G. DONALD WAGNER, PAUL R. FALK, and LAWRENCE H. MURPHY

ENGINEERING DESIGN AND ELECTRONIC FABRICATION FACILITIES IN THE STEVEN MULLER CENTER FOR ADVANCED TECHNOLOGY

The design, planning, characteristics, and capabilities of the new engineering design and fabrication facilities within the Steven Muller Center for Advanced Technology at the Applied Physics Laboratory are described. The Center provides a broad range of design, engineering, and electronic fabrication facilities to serve the Laboratory. The special requirements of these facilities for modern operations significantly influenced the design and construction of the Center and make it a unique building on the APL campus. Occupancy and operation of these facilities represent a major advancement for the Engineering and Fabrication Branch and will serve the Laboratory well into the twenty-first century.

INTRODUCTION

The Applied Physics Laboratory has a long tradition of designing, developing, fabricating, testing, and fielding hardware to fulfill its mission. Although many of these functions are distributed throughout the Laboratory, hardware design and fabrication were previously focused in Butler buildings 13, 14, 16, and 41. These structures, originally erected in the 1950s, were contiguous rows of World War II surplus steel buildings. Figure 1 is a photograph of the area with the old buildings identified. Most of APL's electronic design and fabrication facilities were housed in buildings 13 and 16, while most of the mechanical design and fabrication facilities were located in buildings 14 and 41. The advent of modern computer-aided design (CAD) and fabrication tools in the 1980s highlighted the need for APL to update its technology, equipment, and facilities. Furthermore, the miniaturization of electronic devices and many space electronic, mechanical, and optical systems required assembly and fabrication under new levels of clean environmental conditions. The absence of clean room facilities for certain electronic fabrication processes was a significant deficiency.

In the mid-1980s, as part of the Laboratory's long-range planning activity, modernization schemes were developed and initiated for updating technology and equipment. In addition, the plans called for updating the facilities, planning new buildings, and creating more clean rooms. New CAD facilities, computer-aided engineering (CAE) workstations, computer-aided processing equipment, and numerically controlled and computer numerically controlled machine tools were also envisaged. Included as well were the addition of new processes for printed wiring board manufacture, microelectronic plasma processing, new photoplotting capabilities, new photolithography processes, laser micromachining, electronic discharge machining, new plating capabilities, sheet

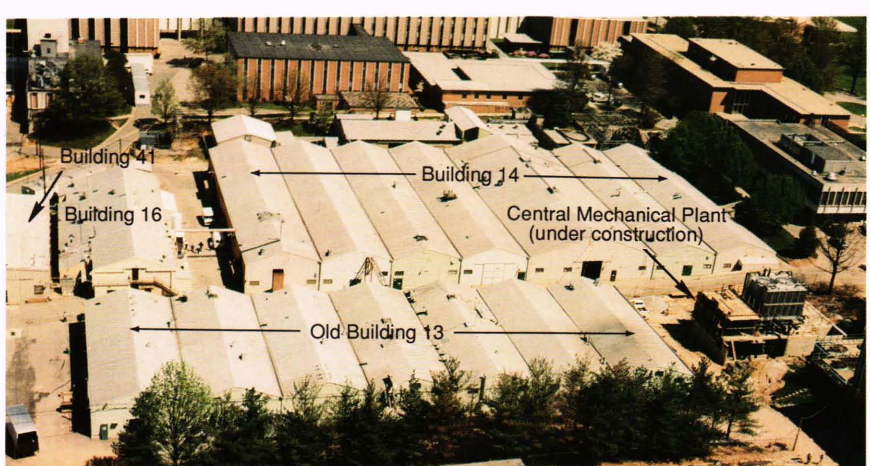

Figure 1. Old Building 13 with other buildings identified.

metalworking processes, and many other capabilities APL will need to remain technologically competitive in the decades ahead.

These long-range plans were presented to the University's Board of Trustees in 1984.[1] The initial phase included plans to replace Butler Building 13 with a new three-story structure to house the Engineering and Fabrication Branch offices, laboratories, and fabrication facilities. Subsequently, to maximize the use of the land and basic structure, floors 4 and 5 were added. The size of the structure was roughly constrained by the original footprint size of the previous structure, and the height was consistent with Howard County guidelines and surrounding structures. Eventually a plan evolved that allowed the floors to be aligned with those of Building 6 so that the buildings could be connected by two bridges.

The formal design of the building was begun in 1984 with the design team of James Goldstein & Partners as the primary architects; Henry Adams, Inc., as the heating, ventilation, and air-conditioning systems (HVAC) and mechanical and electrical (M&E) engineers; Whitman Requardt and Associates as the structural engineers; and the Whiting–Turner Contracting Company as the construction manager. Laboratory personnel worked closely with this team to design and create APL's largest and most complex building.

INITIAL DESIGN CONSIDERATIONS

Originally, the intent was to include only design fabrication facilities to upgrade and modernize APL's outmoded fabrication facilities. A long-range strategy was developed to replace Butler buildings 13 and 14 with modern buildings to house the design and fabrication facilities and also to provide further space for other APL organizations being displaced by the destruction of those buildings. The plan was to proceed in two phases: replace Building 13 first, then Building 14. In March 1984, approval and authorization to proceed with phase 1 of the replacement of Building 13 were given by the Executive Committee of the Board of Trustees. Tax-exempt financing was received from the Maryland Health and Higher Education Facilities Authority. The second phase calling for the replacement of Building 14 has not yet begun.

Since Building 13 had to be demolished before the start of new construction, temporary space had to be found for its occupants. A solution was found in Building 24, which was nearing completion at that time. By delaying occupancy of the planned residents of Building 24, it was possible to temporarily move the future occupants of Building 13 into Building 24. This move occurred in the spring of 1987, and Building 13 was demolished in ten working days with the assistance of one skillfully operated giant claw-like demolition machine (Fig. 2). Subsequently the site was prepared, and the new building, the Steven Muller Center for Advanced Technology (SMCAT), started to rise. Construction of the Central Mechanical Plant (CMP) at the south end of the structure had begun in late 1986 (see Fig. 1). The CMP contains the ice plant systems and heat pump systems needed to serve the SMCAT. It also offers some additional utilities for buildings 1, 6, and 14.

Figure 2. Demolition of old Building 13 circa June 1987.

Following many hard working sessions, a design emerged that included the following major facilities on floors 1 through 3 of the SMCAT:

- Microelectronics Laboratory
  - Hybrid Circuit Laboratory
  - Surface Mount Solder Laboratory
  - Electronic Design and Testing Laboratories
  - Thin Film Laboratory
  - Thick Film Laboratory
  - Photolithography Laboratory
  - Photo Reduction and Photo Plotting Laboratory
  - Vacuum Deposition Laboratory
  - Microwave and MIMIC (microwave/millimeter-wave monolithic integrated circuit) Development Laboratories
  - Other general-purpose microelectronic facilities
- Electronic fabrication and test facilities
  - Printed circuit board fabrication facilities
  - Solder assembly clean rooms
  - Electronic Welding Laboratory
  - Wire wrap facility
  - Encapsulation (Potting) Laboratory
  - Harness and cabling facilities
  - General-purpose electronic assembly facilities
- Materials Laboratory
  - Mechanical Testing Laboratory
  - Metallurgical Laboratory
  - Chemical Analysis Laboratory
  - Scanning Electron Microscope Laboratory
- Quality assurance facilities
  - Electronic inspection facility
  - Calibration and Standards Laboratory
  - Configuration Management Center
  - Project Coordination Center
- Computer-aided design and drafting facilities
  - Workstation areas for CAD/CAE
  - Central facilities for networking stations, peripherals, network management, and so on
- Document Storage Vault for storage of engineering drawings and CAD tapes
- Staff offices, including special training rooms for CAD/CAE operators and engineers and for Quality Team activities

Floors 4 and 5 were to be designed for general APL office or laboratory space using the nominal 150-ft^2 module (standard APL size) or multiples thereof. These were subsequently assigned to the Naval Warfare Analysis Department, Fleet Systems Department, and Computing Branch of the Technical Services Department.

With our detailed knowledge of the occupancy plans, the design of the building focused on the needs of the many special-purpose laboratories, which made the design and construction of the SMCAT unique. Specifically, attention needed to be focused on clean rooms, laboratory utilities, and special equipment needs.

Clean Rooms

Clean rooms are identified by class number: 1, 10, 100, 1,000, 10,000, and 100,000. The clean room class refers to the maximum number of particles greater than 0.5 μm that can be found in 1 ft^3 of air within the room. For example, a class 1,000 clean room can contain no more than 1,000 particles, 0.5 μm in size or larger, per cubic foot of air. (See Ref. 2 for a more complete description of clean room terminology.) The Laboratory has previous experience with clean rooms in The Richard B. Kershner Space Integration and Test Facility.[3] An introduction to the terminology and construction of clean rooms is also presented in Refs. 3 and 4 and will not be repeated here.

Special Requirements

Previous experience with the microelectronic laboratories at APL led us to focus initial considerations on establishing laboratories with an abundance of utilities able to meet general needs, but also capable of modification to meet changing needs. In addition to the normal requirements of establishing floor space, heating, cooling, and so on, special attention was given to the following:

- Low-vibration work sites
- Temperature, humidity, and static control
- Utility requirements for liquids
  - Hot and cold water
  - Deionized water
  - Liquid nitrogen
  - Process cooling water
- Utility requirements for air and gases
  - Compressed air
  - Vacuum lines
  - Nitrogen gas
  - Process gases and purity
  - Exhaust and fume requirements
- Electrical power requirements
- Computer networking
- Screen room and special grounding requirements

FINAL DESIGN RESULTS

The final building design was accomplished and basic construction completed in late 1989 and early 1990. Some general facts describing the SMCAT building were reviewed by Arthur C. Stucki in the *McClure Center Magazine*.[5] Floors 5, 4, 3, and 2 were occupied at that time in the order noted. Outfitting of the special laboratories continued until completion in late 1990 when the first-floor laboratories were occupied. Figure 3 shows the final exterior. The building is reinforced concrete; the exterior walls consist of 1/4-in. spandrel glass and aluminum sheathing to create a modern attractive structure gracing the APL skyline. The overall dimensions of the structure are 324 ft long by 114 ft wide and 60 ft high, not counting the HVAC penthouse, which adds an additional 19 ft to the central one-third of the building. The concrete structure was designed in three sections (north, center, and south), each vibration-isolated. The CMP is also a separate structure; its machinery is carefully isolated to minimize transfer of vibration to the SMCAT. Since the HVAC penthouse is in the central section, the lowest vibrations were expected in the ends of the structure. Actual vibration measurements, taken with most of the building systems operational, have demonstrated displacements and accelerations lower than the APL specifications (horizontal and vertical displacements, ≤0.25 μm over a frequency range of 0.1 to 30 Hz; maximum acceleration, 0.001 g between 30 and 200 Hz).

A simplified exploded view of the SMCAT depicting general laboratory assignments is shown in Figure 4. The laboratories generally occupy the central core area of the building, and personnel office areas occupy the outer perimeter. Placement of the laboratories in the core area gives them optimal access to the required utilities; placement of the offices on the perimeter provides them with daylight windows.

Local terrain required that the first floor be at ground level on the east side and gradually slope below ground level on the west side. This design worked well since it allowed for an additional at-grade entrance with loading dock to be incorporated at the southwest corner of the building on the second floor. This entrance was desirable for transporting satellite structures and other large items of hardware and equipment into the engineering and fabrication facilities.

The Document Storage Vault, designed to meet the requirements of the National Fire Protection Association

Figure 3. The Steven Muller Center for Advanced Technology.

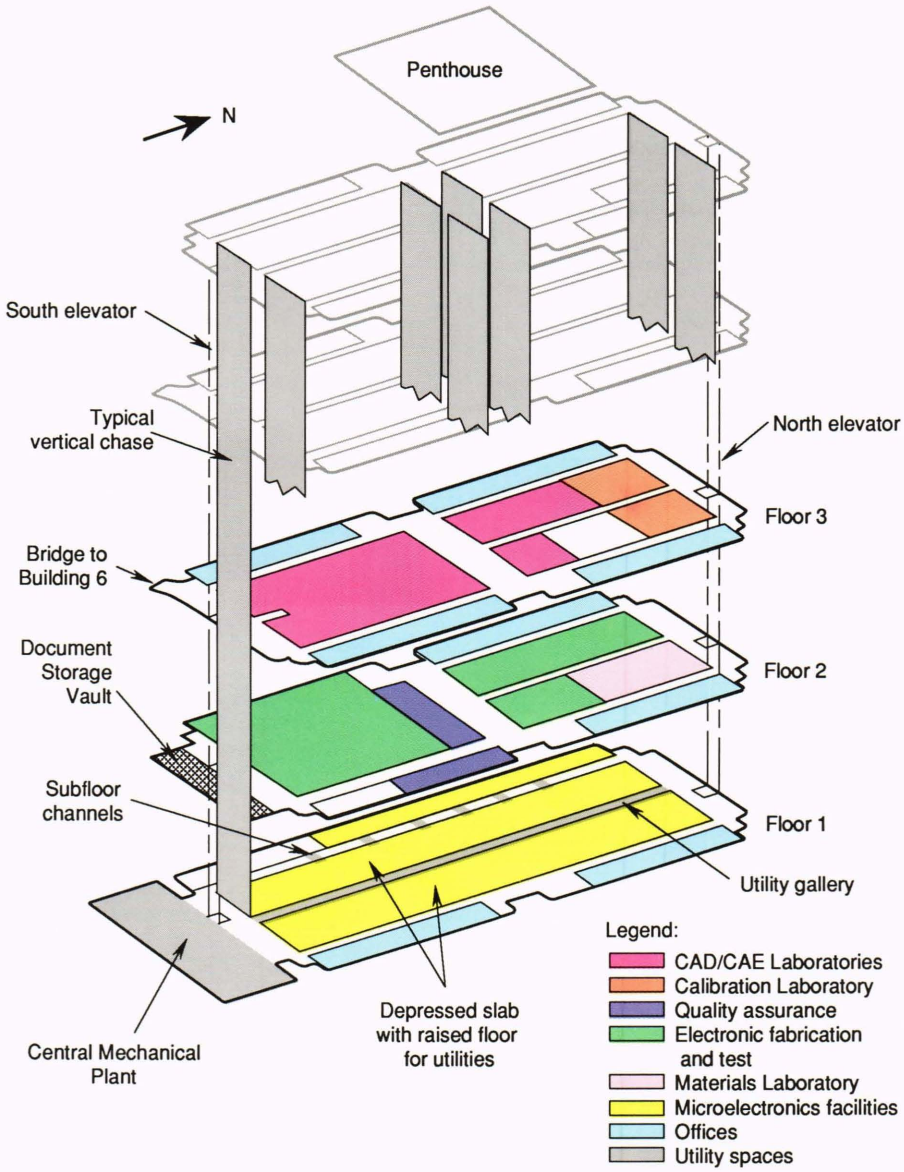

Figure 4. A simplified exploded view of the new Building 13 depicting general laboratory assignments on the first three floors.

Table 1. Clean room parameters.

Floor level	Clean room class	Area (ft^2)	Required air changes/hour
2	100,000	8,000	22
1	100,000	5,800	22
1	10,000	5,000	67
1	1,000	1,200	150

(STD-232-1980 for Class A "Vital Records"), was constructed atop the CMP. The vault is an all-concrete structure (fire rating, 4 hours) and is further protected by a Halon fire protection system. The space (10,404 ft^3) is intended for storage of original manual drawings, CAD drawings and tapes, aperture cards, and other valuable engineering documents.

Forty clean rooms are housed within the facility, comprising about 20,000 ft^2 of floor area (see Table 1). The design of the clean rooms offered the greatest challenge to the architects, HVAC engineers, construction managers, and potential APL occupants. Many trade-offs regarding interstitial height, utility space, construction materials, clean construction practices, air change requirements, energy losses, differential air pressures between adjacent rooms, and other considerations were necessary. Ultimately, a compromise was reached, and a vertical-flow conventional clean room design was used throughout the facility. Figure 5 shows the fundamental design concepts used throughout the Building 13 clean rooms; the partition details are also shown. Steel studs and foil-backed gypsum are used to create clean air returns to eliminate redundant duct work. Small channels between the steel studs are used for utility conduits, electrical wiring, and so on.

Rooms in Building 13 are environmentally controlled by a variable-volume dual duct system zoned for the specific occupancies. Primary cooling is supplied by a combination of an 8400-ton-hour ice storage system (at

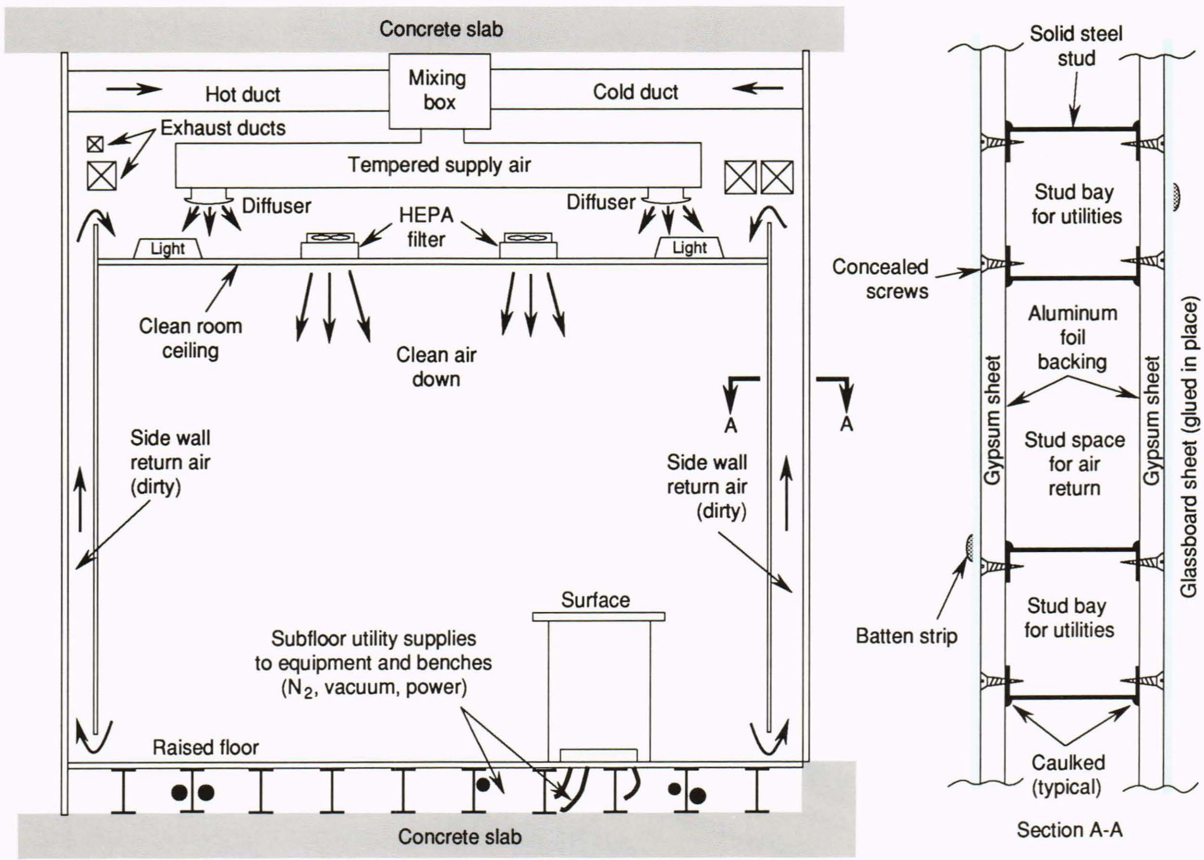

Figure 5. Clean rooms in Building 13: simplified cross section (HEPA = high-efficiency particulate air) (left); horizontal cross section through clean wall section (right).

the south end of the CMP) and two 500-ton centrifugal chillers within the CMP. The primary cooling water temperature is 36°F, which allows for reduced pipe and duct sizes in the building in comparison with a normal cooling system. Primary heating is provided from heat pumps in the CMP that reclaim heat from the condenser water rather than reject it at cooling towers.

The air system involves eight air-handling systems; two provide heating for office areas, four provide cooling for office areas, and two are dedicated to the clean room areas, supplying both cooling and exhaust makeup air.

The two clean room air-handling units field 70,000 ft^3 of air per minute, a portion of which is maintained at 42°F to cool the rooms. The remainder is maintained at 70°F to provide makeup air to the exhaust systems. Clean room high-efficiency particulate air (HEPA) filtration is furnished by ceiling-mounted fan/filter modules in each room, the number of units depending on the room classification and exhaust requirements. The 290 HEPA filter units in the facility have a total air capacity of 264,000 ft^3 of air per minute. The small HEPA filter units are located in the interstitial ceiling space at the suspended ceiling level and are driven by 1/3-horsepower fans. The number of ceiling filter units is selected to tailor the clean room class to the required number of air changes per hour listed in Table 1 (e.g., a class 100,000 room requires a few HEPA filter units; a class 1,000 room requires nearly a full ceiling complement of units). This system will allow APL to upgrade or downgrade a clean room class by adjusting the number of HEPA filter units. Filter units will be replaced as they become saturated with particles. The expected useful life of a filter varies from five to twelve years, depending on the local particulate concentration.

Each laboratory or suite of laboratories is exhausted separately to allow for future modifications without major effect on adjacent spaces. The different types of exhaust (e.g., fume hood, equipment, general) are separated as well.

Another major challenge was the routing of utilities to the laboratories, which was accomplished by a combination of a depressed floor, vertical chases, and a dedicated utility gallery in the center of the first floor. This gallery serves as the major utility trunk by allowing direct access to all laboratories adjacent to it. Access to the second floor laboratories is also possible through twenty-four openings in the concrete floor (each opening is 4 in. × 10 in.). Since the gallery lies directly below the second-floor central hallway and the openings are on both the east and west sides of the gallery, they can readily serve all central laboratories on the second floor. The gallery is not a clean area, and therefore equipment not allowed in a clean room can be installed there and connected through the wall to the adjacent clean laboratories.

Several utility rooms are also appended to the gallery to house toxic gas cabinetry, nontoxic gas tanks, roughing pumps, a chilled water system, and other items not allowed in clean rooms. Figure 6 is a photograph of the gallery showing a typical installation of roughing pumps and some of the plumbing lines. All piping, ducting, wiring, and so on, have been clearly labeled for easy access.

Fourteen vertical chases were designed to permit further vertical connection of utilities, air-handling ducts, fume hood ducts, and other intrafloor piping and wiring. About 100 wooden chase doors on each floor provide easy access to these areas for troubleshooting, repair, or future modification.

The area within the central core of the first floor has been excavated 18 in. below grade to allow for the use of a raised floor in this most utility-intensive area. This depressed floor area allows further access to the entire central laboratory area with all types of utilities. The west corridor includes subfloor channels to extend utility access to the laboratories on the west side of the first floor. Figure 4 schematically shows the potential routing channels for utilities throughout the SMCAT.

The facility uses several process gas and water systems. A central liquid nitrogen system (3000-gal capacity) is provided adjacent to the building. The nitrogen boil-off from the liquid system supplies pure (99.999%) gaseous nitrogen to the facility. Many high-purity gases are used. High-purity gas piping systems are typically 316L stainless steel welded tubing. Coaxial double-wall 316L tubing is provided for the appropriate gas systems to yield the safest conditions.

Two central oil-free air compressors, each with a capacity of 200 standard cubic feet per minute (SCFM) at 125 psig, are available for Building 13. A central vacuum system includes two water-sealed pumps with a capacity of 39 SCFM each at 19 in. of mercury.

The pure water requirements for the clean room areas are met by a central reverse osmosis (RO) system with a storage capacity of 1200 gal. The RO processed water resistivity is greater than 0.2×10^6 Ω·cm. A continuously recirculating pumping system helps to maintain purity levels. A deionized water system further treats the RO water to yield 18×10^6 Ω·cm water. This system also has a continuously recirculating pumping system with a 20-gal/min capacity. Recirculating-type faucets used in high-purity water systems reduce the contamination caused by stagnant water in dead-end piping. A central process cooling water system, circulating 80 gal/min and maintained at 60°F, is available for those pieces of process equipment requiring water cooling.

Each room has its own environmental control thermostat. Additional cooling, heating, and humidification units are located in areas requiring tighter environmental control.

Lighting has been designed to accommodate various tasks and ranges from 50 to as high as 200 fc for selected tasks. Red and yellow filters are furnished in various areas for photosensitive materials. Special low-glare lighting in the CAD areas is also available. Sealed clean room lighting fixtures in class 1,000 and 10,000 rooms have been provided.

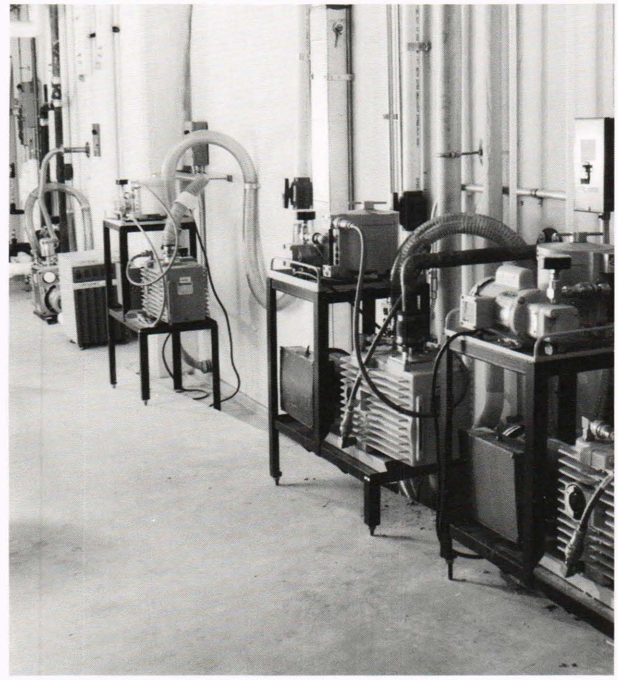

Figure 6. Utility gallery on the first floor of the Center.

The SMCAT has a higher than usual electrical power density: over 25 W/ft^2 available, including lighting, equipment, and HVAC loads. The HVAC electrical loads are separated from other equipment for noise isolation. Isolation transformers have been provided for the variable-speed drives. Chillers are on their own transformers. The facility has been designed for maximum flexibility. Voltages of 120, 208, 277, and 480 are available on all floors. Multiple specialty services include drop cords, power poles, surface raceways, and isolated and phased circuits throughout. For future modification, each laboratory has its own panelboard so that a change in one laboratory will not affect other areas.

For maximum flexibility in the future, a single coordinated grounding system was installed throughout Building 13. At the base of the system is a large ground grid, which uses chemical-type electrodes for low-resistance grounds and a design that does not form any complete loops. The resistance of the ground grid is less than 1 Ω, which should be low enough for any application.

Separate ground wires from the ground grid are connected to areas where individual grounds are required (e.g., screen rooms). By running separate grounds up from the grid for each application, noise on the system from other functions in the building can be substantially reduced, while still achieving very low impedances that are possible only with large grids.

A ground bus is in place in one of the chase areas on each floor, tied separately back to the ground grid. This ground bus is used for large equipment not sensitive to electrical ground noise. Equipment that requires special grounding and is sensitive to electrical noise is connected to the chemical ground grid.

CENTRAL MONITORING SYSTEM

The need to preserve the clean environments of the clean laboratories on the first and second floors requires an elaborate strategy of safeguards. Among those safeguards are specialized clean clothing (nonparticulate shedding), air showers, and sticky floor mats, as well as training for personnel occupying the clean facilities, unique cleaning methods, and noncontaminating methods of accomplishing work. Figure 7 shows technicians working in the class 1,000 environment of the Photolithography Laboratory. Despite these measures, a method is required to monitor and collect data to verify that the environmental control systems are performing as required. A Central Monitoring System (CMS) has been designed and installed for this purpose within most of the critical clean room facilities.

The CMS is strategically located at the clean room entrance and is routinely monitored for overall performance of the building's systems. Computer-generated screens are available to facilitate the monitoring task. Figure 8 shows the menu screen used for selection of the data presentation. Many displays are possible that enable the operator to view the entire first floor of the facility and observe alarms, specific values of particulate counts, temperature and humidity data, differential pressures in the clean areas, fume hood and exhaust hood sail switch status (on/off), gas sensor status, alarm summaries, and other operational utility functions. Figure 9 shows the entire first-floor facility map and the locations of the various sensors. Other sensors (differential pressure, exhaust duct flow, and mechanical system status) are accessed via other menus, which are normally displayed in a spreadsheet-style format. Figure 10 shows examples of spreadsheet formats available for the particle count sensors, the toxic gas leak detector, and H_2O leak detectors.

In Figure 10 (top), the actual particle counts ≥0.5 μm and ≥5.0 μm are displayed with the alarm status. All 0.5-μm sensors are in the acceptable range (green status), but two locations (rooms N127 and N137) show an excessive number of particles ≥5.0 μm. In Figure 10 (bottom), the status of the toxic gas and H_2O leak sensors is displayed. The toxic gas sensors are listed individually, and their status is shown by red (alarm condition) or green (normal operations). Detectors for sensing water or other liquid leaks within the raised floor area are listed by room number.

Figure 11 shows some 0.5-μm particle-count data taken from three sensors during a twelve-hour period. Counts at the three sites were low during the midnight to 8 AM period. As the systems were turned on, the APL workers entered; as the activity increased, the particle counts increased. The cause of the major increase at about 11:30 AM has not been identified but could have resulted from the initiation of a dirty process or additional fit-up construction. The system allows for storing these data (up to three months) on the hard disk and archiving to floppy disks. A statistical package also permits the generation of more detailed analyses and a wider range of graphical presentations.

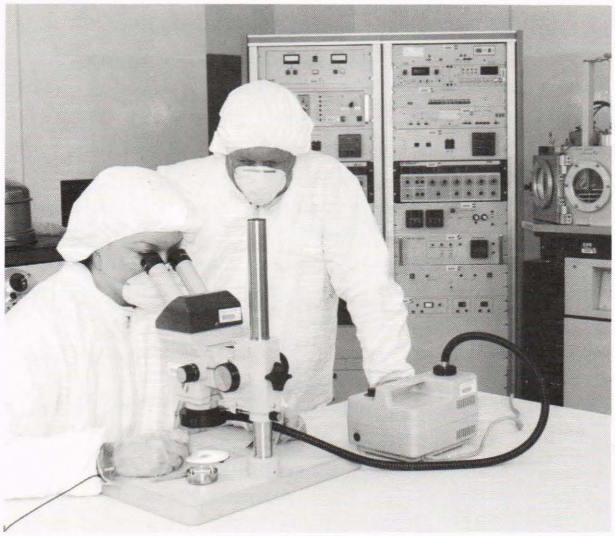

Figure 7. Technicians in the Photolithography Laboratory.

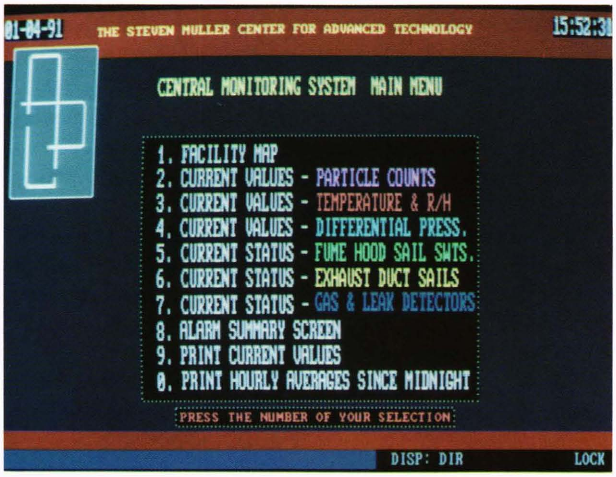

Figure 8. Main menu for the Central Monitoring System.

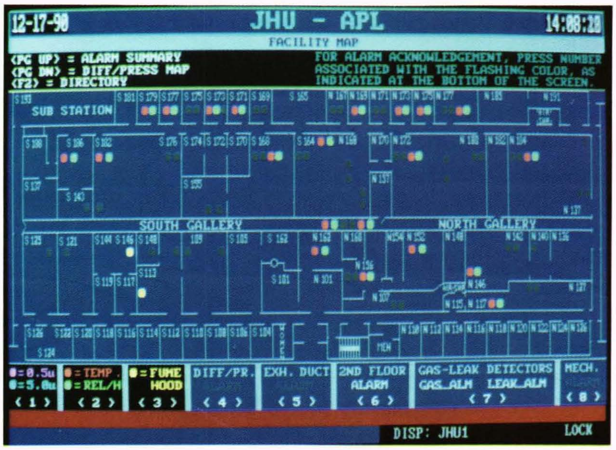

Figure 9. Central Monitoring System showing a map of the first floor.

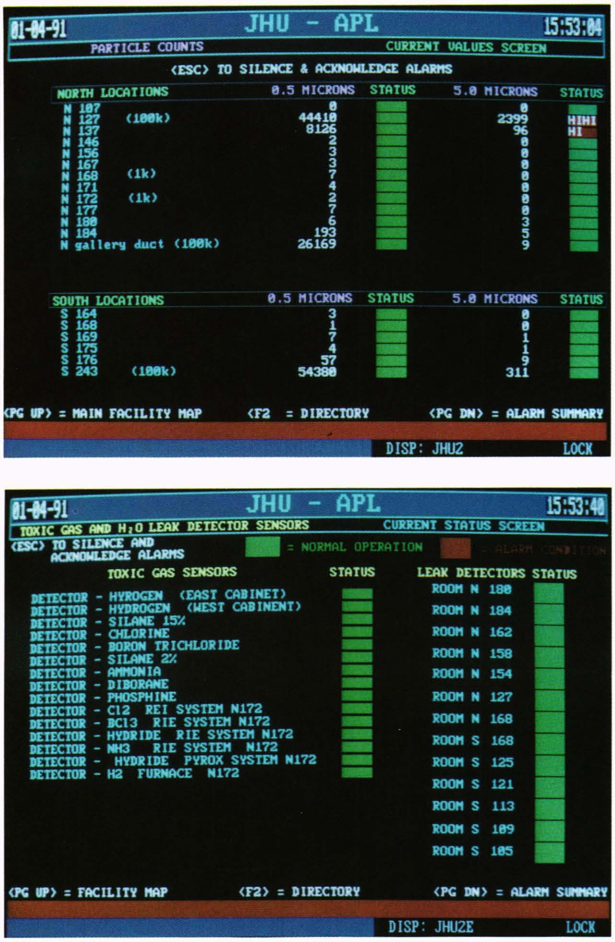

Figure 10. Detailed display of monitored data: particle count display (top); toxic gas and H_2O leak detector status (bottom).

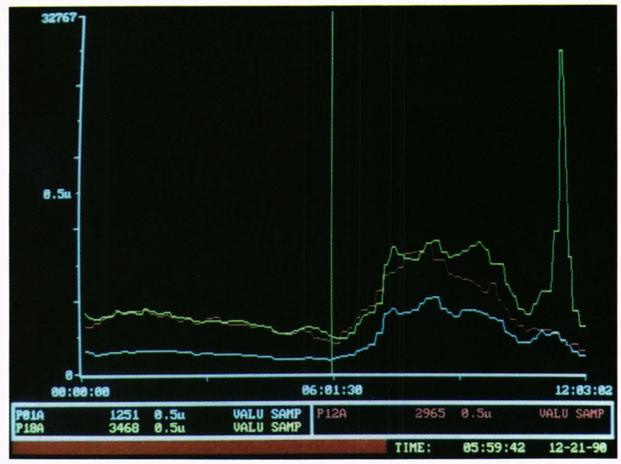

Figure 11. Twelve-hour record of particle counters P01A, P18A, and P12A (corresponding to room numbers) taken on 21 December 1990.

CONCLUSION

The SMCAT is the largest single building on the APL site, with a gross area of 193,000 ft^2. The flexibility and adaptability of the SMCAT will allow easy reconfiguration of the working laboratories as technology progresses. This ability will help APL keep pace with new technologies without the expense and delay caused by having to construct new facilities or completely revamp existing ones. The future of the SMCAT certainly holds the promise of serving the Laboratory into the next century with a new responsiveness f or t echnological growth.

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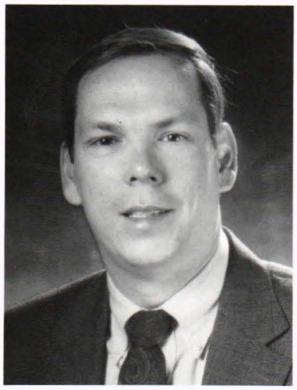

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