomena that can be measured in relative terms. The following characteristics are useful in measuring cleanliness:

(1) Acidity or alkalinity of a surface
(2) Wettability of a material
(3) Spectrophotometric analysis
(4) Bacteriological culturing
(5) Ultraviolet reflection
(6) X-ray diffraction
(7) Electrical conductivity
(8) Light scattering
(9) Changes in weight

It is extremely important when sampling and measuring contamination that precautions be taken to prevent reading extraneous contamination. It is a common error, for example, to use a contaminated bottle to collect the fluid sample. Tubing and pumps are also a source of contamination of the sample.

Two common techniques used to evaluate the presence of organic contaminants are the water break test and the atomizer test. These tests depend on the ability of water to wet metallic and inorganic surfaces, but not to wet oily or greasy organic materials. Although this phenomenon of differential wettability has been observed for many years, there appears to be only limited appreciation of its high sensitivity for differentiating the nature of wetted surfaces.

Water break test.—The water break test is performed by immersing the surface to be tested in a beaker of deionized water and withdrawing it in a vertical direction. If the surface is free of hydrophobic materials, the draining water film will remain as a thin uniform layer covering the entire surface of the part. This film will show no breaks or discontinuities until it becomes so thin that evaporation causes local drying or until interference colors are observed. On a surface contaminated with hydrophobic matter, the draining water film will break up and withdraw into wetted areas leaving the nonwetted areas exposed. The length of time necessary for the water break to occur is an indication of the amount of contamination present. On grossly contaminated parts, the water break will occur immediately on withdrawal. Where contamination is present in amounts of only a single molecular layer, a period of 30 to 60 seconds draining may be necessary before the water film becomes thin enough to break.

Atomizer test.—The atomizer test subjects the dry surface to be tested to a fine spray of deionized water. The surface is sprayed for a period of 3 to 30 seconds at a distance of 18 to 24 inches from the atomizer. An ordinary oral atomizer may be used, but poor drop size reproducibility usually results. It is recommended that an artist's air brush atomizer be used. The interpretation of the test is based on the wetting pattern. In the absence of hydrophobic contaminants, the impinging water droplets will wet the surface and spread immediately to form a thin continuous film. Where a hydrophobic film covers the surface, the spray droplets will not spread, but will remain as fine droplets. They will form a high contact angle with the surface. When organic materials are present, not as uniform films but as discrete areas of contaminant, the droplets become dammed up where they contact the hydrophobic spill. In the hydrophobic areas themselves, fine droplets form as on a uniformly contaminated specimen. Where only traces of contaminant are present (a fraction of a monolayer) a transitional pattern appears. This may be obscured if further spraying floods the surface. This transition pattern appears as many dammed areas of uniform water films contacting each other.

Several conclusions can be drawn from these phenomena. The atomizer test is from 3 to 30 times more sensitive than the water break test. It is capable of detecting contaminants in amounts as small as 0.16×10^{-7} gram per square centimeter. These tests detect less than one molecular layer of polarized soils. The atomizer test is able to detect a small fraction of a monolayer. The more strongly oriented the contaminating molecule, the more easily it is detected by either test. Differences in the sensitivity of the two tests are the result of the dependence of the atomizer test on an advancing contact angle, while the water break test depends on a receding contact angle. The interface between the advancing angle and the contaminated area is more

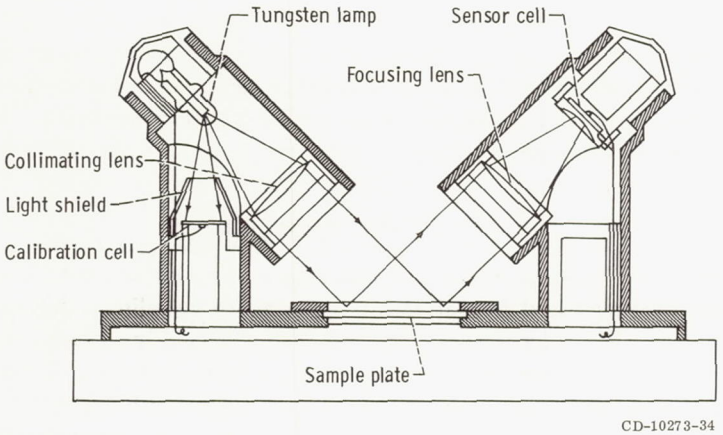


FIGURE 19.—Monitor to sense contamination deposited on surfaces.

easily seen than the interface between the evaporating film and the contaminated area. In the atomizer test, the water droplets arrive as fine, discrete droplets and, therefore, show less tendency to cover and obscure small contaminated areas.

Contamination monitoring systems.—Recent developments have produced a monitoring device (fig. 19) that detects and indicates directly the amount of contamination deposited on a given surface. The monitor (see NASA Tech Brief 68–10089) uses an optical system in conjunction with a collimated light source and associated electronics. Light from a tungsten lamp is projected through a collimating lens onto the sample plate. The reflected image passes through a second lens that focuses on a silicon sensor cell. The signal from the sensor cell is proportional to the signal from the light source. An additional silicon sensor cell is located in the tungsten lamp housing to sample the lamp output continuously for calibration. Any change in the monitor output is proportional to the change in the optical absorption characteristics of the sample plate surface. Contamination will influence the reflectivity of the surface. The advantages of a continuously monitoring system such as this are obvious.

During November 1967, the Ametek Technical Products Company introduced a new process for measurement of surface residues. This process analyzes the rate of evaporation of a carbon-14 labeled radioactive test solution. The radioactive tracer is contained in a high-boiling-point, but completely volatile, solvent. A solution of less than 1 microgram of this high-boiling-point solvent is made in a low-boiling-point solvent. The process consists of applying this solution to a surface, allowing time for the low-boiling-point solvent to evaporate, and then measuring the rate of evaporation of the high-boiling-point radioactive material. The rate of evaporation is monitored by a radiation detector placed directly above the test surface. For a given set of conditions, the observed rate of evaporation from a clean surface is always reproducible, and variations from the norm can be independently calibrated for various surface phenomena and surface residues. The MESERAN System, as it is called, is quantitative from less than a monolayer (0.1 μg/sq cm) to at least 100 molecular layers. The test can be made in a few minutes.

Clean Room Packaging

Packaging materials.—When items have been precision cleaned, they must be adequately packaged to maintain this degree of cleanliness during storage, shipping, handling, testing, etc., until final assembly or use. Practice has shown that the best way to package such items is in a flexible, heat sealable, transparent plastic film which has been cleaned to the same stringent level as the item to be packaged. Only three packaging materials are suitable, and none of these possesses all the desired characteristics to a high

degree. These are polyethylene, nylon, and aclar films. Polyethylene is relatively inert. It is inexpensive, easy to clean, and easy to seal. However, it is soft and sloughs when flexed. Also, polyethylene shows considerable distortion due to swelling in the presence of oils. It is most useful as an outer packaging material over a more suitable interior package. Polyethylene, however, is an excellent moisture barrier. Polyethylene bags are usually 6 mils thick for clean room use, and several sizes as well as sheet stock are available.

Nylon (polyamide) is the lowest sloughing material available for packaging. It generates few particles when exposed to light abrasion and flexure. For clean applications, nylon film 2 mils thick is most frequently chosen. However, nylon containers are not liquid-oxygen compatible. They constitute a potential hazard when sloughed particles encounter liquid oxygen or other highly oxidizing chemicals. Nylon does not provide a good vapor bar-

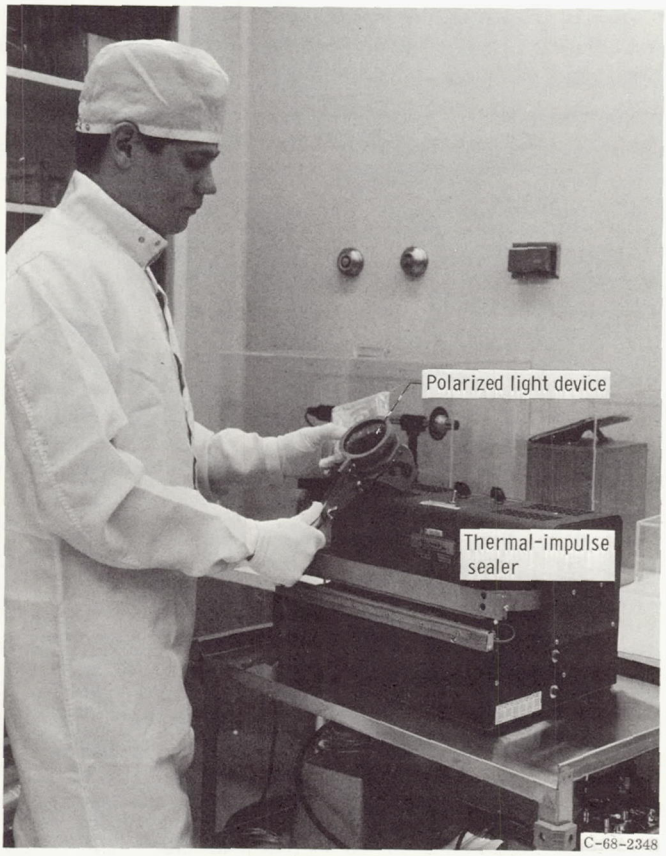


FIGURE. 20.—Inspection of seal of clean room packaged part. Typical thermal-impulse sealer is shown.

rier. However, this characteristic can be used to advantage when thin gage nylon is used to contain a desiccant. The desiccant package can be enclosed with the nylon package part inside a polyethylene outer bag.

Aclar, a fluoro-halo-carbon film, is the only packaging material, to date, accepted by NASA as liquid-oxygen compatible. It is also an excellent vapor barrier and is oil resistant. It is available in 2- or 5-mil roll stock. Aclar abrades more than nylon and thus has a tendency for self-contamination.

Polyethylene films have been surface coated with finely divided granules of conductive material to reduce the accumulation of static charge. Several forms have been marketed, but unfortunately they are usually opaque and often tend to slough particles, making their use of limited value. Recently, packaging materials have been made daylight fluorescent so that particulate matter produced from the packaging material could be distinguished from that introduced with the cleaned item. Both polyethylene and nylon films are available with fluorescent additives.

The best method of sealing a clean packaged bag is with a thermal-impulse sealer. A typical impulse sealing and inspection operation is shown in figure 20. The impulse sealer assures that the proper heat level is applied to the material for a suitable duration at a fixed pressure. For example, nylon packages are sealed with a heat impulse for 1.8 seconds, at a pressure of 30 psi, and a dwell time of 1 second. Both aclar and polyethylene require a dwell time of 2.5 seconds. Aclar requires an increase in pressure.

A good technique for inspecting a thermal seal is to pass polarized light through the seal. Diffused light patterns of stress are visible, and any poorly sealed areas or holes are readily apparent. The device shown in figure 20 has a light source and two polarized lenses. The sample is passed between the lenses for inspection.

Precision packaging checklist.—Although there are no fixed rules for use in precision packaging, the following list may be used to develop a suitable technique:

(1) Determine the optimum packaging material based on resistance to sloughing and compatibility with the packaged item and the service medium.

(2) Determine the optimum packaging and closure methods (heat seal envelope, blister package, wrap, can or bottle, etc.).

(3) Provide for temporary protective packages and in-process handling containers.

(4) Develop a method for indicating precision packaging and level of cleanliness (color, code, label, etc.; see example shown in fig. 21).

(5) Develop a method for purchasing, storing, handling, etc., of clean packaging material.

(6) Provide a capability for cleaning packaging maerial.

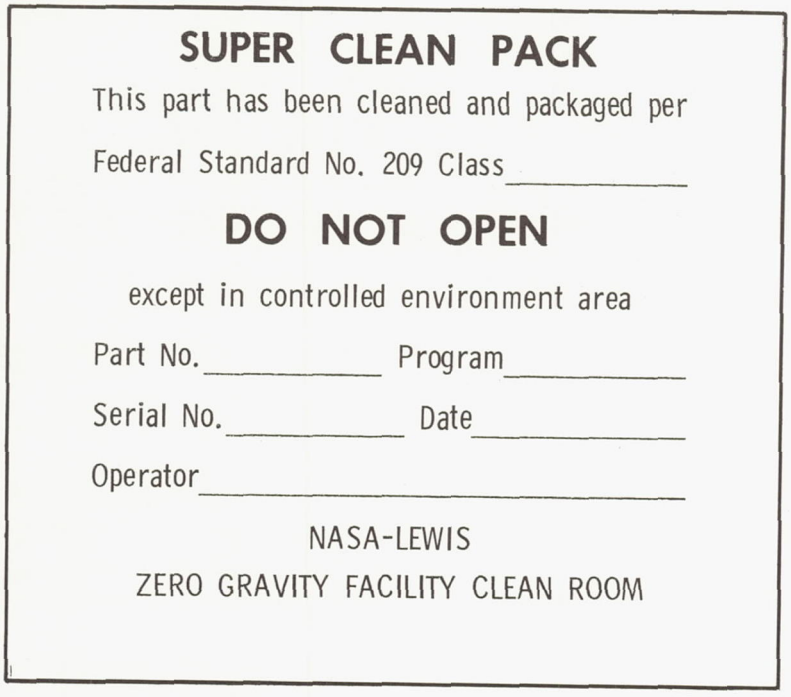


FIGURE 21.—Clean room package label used to identify cleaned parts. Label is printed on vinyl material to minimize sloughing.

(7) Develop a procedure for sampling and measuring the contamination level of the packaging material.
(8) Develop tamper-proof seal devices.
(9) Avoid vacuum packages because they draw in contaminants.
(10) Do not tear clean packages because the tearing action generates particulates, but use scissors.
(11) Treat a precision packaged item as an inseparable unit.
(12) Develop storage and inventory procedures that will ensure the integrity of the package.
(13) Provide protection beyond the precision packaging with a durable overpack.
(14) Design the package to allow the least possible relative motion between the part and the packaging material.

GLOSSARY OF CLEAN ROOM TERMS

absolute rated filter. A device that essentially retains all particulate matter whose smallest dimension is equal to or greater than the absolute rating.

aerosol. Particulate matter suspended in a gas.

agglomerate. A group of particles that have combined to form a larger particle.

air shower. A de-duster of personnel that uses air velocity to remove particulate matter.

airborne particulate matter. Particulate matter suspended in ambient atmosphere.

air lock. A small chamber with interlocked doors functioning to maintain pressure during entry and egress from a clean room; also a small chamber used for passage of components, tools, etc.

ambient condition. Environmental condition such as pressure, temperature, etc., which is normal for the location.

clean area. The entire area within the confines of the outer entrances to the clean room, including the entryway.

clean room. A type of controlled environment facility in which all incoming air passes through a filter capable of removing 99.97 percent of all particles 0.3 micron and larger. In a clean room the temperature, pressure, and humidity are controlled. External sources of particulate contaminants are excluded, and internal sources are controlled to required cleanliness levels.

clean work station. An individual work bench which has a high-efficiency particulate air (HEPA) filter and provides essentially laminar flow across the work area.

contaminant. Any unwanted foreign material which is detrimental to the required operation or reliability of a part, component, subsystem, or system.

controlled environment facility. A specified work area that has the primary objective of controlling one or more physical, chemical, or biological variables.

controlled work area. A specified work area in which access, operations, and environment are controlled.

conventional clean room. A clean room in which the airflow patterns are random.

crossflow clean room. A clean room in which the air enters through an entire wall with filters and is exhausted through the opposite wall; air travel within the room is predominantly horizontal.

deionize. Removal of free ions from a liquid.

demineralize. Removal of suspended soluble minerals such as calcium carbonate from water or other liquids.

downflow clean room. A clean room in which the air enters through an entire ceiling of filters and is exhausted through the floor; air travel through the room is predominantly vertical.

fiber. A particle whose length is 10 times its width (minimum length 100μ).

filter rating. The filtering capability expressed in percentage of a medium to restrict passage of matter as established by testing techniques, such as pore size, bubble point, and dioctyl phthalate (DOP).

first air. The air which issues directly from HEPA filters before it passes over any work location.

fluid contaminant. Liquid, gaseous, or particulate matter suspended or dissolved in a liquid.

flush. Rinsing a component, system, etc., using a liquid as the rinsing medium.

fume hood. A work station that has a specially provided exhaust system for control of vapor contamination from volatile liquids; usually provided with a sink and disposal facility.

gross cleaning. Preliminary or rough cleaning to remove scale, rust, metal chips, shop dirt, etc.; this cleaning is done in a normal work area to visual inspection standards.

high-efficiency particulate (HEPA) filter. A filter that is at least 99.97 percent efficient by volume of 0.3-micron particles, as determined by the dioctyl phthalate (DOP) test.

laminar flow. A unidirectional airflow made up of thin layers.

laminar flow station. A work station having laminar airflow characteristics in the entire work area.

light scattering. A technique for detecting, counting, and sizing fluid-borne particulate matter passing through a high intensity light beam; the distorted light beams are converted to electrical impulses by a photomultiplier tube and registered on appropriate counters and tapes.

membrane filter. Porous material composed of pure and biologically inert cellulose esters, polyethylene, or other materials.

micron. A unit of measurement equal to one-millionth meter, or approximately thirty-nine one-millionths inch (0.000039 in.); 25 microns is approximately equal to one-thousandth inch.

nonvolatile residue (NVR). Soluble or suspended material and insoluble particulate matter remaining after controlled evaporation of a filtered volatile liquid, usually measured in grams; filtration is normally through a 0.45- or 0.8-micron membrane filter.

particle. A piece of matter with observable length, width, and thickness, usually measured in microns.

particle counter. Automatic electronic device designed to separate, size, and count individual particles.

particulate matter. A general term applied to matter of miniature size, with observable length, width, and thickness and contrasted to nonparticulate matter without definite dimensions.

precision cleaning. Final or fine cleaning accomplished in a controlled environment to remove minute quantities of contaminants to better than visual standards.

precision packaging. Packaging or protection to preserve precision cleanliness for a specified period and condition.

random flow clean room. Air enters the room through diffusers located on or near the ceiling and is exhausted through openings near the floor; air within this type room follows a random pattern.

rinse test. A test to determine cleanliness by entrainment or by solution of soluble materials with a suitable rinsing liquid; the liquid is sloshed or agitated over the critical surfaces of the component to ensure entrainment of particles.

silt. Particulate matter settled from fluid generally in particle size ranging less than 5.0 microns.

slough. A process of shedding or discarding fine particles when a surface is rubbed; the particles that are shed are also known as slough.

tunnel flow clean room. A room where the incoming air enters through an entire wall or ceiling of filters and is generally exhausted through an opposite open area; air travel within the enclosure is unidirectional.

visibly clean. Freedom from surface particulate matter approximately 50 microns or larger and from all films other than known innocuous films.

visual cleanliness. The degree of freedom from contaminants that may be detected by the unaided eye; special lighting effects, ultraviolet light, wipe test, water break test, and similar means may be used as techniques to determine visual cleanliness.

white room. A room designed to be free of dust and other contaminants but not controlled to the same level as a clean room.

work station. A work bench or similar working enclosure that has its own filtered air supply.

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BIBLIOGRAPHY

Background Information

ANON.: Clean Room and Work Station Requirements, Controlled Environment. Federal Standard No. 209, Dec. 16, 1963.

ANON.: Standards and Guidelines for the Design and Operation of Clean Rooms and Clean Work Stations. Tech. Order 00–25–203, USAF, July 22, 1963.

AUSTIN, PHILIP R.; and TIMMERMAN, STEWART W.: Design and Operation of Clean Rooms. Business News Publ. Co., 1965.

CADLE, RICHARD D.: Particle Size. Reinhold Publ. Corp., 1965.

KODEL, I. M.: Dust Monitoring in Clean Rooms. Rep. SCTM–131–61(25), Sandia Corp., Aug. 1961.

OFFICE OF MANNED SPACE FLIGHT: Handbook for Contamination Control on the Apollo Program. NHB 5300.3, NASA, Aug. 1966.

Clean Rooms

AGNEW, BOYD: Design Criteria for Laminar Flow Clean Work Stations. Presented at Am. Assoc. for Contamination Control Seminar, Framingham, Mass., Jan. 1964.

ANON.: The Edgegard Principle. Baker Co., Biddelford, Maine, 1965.

AUSTIN, PHILIP R.; and TIMMERMAN, STEWART W.: Design and Operation of Clean Rooms. Business News Publ. Co., 1965.

CADLE, RICHARD D.: Particle Size. Reinhold Publ. Corp., 1965.

OFFICE OF MANNED SPACE FLIGHT: Handbook for Contamination Control on the Apollo Program. NHB 5300.3, NASA, Aug. 1966.

Cleaning Techniques

ANDERSON, D. C.: Static Dissipating Packaging Films. Presented at Joint Symp. of Am. Assoc. Contamination Control, Huntsville, Ala., 1966.

ANDERSON, D. C.: A Brief Guide to Clean Room Packaging. Richmond Corp., Aug. 1966.

ANDERSON, D. C.: LOX-Compatible Packaging Films. Cont. Control, Oct. 1965.

ANDERSON, JOHN L.: Coating Cure Determination by Evaporative Rate Analysis. National Coil Coaters Assn., Nov. 1, 1967.

ANON.: Excerpts from MESERAN Technical Manual. Ametek/Technical Products Bull. 9167, Ametek, Inc., Summit, N.J., Aug. 1967.

ANON.: General Characteristics of Atlas Surfactants. Publ. LG–60, Atlas Chemical Industries, Inc., Wilmington, Del., Feb. 1965.

ANON.: Statitrol. Scientific Enterprises, Inc., Broomfield, Colo., 1966.

BALSMY, R. E.: A Procedure for Positive Identification of Packaging Particulates. Tech. Info. Bull., Scientific Enterprises, Inc., Broomfield, Colo.

DROST-HANSEN, WALTER: Aqueous Interfaces—Methods of Study and Structural Properties. *Part I. Ind. Eng. Chem.*, vol. 57, no. 3, Mar. 1965, pp. 38–44; Part II, vol. 57, no. 4, Apr. 1965, pp. 18–37.

FEDER, D. O.; and KOONTZ, D. E.: Detection Removal and Control of Organic Contaminants in the Production of Electron Devices. Symposium on Cleaning of Electronic Device Components and Materials. Spec. Tech. Publ. No. 246, ASTM, 1959, pp. 40–65.

LIEBERMAN, A.: Contaminant Effects Study. Rep. ARF 32165, Armour Research Foundation, Aug. 1966.

LINFORD, H. B.; and SAUBESTRE, E. B.: A New Degreasing Evaluation Technique; The Atomizer Test. Bull. TP73, ASTM, May 1953, pp. 47–50.

LYNCH, L. W.: Plastic Films—Their Usefulness in the Fabrication of Transparent Barrier Materials. Rep. 54–1763, Rhode Island Arsenal Lab., May 1964.

PRICHETT, P. P.: The Utilization of Pure Water in Electronic Device Manufacture. Symposium on Cleaning of Electronic Device Components and Materials. Spec. Tech. Publ. No. 246, ASTM, 1959, pp. 205–213.

SHEEHY, R. N.: Monitor Senses Amount of Contamination Deposited on Surfaces. NASA Tech Brief 68–10089, 1968.

TAYLOR, JAY E.: An Apparatus for the Continuous Production of Triple Distilled Water. J. Chem. Ed., vol. 37, no. 4, Apr. 1960, pp. 204–205.

Clean Room Environment

AUSTIN, PHILIP R.; and TIMMERMAN, STEWART W.: Design and Operation of Clean Rooms. Business News Publ. Co., 1965.

ANON.: Improved Atmospheric Particle Analyzer. NASA Tech Brief 67–10231, 1967.

ANON.: Standards and Guidelines for the Design and Operation of Clean Rooms and Clean Work Stations. Tech. Order 00–25–203, USAF, July 22, 1963.

KODEL, I. M.: The Role of the Manufacturing Development Engineer in Dust Monitoring at Sandia Supplier's Plant. Sandia Corp., Albuquerque, New Mexico.

LIEBERMAN, A.: Clean Room Technology Related to Aerospace Hardware. IIT Research Inst., Jan. 1966.

MAGILL, PAUL L.: An Automated Way to Count Fine Particles. Air. Eng., vol. 4, no. 10, Oct. 1962, pp. 31–34.

WHITBY, K. T.; and CLARK, W. E.: Electronic Particle Counting and Size Distribution Measuring System for the 0.015 to 1 μ size range. Tellus, vol. 18, no. 2–3, 1966, pp. 573–586.

WHITFIELD, W. J.; and MASHBURN, J. C.: The Development of a Faster Monitoring System. Contamination Control, vol. 6, 1967, pp. 10–11.

Clean Room Operation

AGNEW, BOYD: Design of an R & D Clean Room Complex for Guidance and Control Systems. Presented at the Fourth Annual Technical Meeting and Exhibit, Am. Assoc. Contamination Control, Miami Beach, Fla., May 25–28, 1965.

ANON.: A New Approach to Clean Room Design. Rep. SC–4673 (RR), Sandia Corp., Oct. 1962.

ANON.: Quality Control Manual. QCM 415, Rev. B., Norden Div., United Aircraft Corp., Nov. 1965.

AUSTIN, PHILIP R.: and TIMMERMAN, STEWART W.: Design and Operation of Clean Rooms. Business News Publ. Co., 1965.

FLINN, L. F.; and GOSMA, J. B.: General Dynamics/Pomona Crossflow Clean Room, Mar. 1963.

GIBSON, WILL: Design of an R & D Clean Room Complex for Guidance and Control Systems. Presented at the Fourth Annual Technical Meeting and Exhibit, Am. Assoc. Contamination Control, Miami Beach, Fla., May 25–28, 1965.

LINDEKEN, C. L.: Selection, Installation and Maintenance of White Room Filters. Air Engineering, Feb. 1963.

OFFICE OF MANNED SPACE FLIGHT: Handbook for Contamination Control on the Apollo Program. NHB 5300.3, NASA, Aug. 1966.

PATNOE, C. L.: Clean Room Wall Built of Blower-Filter Modules. Plant Engineering, Aug. 1965.

WHITFIELD, W. J.: The Basic Function of a Clean Room. Sandia Corp., 1967.

Clean Room Personnel

ANON.: Improved Techniques Handle Clean-Room Problems. SAE J., vol. 72, no. 3, Mar. 1964, pp. 54–59.

GUVURIN, E. J.: The Role of Human Factors in Whiteroom Manufacturing Reliability. Presented at the Seventh Military and Industry Missile and Space Reliability Symposium, San Diego, Calif., June 18–24, 1962.

LEVENSON, H. J.: Clean Room Rules at Norden Division. J. Am. Assoc. Contamination Control, vol. 2, no. 8, Aug. 1963, p. 14.

NITSCHKE, WERNER R.: Considering the Human Factor in Clean Room Environments. Paper AD68–351, Am. Soc. Tool & Mfg. Eng., 1968.

SINAIKO, H. WALLACE, ed.: Selected Papers on Human Factors in the Design and Use of Control Systems. Dover Publ., Inc., 1961.

Glossary of Clean Room Terms

ANON.: Clean Room and Work Station Requirements, Controlled Environment. Federal Standard No. 209, Dec. 16, 1963.

ANON.: Definitions for Contamination Programs. Standard C–1, NASA Manned Spacecraft Center, Aug. 1966.

ANON.: Quality Control Manual. QCM 415, Rev. B, Norden Div., United Aircraft Corp., Nov. 1965.

AUSTIN, PHILIP R.; and TIMMERMAN, STEWART W.: Design and Operation of Clean Rooms. Business News Publ. Co., 1965.

U.S. GOVERNMENT PRINTING OFFICE: 1969 O—350–354