The Birck Nanotechnology Center
Facility Safety Systems

As with any large, multi-floor facility, the BNC has general safety concerns related to electrical hazards, fall protection, confined-space entry, and similar hazards. 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 document. 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 here.

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 Escherichia coli (e-coli), are also in use. Additionally, nanoscale materials – many with indeterminate toxicity levels – are generated and used in the facility. These include carbon nanotubes and nanowires created by physical vapor deposition and graphene films created by epitaxial deposition. 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.

Figure 1: Acid and solvent fume hoods bulkhead-mounted in the BNC cleanroom. Bulkhead mounting equipment allows the separation of the operational side of the equipment (shown) from the maintenance side of the equipment, accessible through the cleanroom chase.

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 a second language to many researchers, and a trainer – generally a member of the engineering staff – 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.

Safety issues are best addressed during the design phase of a project. By designing safety systems into the facility and by considering the safety aspects of all the design considerations, engineering controls can be used to ensure safety rather than relying on operational controls. For example, fixed barriers are 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 key. 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. The NIOSH Prevention through Design (PtD) initiative is based on these principles. Though the PtD initiative was developed well after the design of the BNC, the BNC is considered a prime example of the PtD concept.

"*Make it easier to do it the safe way*"

Provide safety glasses at the entrance to any laboratory that requires their use	Place a sharps container close to a workstation using sharps, with the waste basket further away	Provide an apron and goggles close to any chemical hood and clearly mark the area where they must be worn

A one-sentence summary of the design goal of the BNC 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 to perform the task in a less-safe manner.

The importance of incorporating safety in the design of a facility must be supported through manpower. At the BNC, a senior safety engineer was assigned to the user team to assist in this process. A certified industrial hygienist and highly experienced safety professional was assigned at the early design stages and became the facility Safety Manager when operations commenced. It was also the responsibility of the BNC Engineering Staff to ensure that the best safety practices were designed into the facility. The Facility Manager was involved from the early planning stages, and was heavily involved throughout the design process. He had extensive safety experience as well as cleanroom design and operational experience, and was a principle member of the NFPA 318 Committee, Fire Standard for Cleanroom Manufacturing Facilities. Finally, faculty who would be working in the facility provided strong technical support.

The implementation of the BNC 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.

An example of a hazard assessment would be the installation of a Class 3B laser for a laser-assisted-deposition system. The laser uses fluorine gas which must be changed periodically, it uses high-voltage power supplies for its operation, and it produces hazardous light levels when the system is open for maintenance. Once identified, each of these hazard potentials was addressed during the facility design.

The fluorine gas hazard was mitigated using concentric tubing, exhausted enclosures, and monitoring. The voltage hazards were addressed using appropriate lockout/tagout points designed into the laboratory, and the laser hazards were mitigated by door-lock controls, lockout/tagout points, and cubbies for laser glasses at the lab entrances.

The hazard identification process involves the use of cross-disciplinary teams working together. Faculty, staff, and maintenance personnel provide the bulk of the input, but other disciplines, such as housekeeping, can also provide valuable insight. The teams are generally led by a safety professional who works to extract information from the various groups and gel it into a usable format.

Each potential then becomes an opportunity to design engineering controls to mitigate the risk. Depending on the complexity of the design solution, costs ranged from nominal to relatively expensive systems, such as the door interlocks that block the laser when a door is opened. It is difficult to generalize on the cost of the engineering controls because of this wide variation.

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. An example of the use of PPE in lieu of engineering controls would be the use of a fume hood. While the hood has appropriate engineering controls such as a monitored exhaust flow and a physical barrier (the sash), the separation of the user from the chemicals is incomplete. The sash must be raised to allow the pouring of chemicals into a beaker, and the user must reach into the hood to work with the samples being reacted. Therefore, the engineering controls do not provide adequate protection to the user. PPE, consisting in this case of goggles, gloves, and a coat-apron, is required.

Like the hazard assessment, these engineering controls are updated as new information becomes available and as the design process continues. This new information may be as a result of research reported in journals and at conferences, or may be as a result of changes in codes and best practices. It is the role of the technical staff – safety and process – to keep up with these changes. As the design process continues, new information may be gleaned from the basis of design that the A&E constantly updates and from the design details that emerge from the developing documentation. It is the role of the technical staff and safety staff to review all of these information sources and update the hazard assessment accordingly. Changes in the hazard assessment will always foster a review of the control plan.

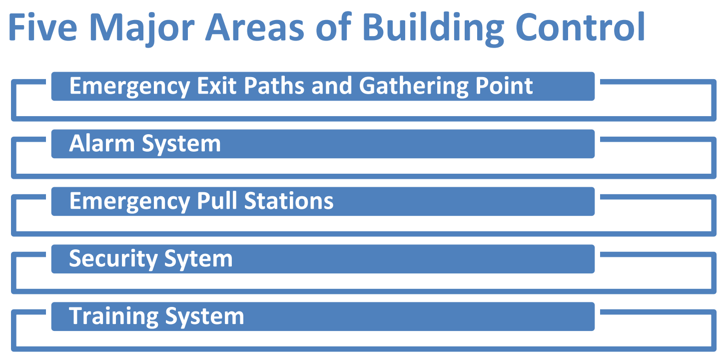
These principles were used throughout the design process. A thorough hazard analysis was completed, and hazard potentials were continuously reviewed. Since the highest potentials were in the fabrication portions of the facility, the cleanroom facility was designed using the best practices used in the 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. Even though NFPA 318 is not a mandatory code for research facilities, it provides the best practices for dealing with the types of materials that would be used in the facility. For this reason, there was full support for the implementation of these designs in the building design process. Best practices were also gleaned from Semiconductor Equipment and Materials International (SEMI), the Santa Clara Toxic Gas Model Ordinance, and documents from the Semiconductor Environmental Safety and Health Association (SESHA).

Best practices from the pharmaceutical industry were applied in the design of the biological areas, such as the separation of bacterial laboratories from cell-culture laboratories. Handwashing stations – completely hands-free – were built into the entrance and exit areas of the BSL-2+ laboratories. UV sanitization lights were incorporated into the room design, with appropriate door interlocks and window coverings. Full-exhaust biosafety cabinets were accommodated for all biohazard work.

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 Centers for Disease Control and Prevention (CDC) standards, such as the BMBL mentioned previously, and designed-in engineering controls to minimize hazards.

At the time, the NIOSH guide to the use of nanoscale materials was not published, therefore it was not available as a resource. Today, that would be a prime document to use during the facility design process.

Finally, the facility was designed in full compliance with Purdue University safety and environmental practices. A new program of certification 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. Note that it is important to consider the natural disaster potentials in the area of the facility being constructed. With the BNC being located in the Midwest, tornados are a significant problem while earthquakes are not. The building emergency plans must comprehend these local factors.

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 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.

Maintaining the safety of these groups is twofold. First, the security system must be designed to keep these groups in the public areas of the facility, away from the research work. Second, the design of the alarm system gives specific direction as to what to do in the event that the alarm sounds. This, coupled with building-orientation training for tour guides, promotes a safe evacuation of the facility should the need arise.

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.

The security system for the facility is a combination of card-access levels and the issuance of keys. The public areas of the building are open during normal business hours, 7:00 AM to 6:00 PM. During these hours, people may enter the atrium areas, the cleanroom viewing aisle, the conference rooms, and the rest rooms. Outside of these hours, access to these areas is limited to those who have gone through any level of BNC training. Once the training has been received, the individual's BNC identification card is activated, allowing access through three sets of outside entrance doors. Offices can be reached through these public areas and are individually locked. They are not part of the card-access system, so individual keys are issued for office access.

The second level of access is the laboratories and cleanroom, dependent on the training matrix described previously. Once the entrance requirements have been met, the BNC identification card is activated for the appropriate area. The cleanroom is a scan-in, scan-out system such that the cleanroom population is always known. The laboratories are scan-in only.

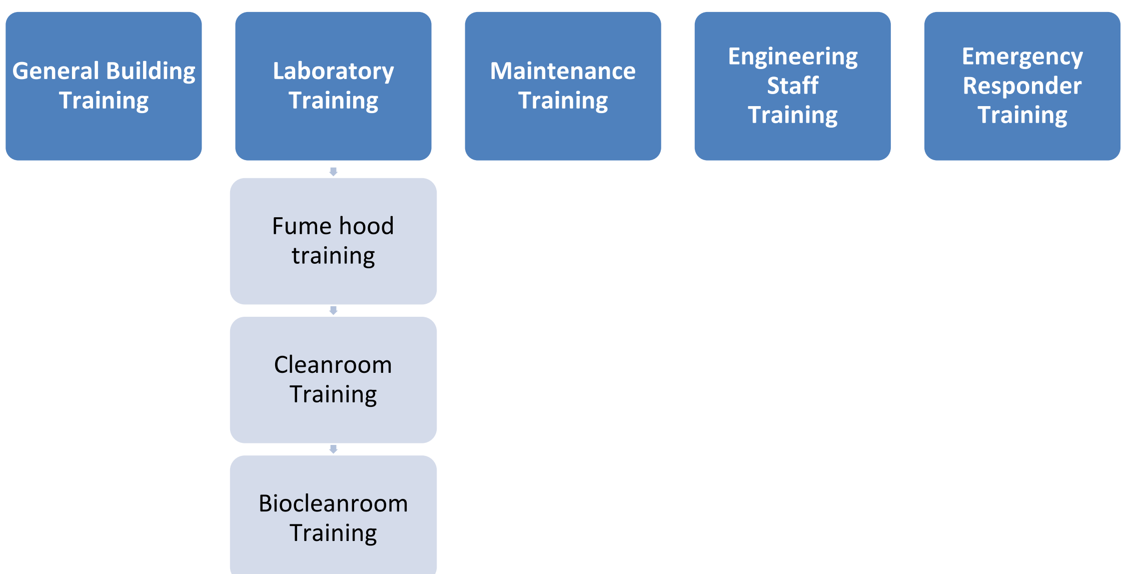
The third level of access is "all doors, all the time." This is granted only to engineering staff and maintenance staff, and allows access to restricted areas such as the subfab. It also grants access to all laboratories in the facility.

Key-access to building exterior doors is granted to the engineering staff and select other individuals who need this level of access. This allows entry to the building in all conditions, including a power outage or emergency situation. It also allows access to all exterior doors, not just those with card-access capability.

There are two levels of key access to interior doors. One master key allows access to all interior doors except offices, the other includes office access. The former is issued to all technical staff members, the director, and the managing director. The latter is only issued to the Facility Manager, the Building Manager, and the Emergency Response Team.

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, and similar groups 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.

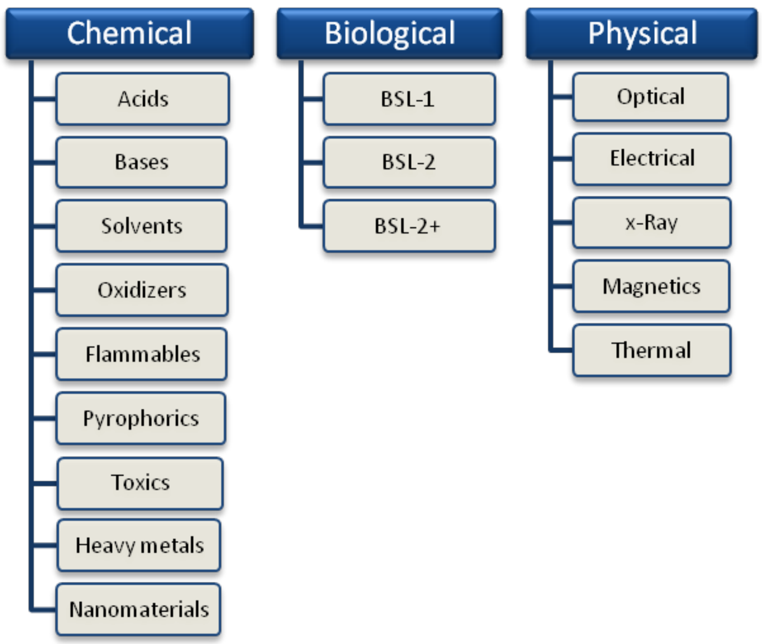
To develop the training plan for the BNC, a list of categories of people to be trained was developed, beginning with those who will simply reside in the facility through those who will be designing equipment installations. Once this exhaustive list was developed, the various groups were analyzed for similarity of need in an attempt to minimize the number of courses to be developed and taught. In addition, a hierarchy of courses was developed to prevent duplication of material presented to any individual group. This manifested itself in a set of prerequisites for the more in-depth courses. Ultimately, this led to several independent training courses for specialized groups and a set of progressive courses for user groups. The users would take whichever courses in the matrix that are appropriate to their usage of the facility.



In addition to those shown above, specialty laboratory training would be required depending on the laboratory. These specialty courses would include laser safety, x-ray safety, and biosafety levels one and two. To prevent the duplication of effort, those specialty classes already taught at the university were incorporated into the training matrix.

Once the user completes the training required for access, they can schedule specific equipment training. This training is taught by the engineer responsible for the equipment, and includes all safety and operational issues involved in equipment usage. Depending on the complexity of the equipment, this training can range from one hour to several days.

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.

There is little agreement on the hazards of nanomaterials but a conservative approach to nanomaterial safety was taken. Nanomaterials used in the BNC are either bonded to surfaces or used in liquid solutions. This greatly reduces the potential for exposure through inhalation. To further mitigate risk, respirators – fitted by the safety department – are worn by those working in laboratories where nanomaterials are grown or deposited. Gloves are also worn by workers in the nanomaterial laboratories.

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

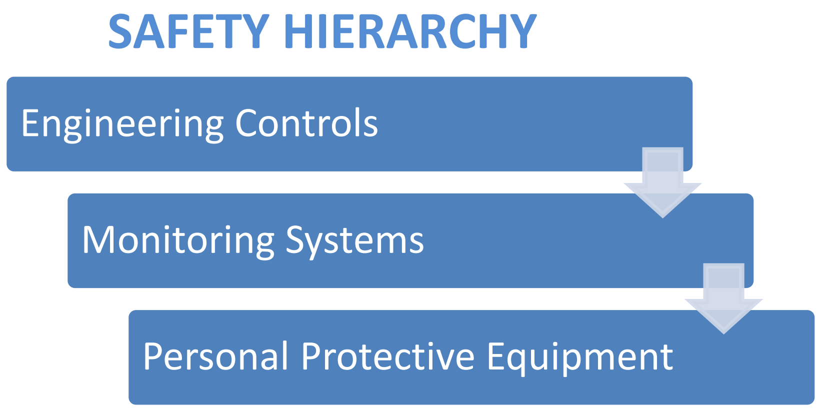
- Laboratory security system
- Specialized training prior to access
- Negative-pressure laboratories
- HEPA filters in all outgoing air
- Personal protective equipment/easily identifyable

Gas Hazard Mitigation Design

Most of the hazards present in a nanotechnology facility relate to areas that are well understood in specific industries. It is the bringing together of different technical backgrounds that underscores the need for cross-disciplinary safety information. The designs shown in this example are standard in most semiconductor fabrication facilities, but are not necessarily applied to nanotechnology facilities using the same – or similar – incoming materials. The application of these known technologies is a critical element in the design of a facility using nanoscale materials.

The mitigation of gas hazards was chosen as the example of the overall safe-design concepts used in the BNC. 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. Last, 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. These have proven fairly effective, and have been looked upon favorably by most users. The cameras have been used to clarify an event and "clear" a user in the past, setting the tone for a positive response to their presence.



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.

Figure 2: Automated-purge gas cabinets used in BNC. These cabinets are required for all gases rated 3 or above in any NFPA hazard category. The cabinets are located in secure, isolated rooms at the perimeter of the facility. In addition, each cabinet is locked to provide further security.

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 region 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 region 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 trigger 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.

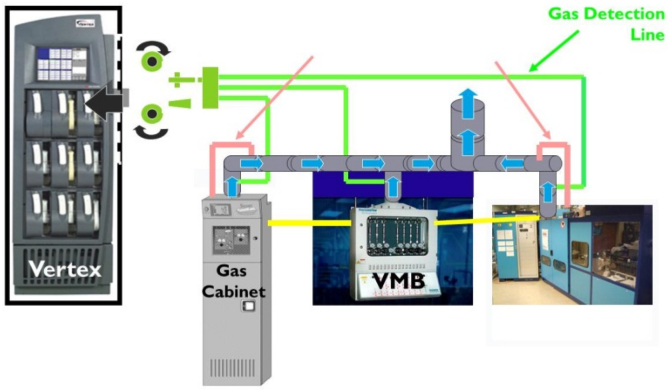


Figure 3: A combination of gas monitoring (sniffing) sensors and pressure sensors are used to ensure the detection of any leak. Automated monitoring provides notification automatically should a leak occur.

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.

Figure 4: In the event of an emergency being recognized by a facility occupant, push-button stations allow one-touch evacuation of the facility and gas shut-off.