Session No. 721

Implementing Prevention through Design: A Case Study of a Nanoscale-Research Facility

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Introduction

The Birck Nanotechnology Center is a large university facility located in Discovery Park on the campus of Purdue University in West Lafayette, Indiana. The facility was specifically designed for interdisciplinary collaborative research in nanotechnology, with cleanroom and laboratory areas purposely designed to support the specialized equipment necessary for this type of research.

Planning for the facility began in 2001 and the facility was considered fully operational in 2006. While this predated the NIOSH Prevention through Design initiative, the design concepts of the building are representative of PtD principles. The case study of the design of the Birck Nanotechnology Center facility (BNC) demonstrates the methodology necessary in designing a high-technology facility that integrates accident prevention into building design.

This paper will describe the general characteristics of the facility and its operation, the safety challenges inherent in this type of facility, and the motivating factors in adopting Prevention through Design principles. It will then explore the design methodology used to mitigate gas hazards through an in-depth analysis of the design features and their function.

The Birck Nanotechnology Center Facility

The Birck Nanotechnology Center is a 286,000 square foot[1] research facility at Purdue University. Unlike traditional department-owned facilities – generally containing a mixture of classrooms and laboratories – this facility operates across department lines, housing researchers from 35 schools and departments. There are no classroom facilities in the building.

The facility consists of two distinct areas. The office and laboratory area is a "B" rated occupancy containing offices, conference rooms, and laboratories. The laboratories are designed specifically for the type of research that is being supported – biological laboratories (BSL-1 and BSL-2+), deposition/epitaxy laboratories, laser/nanophotonics laboratories, surface-analysis laboratories, electron-microscopy laboratories, etc.

The 25,000 square foot BNC cleanroom, the Scifres Nanofabrication Laboratory, consists of a nanofabrication cleanroom joined to a 2,500 square foot pharmaceutical-grade cleanroom. Pass-through units allow materials to be passed between the cleanrooms without breaking cleanliness protocol. Personnel, however, must exit one cleanroom and re-gown in the appropriate cleanroom garments prior to entering the other cleanroom.[2]

The facility houses fifty faculty with either primary or secondary offices, and approximately 250 graduate students work in the facility. These faculty and students represent 35 schools and departments, creating a special challenge from an EH&S standpoint. Supporting the operation are an engineering staff of 25 people as well as 11 business and secretarial staff.

Another complexity related to EH&S is the diversity of the research. While many nanotechnology facilities concentrate on two or three major thrust areas, the BNC has eight.

BNC Major Thrust Areas
Nanoelectronics and microelectronics
Nanofabrication of NEMS and MEMS devices
Nanophotonics
Materials growth and deposition
Bio-nanotechnology
Nanoscale metrology
Electronic characterization
Theory and computation

The 21,000 square feet of BNC laboratories are arranged as laboratory modules on an 11' x 22' grid, with the facility containing 88 modules in four wings. Each laboratory consists of one or more modules, with the largest laboratory being a seven-module lab. Utilities are run along the outside walls of the laboratories, and multiple-module laboratories have overhead service carriers on 11' centers. Each wing contains two rows of laboratories with an intervening service galley. These service galleys contain all utilities needed in the laboratories as well as vacuum pumps, chillers, etc. that would cause vibration, EMI, or acoustic noise in the laboratory.

The cleanroom has three levels, a fifteen-foot-tall subfab that is separated from the airflow path, the cleanroom level, and an air-handling deck housing the makeup and recirculation air handlers. The cleanroom level has above-the-ceiling air-distribution boxes, and an ULPA-filtered ceiling and a perforated raised floor that stands two feet above the concrete waffle slab. The interior of the cleanroom utilizes a bay-chase design, with air supplied in the ceiling of the bays and returned through the chases. Equipment is bulkhead-mounted through the chase wall, with the operational side of the equipment accessible to the cleanroom and the maintenance side of the equipment accessible from the chase.

Support equipment that would contaminate the airstream, such as vacuum pumps and chillers, are located in the subfab and connected to the equipment in the cleanroom through openings left in the pan of the waffle slab.

Forty-five percent of the cleanroom operates at ISO Class 3 (formerly known as Class 1), forty percent at ISO Class 4, and fifteen percent at ISO Class 5. The vibration level in the cleanroom is within NIST A levels, extremely quiet for a second-floor cleanroom.

Safety Considerations

As with any large, multi-floor facility, the BNC has general safety concerns related to electrical hazards, fall protection, confined-space entry, etc. While all of these hazards were addressed in the design of the facility, only the specialized hazards related to a high-technology research facility will be addressed in this paper. For example, the design of tie-off points throughout the facility were critical for the safe repair of equipment, but this is a standard consideration in all facilities so is not included in this paper.

Operational factors in the Birck Nanotechnology Center provide significant challenges in terms of the safety of those working in the facility. Most significantly, there is a wide range of hazardous materials used in the facility. Hazardous chemicals in gaseous, liquid, and solid forms range from highly toxic materials to pyrophoric and detonable gases. Active biological species in the BSL-2+ category, such as anthrax and e-coli, are also in use. Additionally, nanoscale materials – many with unknown toxicity levels – are generated and used in the facility. Physical hazards are also a major consideration. Optical systems with Class 3B and Class 4 lasers are present in several areas of the facility. Electron microscopes, analytical equipment, and electrical-testing equipment use very high voltages and sometimes high currents. Test equipment using high magnetic and electrical fields, such as a Hall-effect measurement system using an 8 Tesla magnet, provide hazards to personnel with pacemakers and/or other sensitive devices. Finally, the use of liquid helium and liquid nitrogen present thermal hazards to people working in the vicinity of those systems.

Complicating the use of these materials and physical hazards is the diversity of technical backgrounds of the researchers. The strength of the facility is in its collaborative character, but this places biologists in roles where they are working with semiconductor gases and electrical engineers using BSL-2+ agents. The depth of knowledge regarding the handling of these diverse materials is often lacking.

Another complicating factor is the around-the-clock operation of the facility. Graduate students often “go nocturnal” – a significant amount of research in the facility is performed between midnight and 5:00 AM. The cultural diversity of the researchers is also a factor in the implementation of safety programs. English is second (or third or fourth) language to many researchers, and a trainer may be unsure whether a new researcher has fully understood the material presented. Additionally, different cultures have varied attitudes toward obeying rules and reporting mistakes or accidents. Finally, the very creativity that makes graduate students excel often falls at odds with following rules.

All of these considerations are compounded by the fact that this is a public facility on a college campus. Unlike industrial facilities where strict access controls can be enforced, this facility has large public areas that are frequented by children, students, and families.

Prevention through Design

The NIOSH Prevention through Design initiative provides the best solution to this complex set of challenges. In brief, the PtD initiative proposes the utilization of engineering controls rather than relying on operational controls to maintain safety. For example, fixed barriers would be designed into systems rather than requiring the use of personal protective equipment. Another example would be the use of card-access security systems to restrict access to potentially hazardous locations.

Implementing these controls during the design phase of a building, a process, or a product is a key element of the PtD initiative. Early implementation allows for the use of more effective control schemes, as the designer is not constrained by existing architecture, machinery, or processes. Additionally, it is much more cost effective to implement controls early in the design cycle rather than retrofitting existing systems or placing construction change orders.

A one-sentence summary of the goal of PtD is to "Make it easier to do it the safe way!" If building, process, and product designs comprehend safety principles in their early-design stages, controls can be built in that lead people to safe operation. Conversely, if doing something the safe way is awkward and/or difficult, there will always be a temptation present to perform the task in a less-safe manner. PtD tasks the designer to make the easiest way also the safest way.

The implementation of PtD in building design follows these principles. First, the designers must identify safety hazard "potentials" in the early planning stages of the facility. A thorough hazard assessment of facilities, processes, raw materials, finished products, and byproducts must be completed and updated as more information is obtained. The hazard assessment is a living document that is constantly updated during the design process.

Each potential then becomes an opportunity to design engineering controls to mitigate the risk. The use of procedural controls should be avoided, and considered as the "last resort" if appropriate engineering controls cannot be designed into the facility, process, or product. Like the hazard assessment, these engineering controls are updated as new information becomes available and as the design process continues. Changes in the hazard assessment will always foster a review of the control plan.

PtD in the Birck Nanotechnology Center

Although the PtD initiative had not been announced when the design of the Birck Nanotechnology Center was completed, PtD principles were used throughout the design process. A thorough hazard analysis was completed, and hazard potentials were continuously reviewed during the design process.

Since the highest potentials were in the fabrication portions of the facility, the cleanroom facility was designed using the best practices used in the design of a semiconductor manufacturing facility. In addition to following applicable building codes, non-mandatory codes were applied where appropriate. For example, NFPA 318 Standard for the Protection of Semiconductor Manufacturing Facilities was applied to the cleanroom areas of the BNC, even though that code is not mandatory for research facilities. Best practices were also gleaned from

Semiconductor Equipment and Materials International (SEMI), the Santa Clara Toxic Gas Model Ordinance, and documents from the Semiconductor Safety Association (SSA).

Best practices from the pharmaceutical industry were applied in the design of the biological areas. A world-renowned pharmaceutical company reviewed designs and offered methods of designing in safe practices for the biocleanroom facility. The biological laboratories made use of CDC standards and designed-in engineering controls to minimize hazards.

Finally, the facility was designed in full compliance with Purdue University safety and environmental practices. A new program of certification[3] of laboratory facilities at Purdue had just been initiated by the internal Purdue EH&S organization, Radiological and Environmental Management (REM), and the principles of this program were designed into the BNC.

Five major areas of overall building controls were considered. The design of emergency exit paths to quickly and easily route people away from hazardous areas during an evacuation was integrated into the building design, and coupled with a plan to allow the gathering of evacuated personnel in a protected, indoor location. All plans were considered based on worst-case scenarios, such as the evacuation of personnel at 3:00 AM during a bitter Indiana winter. Also designed into the system was a swipe-in, swipe-out card access system for the cleanroom to allow emergency responders to gauge whether any personnel were left in the cleanroom following an evacuation – a potential rescue situation.

Alarm systems were designed to ensure that there was a clear understanding of what actions are required for given situations. A voice-over announcement system was implemented that contains various context-sensitive prerecorded messages that tell personnel – in short, simple terms – what to do in a given situation. For example, a hazardous gas alarm initiates the evacuation horns and strobes and is accompanied by the message, "The toxic gas monitoring system has detected a leak. Please evacuate the building immediately."

The voice-over message moves the reaction to an emergency away from the memory of the person in the facility when the alarm occurs. This attempts to prevent situations where people flee outside the building when the tornado alarm sounds – leaving them in a far more vulnerable condition. In the BNC, the tornado alarm is accompanied by voice-over text that instructs occupants to seek appropriate shelter areas within the facility.

Emergencies are often discovered by personnel working in the facility, not the trained responders. To minimize hazards and shorten reaction time to emergency situations, emergency evacuation pull stations are located throughout the facility. Triggering these alarms shuts down hazardous gas inputs into the building and announces an evacuation.

A key element of PtD in BNC is the building security system. As was previously mentioned, the BNC is a public building on a major university campus. It has three daycare facilities in proximity to the building, and the facility is located amidst a housing complex. Additionally, tour groups of K-12 classes and outside community groups are frequently in the building. These situations make the development of a building security system with appropriate access controls vital in maintaining a safe environment in the facility.

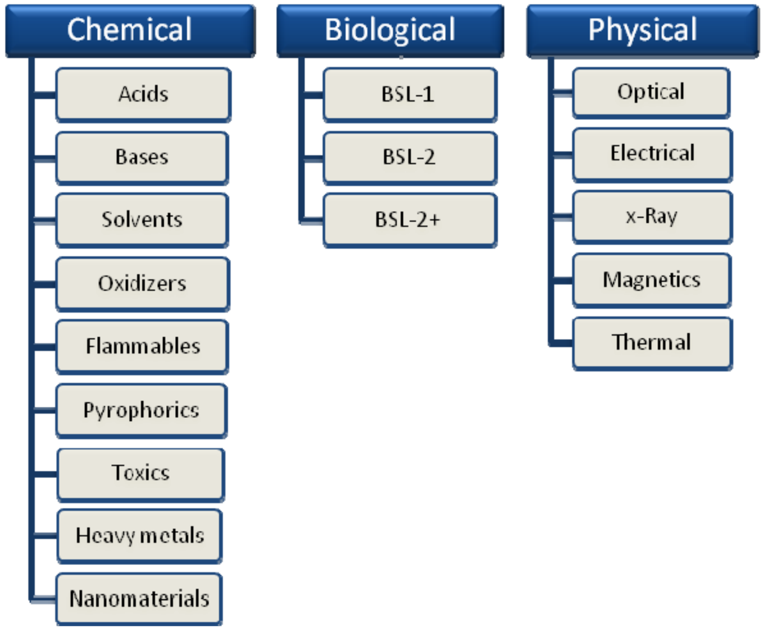
A careful review of potentially hazardous areas of the building was integrated with a review of personnel who needed access to non-public areas of the building. This evolved into a set of access levels based on access needs and training requirements. A combination of card-access levels and issuance of keys was used to allow and deny access, as appropriate.

Programming of the card access system for access to the cleanroom and laboratories also allowed for denial of access on expiration of training or in disciplinary situations. A collection of preset conditions allow for appropriate response to emergencies, such as requiring card-access to the building during an external campus violence incident, such as the Virginia Tech shootings. During emergency evacuations, access to external building doors is via key access only – card access is disabled. At the same time, all interior card-access doors unlock to provide easy access by emergency personnel. Access to the public areas of the facility is also limited to normal business hours – when these areas are generally occupied by BNC personnel.

Closely coupled with the security system is the training system. All building occupants must attend training sessions, the extent of which depends on the desired access levels. Office-only residents – secretarial, business-office, computational personnel, and non-laboratory faculty – receive a short training course covering building emergency response. Completion of this training program allows the issuance of an office key and after-hours public-area access. Faculty who are resident in the facility and supervise students who work in the laboratories or cleanroom receive a more extensive level of training. Students, post-docs, and faculty who actually work in the laboratories and cleanroom receive significantly more extensive training. Specialty programs for emergency responders (fire department, EMTs, police), housekeeping personnel, maintenance personnel, engineering staff, etc. have also been developed and are presented as needed to those groups. In each case, access is dependent on the completion of the training program.

Identification of Hazard Potentials in the BNC

The Birck Nanotechnology Center uses a number of hazardous materials and contains additional physical hazards due to its processing characteristics. The mitigation of standard building hazards were left to the architects – they have ample experience in these areas – but the more specialized hazards were considered by the user group. These were divided into three major categories: chemical hazards, biological hazards, and physical hazards. These were put in a matrix with their status in their life cycle – incoming materials, products, byproducts, and effluents. In the chemical category, the state of the materials was also considered – solid, liquid, or gaseous chemicals. The following chart outlines the three hazard categories:



Of particular interest were the gaseous raw materials. They range from pyrophoric/detonable gases to simple asphyxiants, with different precautions necessary for each category. Of highest concern are the pyrophoric and detonable gases such as silane. Germane, a highly toxic and pyrophoric gas, is also of significant concern. Three flammable gases are in use: hydrogen, dichlorosilane, and methane. Finally, a number of highly toxic gases – such as arsine – provide significant hazard potential.

BNC Implementation of PtD Principles

Chemical Hazards

- Separate Dock
- Secure staging areas
- Special distribution path
- Spill containment
- Emergency exhaust
- Gas detection and monitoring
- Personal protective equipment
- Emergency response consideration

Physical Hazards

- Laboratory security system
- Specialized training prior to access
- Door interlocks for laser laboratories
- Warnings and signs
- Personal protective equipment

Biological Hazards

- Laboratory security system
- Specialized training prior to access
- Negative-pressure laboratories
- HEPA filters in all outgoing air
- Personal protective equipment/easily identifyable

Gas Hazard Mitigation Design

The mitigation of gas hazards was chosen as the example of the implementation of Prevention through Design for the purposes of this paper. Hazardous gases were the impetus for the single most significant PtD effort at the BNC, and are representative of both the principles of PtD and the implementation techniques that were used.

The safety program at the BNC has a clear hierarchy: Prevention => Monitoring => PPE. The goal is to provide prevention programs that consist of engineering controls to eliminate or minimize the hazard. Where these controls are not 100% effective, monitoring systems provide a secondary safeguard, alerting occupants when a potentially hazardous situation occurs. Finally, personal protective equipment serves as a final barrier between the hazard and the individual.

Prevention is the first priority in the mitigation of gas hazards. The first step is to control access to vulnerable areas. A card-access system was developed to separate public spaces from spaces with potential hazards. These potential hazard areas were then classified by access needs and hazard level. For example, very few people needed access to the gas-cylinder delivery cage. This was protected by a distinct lock and key that was accessible to very few individuals. This was also the case for the gas distribution rooms, and a further safeguard with a separate key was designed for the gas cabinets – they provide a high vulnerability point. Camera systems also record the presence of people in those areas to protect against tampering and to document suspicious activities.

The separation of the hazardous materials dock from the general delivery dock removes the hazard of a shared delivery space. People handling heavy or bulky items are not attempting to operate next to people handling hazardous gas cylinders or glass bottles of acids. Those operating on the hazardous materials dock are aware of the sensitivity of that area and behave accordingly. Likewise, people handling routine deliveries and/or large equipment need not be concerned that they are sharing dock area with hazardous materials. This separate dock area also contains an area for the outdoor staging of incoming and outgoing gas cylinders. Codes and best practices highly recommend the staging of these cylinders in an outdoor area, and this location provides security, weather protection, and isolation from routine traffic.

For pyrophoric and detonable gases, further protection is necessary. Calculations, supported by experimentation, have determined that a distance of twelve feet from a silane detonation provides ample degradation of the overpressure wave for human safety. To mitigate the hazards, a special bunker was constructed with three poured-concrete walls, a blow-out wall, and a blow-out roof. Inside this structure are located the gas cabinets for all pyrophoric and/or detonable gases, with a sixteen-foot safety zone created beyond the blow-out wall. The bunker has a locked, explosion-proof door that provides access to a very small number of trained individuals. The gas-cabinet controllers are remote from the bunker, located on the opposite side of the poured-concrete wall. This allows the engineer to be in a safe location while performing purging operations.

For non-pyrophoric/detonable hazardous gases, two gas rooms were constructed. These rooms are accessed from the hazardous material area, but are distinct rooms opening off that area. This provides two levels of security as access to the hazardous material area is limited and a distinct key is needed to access the gas rooms. Each hazardous gas is located inside a gas cabinet within the gas room, with a maximum of two gas cylinders per cabinet. Cylinders sharing a single cabinet must be compatible gases and of like hazard. The gas rooms have explosion-proof electrical components, and flammable gases are in a separate room from toxic gases.

All hazardous gases – gases rated 3 or higher on the NFPA scale in any category – are to be located in gas cabinets within the gas rooms. These rooms are maintained under a negative pressure relative to the hallway and outside world, and the gas cabinets are at negative pressure relative to the room.

These cabinets are automated-purge cabinets with redundant safety features such as excess-flow sensors, reduced-flow orifices, and system-failure shutdown protocols. They utilize high-turbulence construction with high exhaust flow – 200 cubic feet per minute at 0.02 inches of water pressure differential. These are monitored by automated sensors as well as manometers with a visual readout at the cabinet location. All cabinets contain fire sprinklers.

The next area of vulnerability is the distribution piping carrying the hazardous gases to their points of use. The piping used is coaxial stainless steel tubing with an inert gas – argon – filling the interstitial between the tubing. The tubing runs are located in protected areas – in pipe racks and ceiling chases – with control bars (like those in a parking garage) to prevent access by equipment that is tall enough to contact the piping runs.

To back up the engineering controls described above, a dual monitoring system has been implemented. The overall system consists of two sub-systems that are joined together for alarm purposes. One subsystem is a gas-sensing system that draws air from various points, passes that air over a chemically coated tape and looks for a color change on the tape. Tapes are sensitive to specific families of gases, such as hydrides or oxidizers. For gases where the tape technology is inappropriate – such as flammables – pellistor (catalytic) sensors are used.

The sensing system is activated by the presence of the hazardous gas and is able to provide quantitative information. This allows alarm levels to be set by concentration points. In BNC, 50% of the threshold limit value (TLV) for toxic gases and/or 25% of the lower explosive limit (LEL) is used for the warning level, and 100% of the TLV and/or 50% of the LEL is used for the danger level. A warning level triggers a page to appropriate staff members, who will respond to correct the situation. A danger level triggers a building evacuation and alerts emergency responders.

The sensing system is used anywhere outside of the coaxial piping system, such as gas cabinets, valve manifold boxes (VMBs), and equipment enclosures. The sensors are placed in the exhaust ductwork immediately downstream of the potential leak point. This ensures the highest concentration of the gas will be sensed by the system, providing maximum sensitivity in the event of a leak. This design allows the monitoring of the efficacy of the engineering control, preventing the possibility of personnel exposure.

The second subsystem is the interstitial pressure monitoring system. This system monitors the inert-gas pressure in the interstitial between the delivery tubing and the containment tubing. The interstitial pressure is set at 50% of the delivery-gas pressure and the system is sealed. A drop in pressure indicates a leak in the outer-containment tubing. An increase in pressure indicates a leak in the delivery tubing. Either of these incidents triggers a page to the appropriate engineering staff member. A sudden pressure drop to atmosphere indicates a catastrophic failure of a piping run and triggers a building evacuation and activates emergency responders.

In the event of a failure of all other systems – certainly a highly unlikely scenario – a hazardous situation may be recognized by an occupant of the facility. Located at strategic points around the facility are emergency annunciation boxes. These boxes contain a covered mushroom switch – lifting the cover and pushing the mushroom switch shuts down all hazardous gases in the facility and announces a building evacuation. This also triggers emergency responders to come to the facility.

The last level of protection for hazardous gases is personal protective equipment (PPE). For short-term maintenance operations and cylinder changes, self-contained breathing apparatus (SCBA) are used. For longer-term maintenance activities, an air-line cart attached to an SCBA is used. At least two people must be present – buddy system – with both wearing SCBA.

Summary

The Birck Nanotechnology Center accommodates a relatively large population across diverse cultures and technical backgrounds. This provides particular challenges to occupant safety, in that an individual's depth of knowledge may be shallow in certain areas while world-leading in other areas. Cultural differences in dealing with mistakes and accidents also provide challenges to safe facility operation. Additionally, the facility is open to the general public during normal business hours, expanding the number of people in the building at any given time.

The concept of mitigating potentially hazardous situations in the facility design process was an effective way of dealing with these facility-operational challenges. By designing systems and barriers into the initial building design, many of these challenges can be reduced to an insignificant level. The development of redundant elements can eliminate the risks in many cases.

While designed and constructed prior to the Prevention through Design initiative, the Birck Nanotechnology Center in Discovery Park at Purdue University provides numerous examples of the principles of PtD. One example that exemplifies the implementation of those principles is the development of designs that mitigate the risks involved in dealing with hazardous gases. An in-depth look at the design elements used in this mitigation provide an effective case study in the implementation of Prevention through Design.

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[1] Assignable square footage. The facility is 216,000 gross square feet.
[2] The fabrication cleanroom uses an ISO 3 compatible GORE-TEX garment system while the biocleanroom uses a disposable garment system.
[3] This program was originally called "indemnification," with the name later changed to "certification." The program evaluates engineering and procedural controls and audits the compliance to stated policies. Once achieved, and annual recertification is required.