Case Study: Design and Construction of the Draper Laboratory Microfabrication Center

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For 25 years, Draper Laboratory has been active in the areas of microelectro-mechanical systems (MEMS) and multichip modules (MCM), using two separate laboratories. When these laboratories were constructed, cleanroom technology was in its mid-life cycle. To meet evolving R&D needs, the cleanroom facilities recently underwent a major renovation as described in this article.

Keywords:
Draper Laboratory, cleanroom, design, ISO Standards, MEMS, MCM

Draper Laboratory is a not-for-profit research and development laboratory located in Cambridge, Massachusetts. The laboratory is focused on the design, development, and deployment of advanced technological solutions in security, space exploration, healthcare, and energy. Since the late 1980s, Draper has been performing research and development in the areas of microelectromechanical systems (MEMS) and multichip modules (MCM), using two separate laboratories.

When these laboratories were constructed, FED-STD-209[1] Class 100 laboratory spaces were common with local Class 10 areas needed to control particles in critical process areas. The MCM lab was Class 10000 with local Class 1000 areas supporting line/space processes of 25 µm. The MEMS lab was Class 1000 with Class 100 areas supporting feature sizes of 2-5 µm.

To meet evolving research and development needs, Draper needed to upgrade its cleanroom facilities. This article presents the rationale used to design a new Microfabrication Center. We discuss the trade-offs required to retrofit a state-of-the-art processing facility into a building constructed in the 1970s, describe how design specifications were defined, explain how we selected an architectural firm and construction manager (CM), and present the role of a Commissioning Agent (Cx). We discuss construction and commissioning aspects of the project, which was completed in September 2012 and became operational in November 2012. We also present data on temperature, relative humidity, and particle counts.

Design Criteria

The Draper Laboratory headquarters building was designed and built in the 1970s and is shaped like a "C." Three "cores," or building sections, are connected in series as shown in Figure 1. A-Core (left) is eight stories; B-Core (middle) is six stories; and C-Core (right) is four stories. A-Core houses the electrical and steam plants on the first floor, while the B-Core penthouse holds the chilled water plant. The new cleanroom was to be located in C-Core.

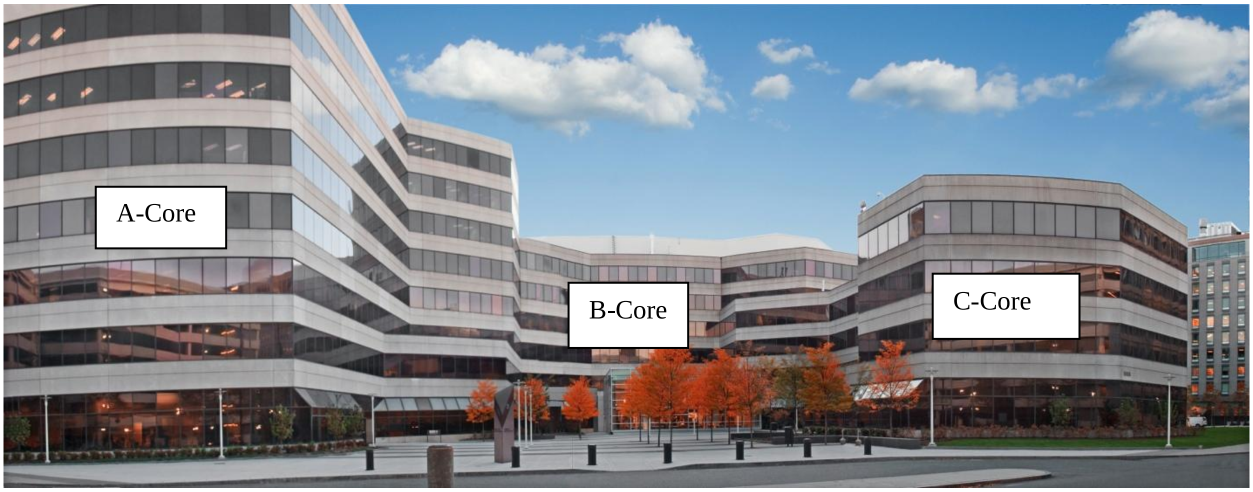

Figure 1—Draper Laboratory headquarters.

The new laboratory was envisioned to support a broad mix of designs and technologies, which led to a design based on functions rather than product flow. Table 1 shows the baseline design requirements.

Table 1 – Baseline Design Requirements for Microfabrication Center

Room Name	Cleanroom Class[a]	Size in ft^2	Floor Type	Temperature/Relative Humidity
Coat	ISO Class 4	360	Raised Floor/ESD Safe[b]	68 °F ± 2 F° / 45% ± 3%
Expose	ISO Class 4	360	Raised Floor/ESD Safe	68 °F ± 2 F° / 45% ± 3%
SEM[c]	ISO Class 6	360	ESD Safe	68 °F ± 2 F° / 45% ± 5%
Develop	ISO Class 5	360	Raised Floor/ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Metal	ISO Class 6	360	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Si Etch	ISO Class 6	360	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Furnace	ISO Class 5	263	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Metrology	ISO Class 6	1525	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Evaporation	ISO Class 6	500	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Sputter	ISO Class 6	366	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Dry Etch	ISO Class 6	515	ESD Safe	68 °F ± 2 F°/ 45% ± 5%
Hall	ISO Class 7	1550	VCT[d]	68 °F ± 2 F°/ 45% ± 5%
Logistics	ISO Class 6	226	VCT	68 °F ± 2 F°/ 45% ± 5%
Gown	ISO Class 7	440	VCT	68 °F ± 2 F°/ 45% ± 5%

[a] Cleanroom Class defined by ISO 14644-1[2]
[b] ESD: Electrostatic Discharge
[c] SEM: Scanning Electron Microscope
[d] VCT: Vinyl Composition Tile

Design Tradeoffs

The headquarters building houses a staff of nearly 1400 and many laboratory spaces, all of which had to remain operational while minimizing disruption of building services, noise, office relocations, impact to abutters, and construction time. The design team reviewed this set of constraints, the requirements listed in Table 1, and the effect of existing conditions on performing the trades.

The first consideration was location of the cleanroom complex within the building; the complex would need easy roof access for makeup air and exhaust. Second, the existing floor-to-ceiling height was only 4.1 meters (13 ft 6 in.). Third, national and local building codes restrict chemical and gas usage on a floor-by-floor basis. Fourth, space was needed for deionized (DI) water and waste water treatment. Lastly, the construction site was a remodel of an existing building; material and personnel delivery required consideration.

After careful analysis, including vibration analysis of the space at different times of day, the team decided to place the Microfabrication Laboratory on the third floor of C-Core. This location allowed easy access to the roof for makeup air and exhaust, space on the fourth floor for electrical room and air chases, and space on the second floor for the DI water plant and reuse of the existing gas room.

Major facility systems, such as chilled water, would have to run from the penthouse in B-Core to the new penthouse on the C-Core roof. Electrical power would have to run from the first floor A-Core electrical room to the fourth floor C-Core electrical room. A new steam plant would be built in the new penthouse on the C-Core roof rather than incur the expense of running the steam lines from the first floor A-Core to the fourth floor C-Core penthouse. By installing a new steam plant we reduce operating cost by not using Draper's main steam plant (which provides heat and humidity control in the cold months) during the summer months. Lastly, the DI water system would be retrofitted and remain on the second floor of C-Core. Waste water treatment would be installed on the first floor of C-Core.

Our baseline design included raised floors, since typical ISO Class 4 rooms have raised floors to ensure unidirectional air flow. However, the low floor-to-ceiling height precluded a raised floor. Therefore, the design team reduced the room width to ensure unidirectional flow under ISO Class 4 and ISO Class 5 conditions and compensated by increasing the length to keep the area the same. The reduced ceiling height and the fact that the cleanroom is on the third floor required the use of fan filter units (FFUs) rather than individual air handlers. Using FFUs allowed placement of one large makeup air unit (MAU) on the C-Core roof, which would be ducted to the plenum space above the cleanrooms. Steam boilers were added to the fourth floor penthouse to reheat the air and control humidity. This common MAU forced all cleanrooms to have identical relative humidity specifications. Table 2 shows the final specification for the cleanroom.

Table 2. Final Design Specifications.

Room Name	Clean Room Class[a]	Size in ft^2	Floor Type	Temperature/Relative Humidity
Coat	ISO Class 4	360	ESD Safe [b]	68 °F ± 2 F° / 45% ± 3%
Expose	ISO Class 4	360	ESD Safe	68 °F ± 2 F° / 45% ± 3%
SEM[c]	ISO Class 6	360	ESD Safe	68 °F ± 2 F° / 45% ± 3%
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[a] Clean Room Class defined by ISO 14644-1[2]
[b] ESD: Electrostatic Discharge
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[d] VCT: Vinyl Composition Tile

Figure 2 shows the completed design of the Microfabrication Center. A total of 1393.5 m^2 (15,000 ft^2) was to be renovated, delineated by the dark line on the drawing. There are four rooms that use DI water and waste water collection: Develop, Metal, Si Etch, and Furnace. These rooms were located together to minimize the DI water piping cost and consolidate drain piping for waste water collection in one area directly above the waste water treatment system located on the first floor. Equipment in the Evaporation, Sputter, and Dry Etch rooms require non-clean space for pumps and compressors. These three rooms wrap around a large chase, which houses the heat exchangers, compressors, and vacuum pumps.

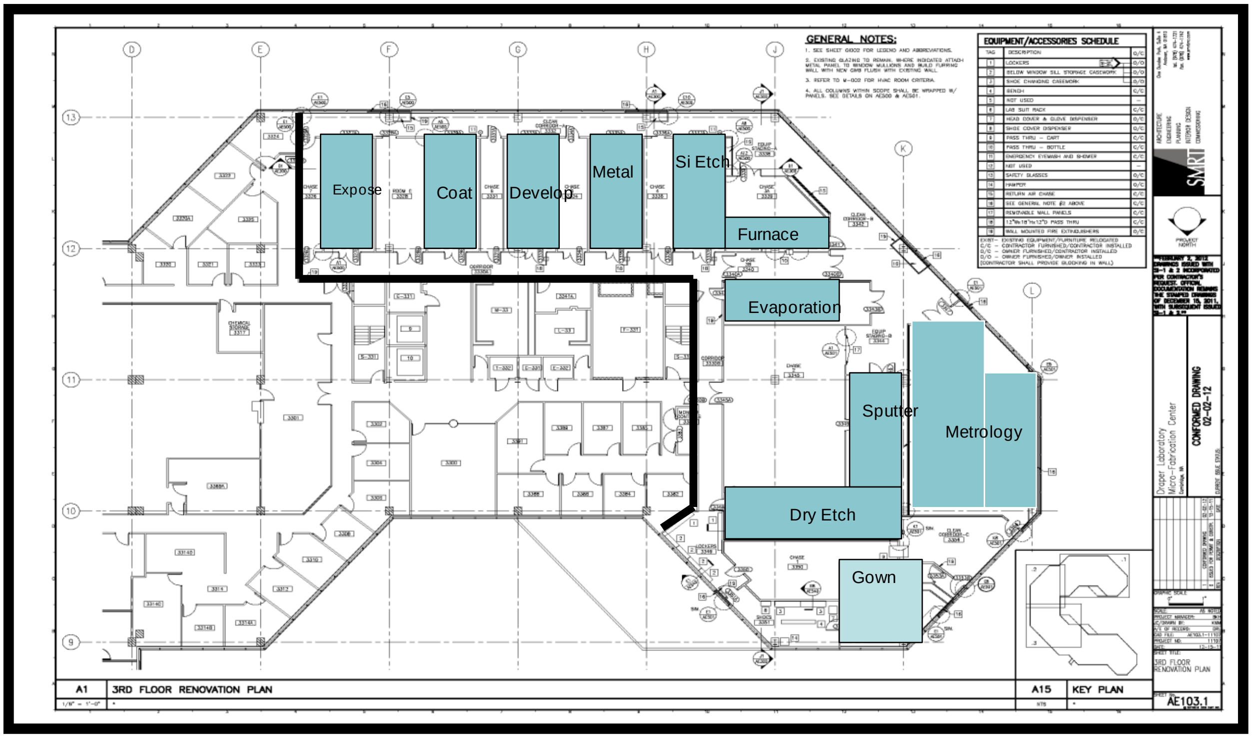

Figure 2—Drawing of the Microfabrication Center.

Design Team Selection

In a typical design-bid construction process, the owner hires an architect and designs a structure, after which bids are sought to estimate the construction cost. If the price is too high, tradeoffs and compromises are made until an acceptable scope and price are achieved. Once this process is complete, a builder is selected and the project starts. Design and construction typically takes 1.5–3 years to complete. Draper's schedule for the project was 18 months.

The engineering team at Draper chose a design-build approach rather than design-bid. In the design-build model, the owner selects an architect and CM as a team working with the owner to design and cost the project. During this design time, long lead items such as makeup air units, exhaust fans, and other special items are ordered in advance. The owner works closely with the design-build team to ensure that tradeoffs make sense and requirements are fulfilled.

To help ensure that requirements were met, Draper hired a Cx. The Cx is an independent engineering company that works for the owner and provides advice during the design, inspects the project during the construction phase, and commissions all the systems at the end of construction. Retaining a Cx adds minimal cost to the project budget and is recommended for any project of this magnitude.

The engineering team created a request for proposal (RFP) using Table 1 as the design basis. The RFP was sent to architect/design firms, stressing that the firms demonstrate a strong background in renovating spaces for cleanrooms. Each firm was invited to tour the facility and submit proposals. After reviewing the proposals, the Draper team selected three firms, invited them to make presentations, performed a reference check and other due diligence, and made the final selection. We repeated the same process for the CM and the Cx.

Cost Control

Once the design is completed and a budgetary price agreed to, the actual cost to the owner must be locked down. Three models are commonly used. The first is a Fixed Fee; that is, the owner has a set of plans and bids are solicited from general contractors prior to project start. While this seems like an inexpensive option, any errors in the design, documents, or conditions, or any modifications to the design, become direct costs to the owner. The second is a Cost Plus model. In this model the CM is paid as work progresses, and changes are billed back to the owner. With this type of project it is extremely difficult to control cost and scope; a good example of a project that was managed with a Cost Plus model is the Big Dig in Boston.[3]

The third cost model is Guaranteed Maximum Price (GMP). In this approach, the owner, designer, and builder agree before construction on the scope and cost of every item in the project. The owner assumes some risk related to possible omissions from the scope, while the designer assumes the risk of ensuring that the design works. The CM is responsible for cost control. This is the most effective model to control scope, time, and cost, provided the owner, construction manager, and designer form a strong, collaborative team.

Project Time Line

The project kicked off in July 2011 and the facilities became operational in November 2012. Figure 3 depicts the project timeline.

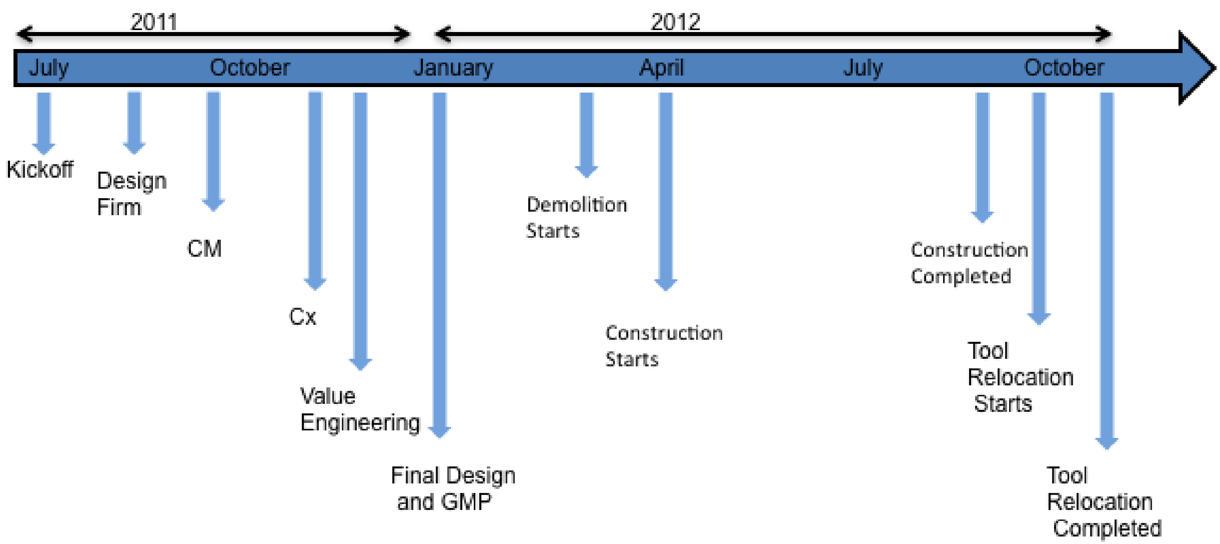

Figure 3—Timeline of the 18-month project.

The selection of the team and design of the new facility consumed 5 months. To vacate 1393.5 m^2 (15,000 ft^2) of office/lab space during construction, 50 people were relocated to temporary sites, and lab spaces were consolidated. This logistical effort started on January 1, 2012, and was completed in 1 month. Demolition of the existing area started in February and consumed 6 weeks. The work was performed in the evening to minimize noise for the employees.

Construction of the cleanroom complex, penthouse additions to the roof, and work on the electrical room started in mid-March and concluded in mid-September. The construction team worked two shifts and weekends to meet the demanding schedule. Issues that arose during the construction phase were dealt with quickly. The owners were on site during the construction phase and met many times daily with the

CM and subcontractors to resolve issues. Weekly meetings of the team were also effective in expediting solutions.

The wall system consisted of corrugated aluminum-clad wall panels running in channels floor to deck. This configuration created a plenum for each cleanroom. Since we did not have individual air handlers for the rooms, we used sensible cooling coils to control cleanroom temperature. The sensible cooling coils were located high on the cleanroom walls (Figure 4).

Figure 4—Installation of the sensible cooling coils and openings for tools.

Chase space and the perimeter corridor were employed to distribute the DI water, nitrogen, compressed air, process vacuum, and process gases (Figure 5). Electrical wiring was run high on the wall to ensure that the bulkhead mounted tools would be below the facilities. The finished Metrology Room is shown in Figure 6.

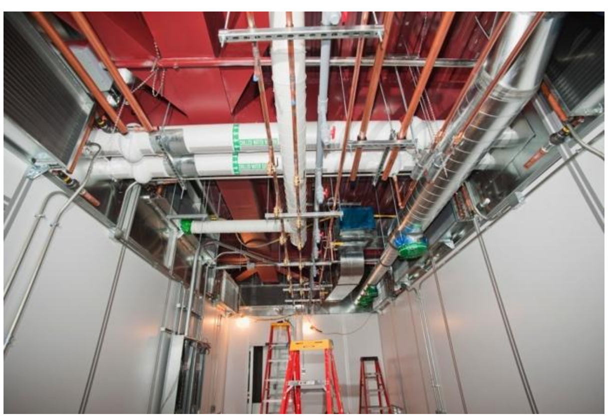

Figure 5—Typical chase.

Figure 6—Finished Metrology Room ISO Class 6.

Cleanroom Operation

The sequence of operation for the new cleanroom complex is as follows: The MAU conditions 679.6 m^3/min (24,000 ft^3/min) of outside air to a temperature of approximately 20 °C (68 °F) and 45% relative humidity; this air is ducted to the plenum spaces above each room. The control system collects relative humidity data from sensors in the Coat, Expose, and Metrology ISO Class 4 and ISO Class 6 rooms. The system uses data from the Coat Room to control relative humidity for the entire complex. Temperature sensors located in each room are monitored by the control system, and a cooling water loop is adjusted at each sensible coil to meet a temperature of approximately 20 °C (68 °F± 2 F°) in each room.

Figure 7 is a schematic of a cleanroom cross-section. Clean airflow is as follows: temperature- and humidity-controlled air is ducted to the plenum space, and the FFU pushes the air into the room in a unidirectional fashion. Air flows down and exits into the chase by return grills. The FFU then pulls the air through the sensible cooling coils for temperature adjustment, and the cycle repeats.

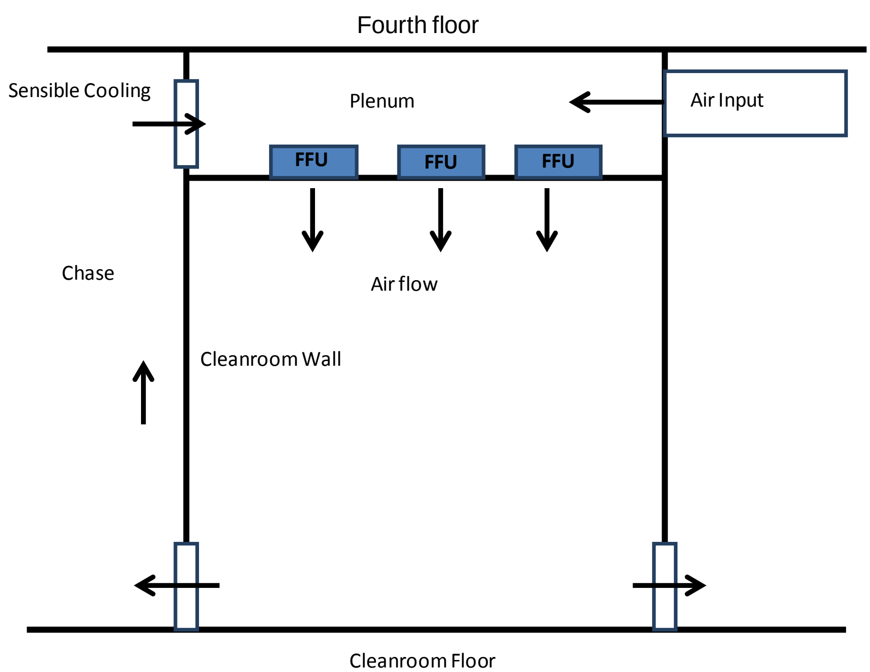

Figure 7—Cleanroom cross-section schematic.

Commissioning of Facility Systems

Commissioning of facility systems commenced in mid-October 2012 and ended in mid-November 2012. The Cx developed a plan and, coordinating with the CM, commissioned all of the major systems. A typical system commissioning would be a team effort consisting of the owner's facility group, CM, manufacturer, and Cx. The unit specification would be crosschecked against the design. The system would then be run and stressed to the design limits. After passing these tests, the unit would be accepted.

Some systems, such as DI water, wastewater treatment, and toxic gas monitoring, are commissioned by the supplier and verified by the Cx. Deviations from the design are noted and fixed. Systems such as exhaust, room pressure, and airflow are tested by balancing firms. Each exhaust drop is measured and adjusted to conform to the tool vendor specification, and total exhaust flow and pressure are adjusted to meet the cleanroom design. The pressure in each cleanroom is measured and adjusted if needed.

Other systems are more complex; therefore, the commissioning process is more complex. Consider the MAU commissioning in the following example: First, the MAU specifications are compared to the design. Then, the installation is reviewed to verify that it follows any special instructions listed in the detailed drawings. Next, the sequence of operations is reviewed and compared to the control software.

The commissioning process can often be complicated by requirements of location and local weather conditions. This project is located in the northeastern United States, where great care must be taken to ensure that water in hot water coils will not freeze due to a boiler or power failure.

The commissioning process for the MAU consists of verifying that all valves and dampers operate. The inputs are then forced to the maximum and minimum operation specifications. Lastly, fail-safe conditions are tested. For example, the steam is shut off, and the valve that shuts off the water to the reheat coil is verified. Once all systems have been commissioned, the Cx issues a report of findings to the owner.

Tool Installation

During cleanroom construction, Draper's engineering team planned the tool relocation. Draper chose this option, rather than outsourcing the process, to reduce cost and maintain control over a very tight schedule. Eight weeks were allotted for tool relocation, during which we would relocate 90 tools, relocate and debug the process vacuum system, retrofit the DI water plant, renovate the gas room, and switch over existing exhaust runs to the new system.

Notebooks were created for each room to help plan the move and estimate costs. Vendor information and photographic records of the existing tools were collected and entered in the notebooks, and these notebooks were used to create a tool matrix. Then the notebooks, tool matrix, and project schedule were sent out to riggers, process piping, HVAC, and electrical contractors to price the tool relocation.

The lab has eight major tools: one photolithographic stepper (Figure 8), two thin film sputtering systems, four dry etch systems, and one thin film evaporator. We decided to have the vendors move these tools, which added about 15% to the budget but also removed a projected 4 weeks from the schedule and reduced overall risk. During the design phase, we discovered that we could improve operations and reduce operating and maintenance costs if we combined existing chemical exhaust streams into the new exhaust systems. However, implementing this change complicated the plan, as the operations of these labs could not be disrupted for any length of time. Further complicating the schedule was coordinating the DI water retrofit, gas room renovations, and process vacuum relocation.

We began to relocate the process tools in mid-September, which started the clock on exhaust, DI water, gas room, and process vacuum. These systems had to be completed in 2 weeks so we could restart the photolithography and wet etch operations (Figure 9). The final tool was relocated and operational by mid-October. During the relocation, we operated functions as they became available, minimizing disruptions to our existing sponsors. Tool relocation was completed in mid-October, with qualification of tools completed by mid-November.

Figure 8—Stepper integration into the wall.

Figure 9—Typical wet bench installation.

Cleanroom Monitoring

Relative Humidity

The DI water system supplies reverse osmosis-grade water to the steam generator. The control system calculates the dew point from relative humidity sensors in the MAU. This calculation is compared to the actual relative humidity in the cleanrooms, and steam from the boilers is used in a steam-to-steam generator to humidify the air stream. The relative humidity in the cleanroom is maintained at 45% ± 3%. Figure 10 shows a 5-hour trend of the Coat Room as provided by the relative humidity sensors in the cleanroom.

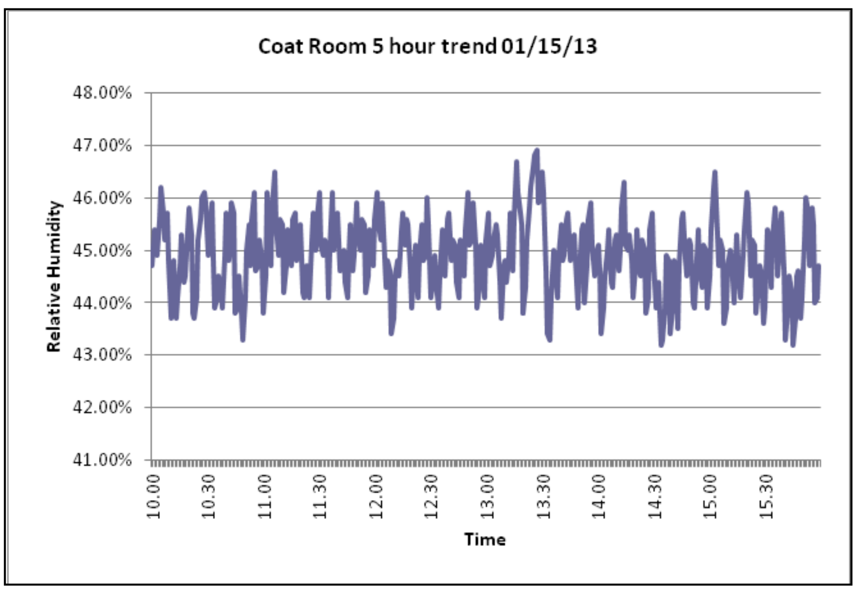

Figure 10—5-hour relative humidity trend of Coat Room.

Temperature Control

The control system reads the temperature in each room, adjusting the water temperature to the sensible cooling coils mounted in the cleanroom walls. The MAU temperature is selected so that the incoming air is at the control set point of 68 °F. Friction and heat load raise the temperature, and the sensible coils maintain temperature control at 68 °F ± 2 °F. Figure 11 is a chart of a 5-hour trend of the Coat Room.

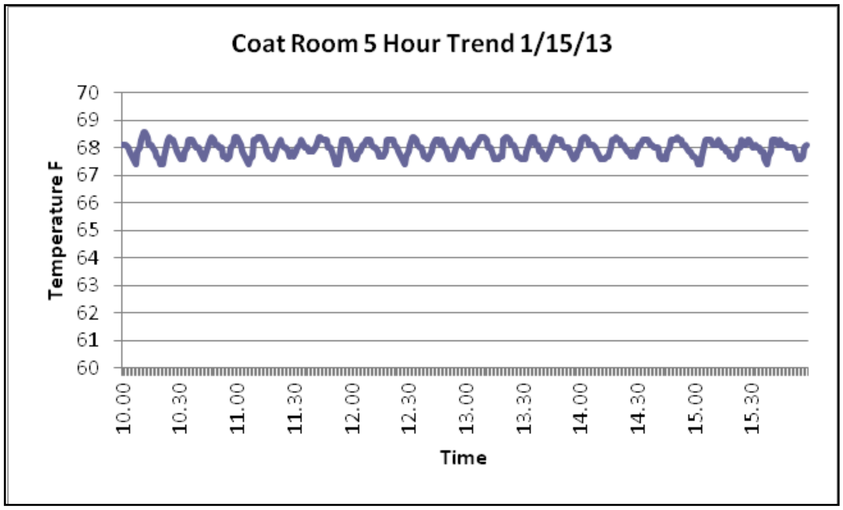

Figure 11—5-hour temperature trend of Coat Room 1/15/13.

Particle Monitoring

The design firm designed each room to conform to standard cleanroom design guides.[4] Table 3 shows the design criteria. The design compares favorably with best practices. Cleanroom certification was performed prior to tool installation, and since that time, engineers have been monitoring particle counts in each room on a weekly basis, using a hand-held particle meter and taking data as prescribed by ISO 14644-1.[2]

Table 3. Cleanroom airflow design criteria.

Room Name	Room Class	Room Volume in ft^3	HEPA Flow ft^3/min	Air Changes Per Hour
Coat	ISO Class 4	3240	20,724	384
Develop	ISO Class 5	3240	15,874	294
Si Etch	ISO Class 6	3240	7280	135
Gown	ISO Class 7	3960	3625	55

Figures 12, 13, and 14 show typical particle count results for the ISO Class 4, ISO Class 5, and ISO Class 6 areas.

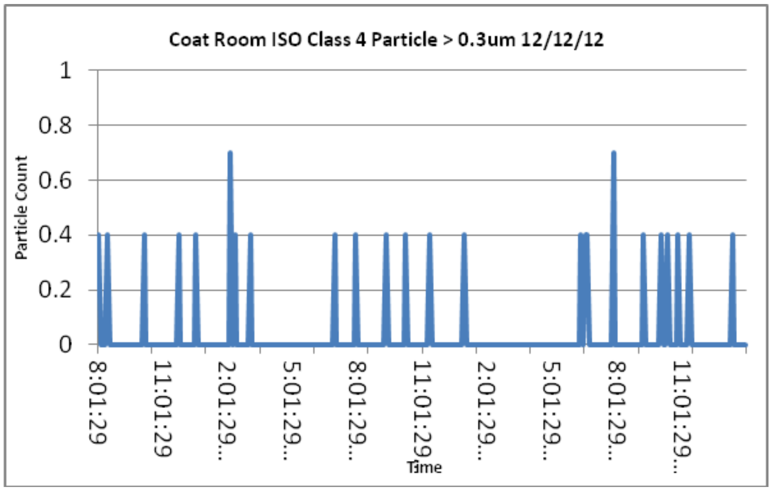

Figure 12—Typical particle count results for Coat Room.

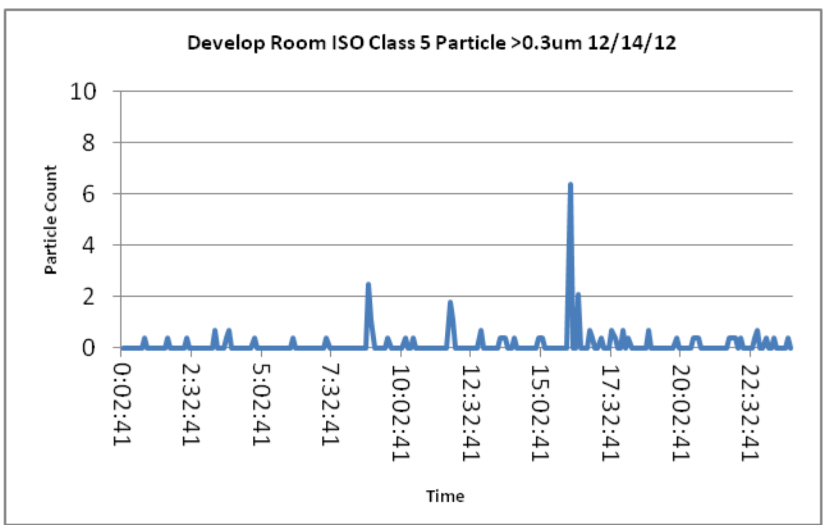

Figure 13—Typical particle count results for Develop Room.

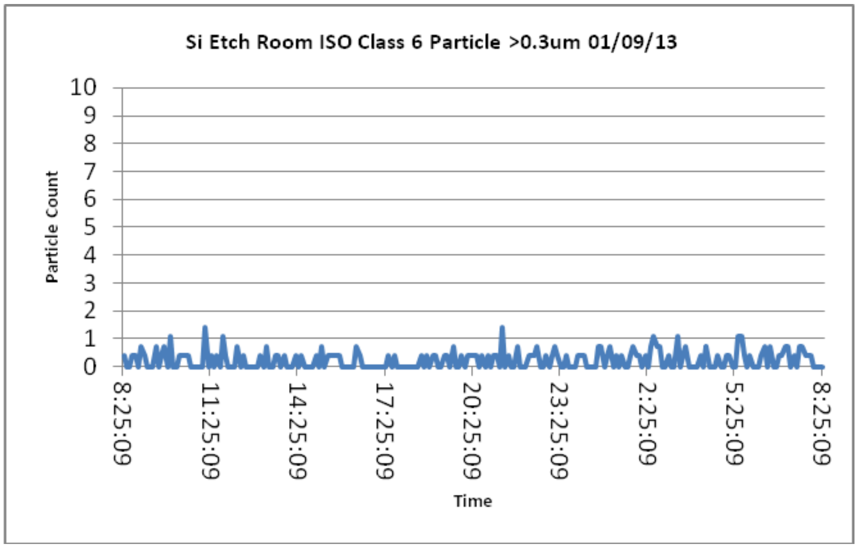

Figure 14—Typical particle count results for Si Etch Room.

Conclusions

The Microfabrication Center project at Draper corporate headquarters in Cambridge, Massachusetts, used a design-build model with a guaranteed maximum price for scope and cost containment. Draper allotted 18 months for the entire project, and the engineering team delivered a state-of-the-art, mixed-use facility in 16 months for a total construction cost of $\$1000/ft^2$. This compares very favorably to the estimated cost of \$1200 to $\$1400/ft^2$.

During this project, Draper learned many important lessons:

- The entire cycle for a new cleanroom complex is long and requires careful planning. There are many stakeholders who must have input, including Finance, Health and Safety, Facilities, Security, Engineering, and others.
- The project must be managed very closely to ensure efficient execution; all assumptions must be documented along the way because project team members may leave the team over the course of the project.
- A design-build model is the most appropriate for this type and scope of project.
- The available budget is usually a key driver in the project design.
- In a remodel, existing conditions will force key decisions on layout and design; be ready to make them quickly.
- Communicate with the stakeholders so that results meet expectations.
- Manage the budget and timeline and beware of scope creep. The GMP model is an effective way to achieve this.
- Final decisions on scope and cost must be made by one person, not a committee.
- Hold at least weekly construction meetings and make decisions quickly.
- Hire a commissioning agent; they are your quality control.

References

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About the Authors

Richard H. Morrison is the group leader of microfabrication operations at Draper Laboratory. He has more than 30 years of experience in process development, pilot production, and production in the microelectromechanical systems (MEMS) and semiconductor industries. This is the fifth cleanroom design project Morrison has installed and commissioned. He received his BSET (1981) and MSTC (2010) from Northeastern University.

Livia M. Racz is the division leader of microsystems technologies at Draper Laboratory. She is responsible for delivering first-of-a-kind microfabricated sensors and systems in the areas of biomedical microelectromechanical systems (bioMEMS), inertial instruments, miniature low power electronic systems, and other areas. Racz received her SB (1989) and PhD (1993) in materials science and engineering from MIT and was the winner of an Alexander von Humboldt Research Fellowship in 1994. As a Humboldt Fellow, Racz worked at the Institute for Space Simulation in Cologne, Germany, on a materials processing experiment that flew on a 1995 Space Shuttle mission.

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