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Facilities Planning for Safety and Emergency Response: Bridging the Gap between Design Features and Safety Planning

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This article describes some of the safety considerations for the design and construction of micro/nano facilities and applicable building code provisions. The two key elements required for safe operation in micro and nanotechnology facilities are: (1) engineered features incorporated into building construction, and (2) administrative features that deal with how people work within the facility.

Keywords
Lab safety, micro/nano research facilities, nanotechnology, nanofabrication cleanrooms, engineered safety features, administrative safety features, code requirements for cleanroom laboratories, H-5 Occupancies

In the life of a conventional research facility, the architecture, engineering, and construction community builds a building and the scientific community uses it. Both groups intend for the building to operate safely, but they approach it from opposite ends of the spectrum. The purpose of this article is to raise awareness of the gap between these two perspectives and present opportunities for bridging the divide. We discuss considerations to help facilities owners, managers, and users in planning facilities, incorporating best practices, and attaining safer operation through their understanding of the building and system designs. This article does not purport to provide advice or to address all possible safety concerns or mediation. It is the responsibility of the owner and the design team to ensure compliance with all applicable codes and standards and safety requirements.

Building designers typically approach safety from the perspective that any concern can be mitigated with a building or engineering feature. This concept is part of their training, and in most cases such features are dictated by codes and regulations. Research scientists, on the other hand, approach safety from the perspective that full awareness of a hazard and application of safe operating procedures will prevent injury or damage. Facility managers and operators must serve both of these perspectives by being knowledgeable regarding the safety features designed into a building project, ensuring those features support the researchers' operating procedures and processes, and avoiding conflicts between the two perspectives.

Hazards encountered in micro/nano fabrication facilities are similar to the hazards in all research buildings and fall into three primary categories: 1) chemical, 2) biological, and 3) physical. However, nanofabrication facilities have the added safety concerns related to novel materials with indeterminate hazards. The National Institute for Occupational Safety and Health (NIOSH) defines methodologies for controlling exposure to the various known and future unknown nanomaterials that could be determined to be hazardous to humans.[1] NIOSH defines a "Hierarchy of Exposure Controls" in priority order as follows:

1. Elimination: change design to eliminate hazard
2. Substitution: replace a high hazard with a low hazard
3. Engineering controls: isolation/enclosure, ventilation (local, general)
4. Administrative controls: procedures, policies, shift design
5. Personal protective equipment (PPE)—respirators, clothing, gloves, goggles, ear plugs

This article focuses on two key elements required for safe operation in micro and nanotechnology facilities:

- Engineered features incorporated into building design and construction
- Administrative features that deal with how people work within the facility

Engineered features include the various forms of built-in, constructed, or fabricated systems used to control exposure to hazards. Examples include rooms and walls, laboratory hoods, safety cabinets, ventilation and exhaust systems, fire alarms, sprinkler systems, and fire control and protection measures. These systems are governed by codes, standards, and guidelines that specifically address the built environment of micro/nano facilities.

Administrative features include those protocols and procedural methodologies initiated to control the activities and behaviors of laboratory users handling nanomaterials and other hazardous materials, such as chemicals. These control features include standard operating procedures (SOPs) developed in each lab, safety procedures and manuals, safety training, and emergency response plans and procedures. The control features address how to handle materials properly, how to use hoods and safety cabinets, what to do if there is an accident or incident, what to do during alarms for hazardous materials or fire, and the use of personal protection equipment (PPE).

This article discusses the need to integrate engineered and administrative exposure control methodologies at the time of the owner's acceptance of new or renovated facilities. Bridging the gap between facility design features and safety planning enables laboratory users to avoid working at cross-purposes with the safety amenities built into the facility. Building owners, managers, and users can be overwhelmed by engaging a new or newly renovated facility, and often fail to capitalize on the safety features that are integrated into the design.

ENGINEERED SAFETY FEATURES

Engineered features can be subdivided into passive features (e.g., fire-rated walls that require no action or automated response) and active features (e.g., fire dampers or automatic door closers that require a sensor and an automated action by a building component).

Engineered features are driven predominately by building codes, standards, adopted guidelines, and professional judgment or best practices. Requirements for engineered features may be dictated by any authority having jurisdiction, such as federal, state, and municipal governments. Model construction codes, such as the International Building Code (IBC),[2] are adopted as laws. These model codes incorporate industry standards by reference; thus, the standards also become law when jurisdictions adopt the codes. Compliance with code requirements is enforced through a plan review process required to obtain permits to build or renovate, and with inspections and approvals required to obtain permits to occupy and operate the facility. Non-compliance with code requirements may result in judicial and litigious consequences. Examples of codes and standards that define the requirements for the construction and occupancy of a micro/nano fabrication facility include the following:

- Building codes, including building, mechanical, plumbing, electrical, and energy codes.
- Fire codes, which are similar to building codes in format and requirements. Fire codes and

building codes reference each other in common sections and requirements.

- National Fire Protection Association (NFPA) Standards
- Occupational Safety and Health Administration (OSHA)
- American National Standards Institute (ANSI)

The design/construction team and facility owner must be familiar with all codes governing the facility to be built or renovated.

Application of Codes and Guidelines

Building code documents define minimum requirements to build facilities of all types, providing safe construction for the occupants. The following are examples of code requirements that have significant impact on the construction of nanofabrication facilities, particularly those with cleanrooms. This list does not purport to be all inclusive.

Use and Occupancy Classifications – Maximum Allowable Chemical Quantities

Building and fire codes classify buildings based on their use and on the quantity of hazardous materials to be stored or housed in the building. For example, laboratories for research and testing are typically classified Business Group 'B' Occupancies in the IBC. Typically, laboratories are separated from the non-laboratory areas of the building in suites of labs. This separation is called a "Control Area." Control Area tables in the IBC define the maximum allowable quantities (MAQ) of hazardous materials. If the quantities exceed the MAQ, then the area would be classified as a hazardous 'H' Occupancy. Lab users are responsible for knowing the allowable limits of chemicals; lab owners and managers are required by law to inventory and report on chemical quantities and to adhere to the code allowable limits.

Areas exceeding the Control Area MAQ limits, or dedicated Hazardous Chemical Storage areas, are High-Hazard Group H Occupancies (H-2, H-3, or H-4 depending on the chemical types). H Occupancies have many code requirements and restrictions due to the hazardous nature of the materials located in these occupancies. Requirements include fire-resistant rated enclosure walls, special exhaust systems (some with neutralizing treatment systems), and explosion control devices, among others.

Micro/nano fabrication cleanrooms are classified High-Hazard Group H-5 Occupancies, due to the high use of very hazardous chemicals. H-5 Occupancies have a separate MAQ chemical table that allows for larger usable amounts of chemicals in the area. Chemicals that are stored or used in micro/nano fabrication facilities and are considered to be extremely hazardous are called Hazardous Production Materials (HPM). The H-5 Occupancy classification has many additional code requirements and restrictions that facilitate high chemical use capabilities, such as fire-rated separation walls (with fire and smoke dampers), shorter allowable exit distances, and special exhaust and chemical drainage and treatment systems.

Code-Required Engineered Features

The following summarizes some of the pertinent and prevalent engineered systems required by building safety codes, in particular for areas where hazardous materials are stored or used in micro/nano fabrication H-5 facilities:

- Fire Separations: fire-rated walls and floors surrounding the hazardous occupancy, intended to prevent the spread of fire. Fire separations typically have a rating of 1 hour or 2 hours, based on their timed-resistance to the passage of flame, heat, and smoke. Fire separations are fitted with fire-rated doors with self-closers, fire dampers on ductwork designed to close in event of fire or smoke detection, and protected penetrations such as conduit and piping which are fitted with fire-retardant sealants.
- Exits: Minimum prescribed number of required exit paths and openings to provide safe egress from each room or area.

- Automatic Fire Suppression System (AFSS): More commonly called fire sprinklers, these systems may be required by the code to provide for life safety.
- Spill Control and Secondary Containment: These requirements apply to liquid chemical storage rooms. Spill control requires trenches or berms at the room perimeter to prevent a chemical spill from spreading. Secondary containment systems assume an event such as a spill has already occurred, and require that the chemical spill and any fire sprinkler water be contained within the same room.
- Alarm Systems: various types and functions required in all buildings:
    - Fire/Smoke Detection and Alarm—the most common type of alarm system, found in almost all building types.
    - Toxic Monitoring Detection and Alarm—required for areas using toxic chemicals such as arsine, cyanogen, diborane, fluorine, germane, hydrogen cyanide, nitric oxide, nitrogen dioxide, ozone, phosphine, hydrogen selenide, and stibine, to name a few.
    - Highly Sensitive Smoke Detection (HSSD)—required where smoke is difficult to detect, such as in cleanroom research facilities where massive amounts of air are moved and capabilities of typical detection systems may be minimized.
- Emergency Control Station (ECS): The IBC requires that H-5 Occupancies (nanofabrication cleanrooms) be provided with a manned control station (Figure 1). This ECS is to be located outside the cleanroom, permanently manned (may be remotely manned), and provided with the following systems:
    - Automatic sprinkler system alarm and monitoring
    - Manual fire alarm
    - Emergency alarm
    - Continuous hazardous gas detection
    - Smoke detection
    - Emergency power
    - Automatic detection and alarm systems for pyrophoric liquids and Class 3 water-reactive liquids
    - Exhaust ventilation flow alarm devices for pyrophoric liquids and Class 3 water-reactive liquids cabinet exhaust ventilation systems

Figure 1. Example of an H5 Emergency Control Station (ECS).

- Emergency Power Requirements: Building and fire codes require that certain engineered safety features be provided with emergency power (emergency generator systems). If the normal power provided to a facility is lost during a storm or other event, emergency power systems start automatically to supplement the lost normal power. This ensures that safety systems in the facility will continue to operate. Life safety systems required to have emergency power back-up include, but are not limited to, the following:
    - HPM exhaust ventilation
    - HPM gas cabinet ventilation
    - HPM exhausted enclosure ventilation
    - HPM gas room ventilation
    - HPM gas detection
    - Emergency alarm
    - Manual fire alarm
    - Automatic sprinkler system monitoring and alarm
    - Automatic alarm and detection systems for pyrophoric liquids and Class 3 water-reactive liquids
    - Flow alarm switches for pyrophoric liquids and Class 3 water-reactive liquids cabinet exhaust ventilation
- International Mechanical Code (IMC)[3] Features: The IMC defines the requirements for engineered systems specific to mechanical systems. Systems governed by the mechanical code include, but are not limited to, the following:
    - Ventilation—the supply side of the air systems
    - Exhaust——the air systems specifically provided to exhaust hazardous vapors from the

chemical HPM used in a facility. Such vapors include, but are not limited to, toxic fumes, corrosive fumes, and combustible and flammable vapors. Exhaust systems are intended to provide dedicated exhaust to keep fumes out of occupied rooms and spaces, and also to mitigate fume hazards by treating the fumes, "scrubbing" them, or diluting them to a non-hazardous state prior to their release into the exterior atmosphere. Exhaust systems for toxic and flammable gases are provided with a back-up fan and emergency power to ensure continuous operation.

- Piped Supply Systems—these include plumbing systems for items such as sinks and also piped systems for hazardous materials such as liquid chemicals and gases.
- Drainage and Waste—these include plumbing systems for items such as sinks and also piped systems for hazardous materials, such as liquid waste systems for chemicals. Drainage systems for hazardous materials typically will be directed through various forms of collection systems or treatment systems. Treatment systems neutralize the waste and make it safe to release into municipal drainage systems.

Other Standards

- NFPA has a series of codes, standards, recommended practices, and guides defining many safety requirements for facilities. Building codes adopt various NFPA standards by reference. For example, the National Electrical Code[4] incorporates NFPA 70 verbatim. The following list summarizes some of the more pertinent and prevalent engineered systems required by the NFPA regarding nanofabrication and laboratory facilities:
    - NFPA 30 Flammable and Combustible Liquids Code—applies to the storage, handling, and use of flammable and combustible liquids, including waste liquids.
    - NFPA 45 Standard on Fire Protection for Laboratories Using Chemicals—laboratory buildings, laboratory units, and laboratory work areas above or below grade, in which chemicals, as defined, are handled or stored.
    - NFPA 55 Compressed Gases and Cryogenic Fluids Code—applies to the installation, storage, use, and handling of compressed gases and cryogenic fluids in portable and stationary containers, cylinders, equipment, and tanks in all occupancies.
    - NFPA 70 National Electrical Code—emergency power, standby power, and uninterruptable power supply requirements.
    - NFPA 72 National Fire Alarm and Signaling Code—Annex E Mass Notification Systems covers the systems that notify occupants of an emergency situation such as fires, earthquakes, and storms.
    - NFPA 318 Standard for the Protection of Semiconductor Fabrication Facilities—applies to semiconductor fabrication facilities and comparable fabrication processes, including research and development areas in which hazardous chemicals are used, stored, and handled and containing what is defined as a cleanroom or clean zone, or both.
    - NFPA 1221 Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems—also known as Mass Notification Systems; covers installation performance, operation, and maintenance of public emergency service communications systems and facilities.
- ANSI is a non-profit testing and standards organization that adopts standards for consistency of performance in products, processes, and systems:
    - ANSI/AIHA (American Industrial Hygiene Association) Z9.5 Laboratory Ventilation—selection, design, and operation of laboratory ventilation systems.

- OSHA is the main federal agency charged with the enforcement of safety and health legislation:
  - Laboratory Standard 29 CFR 1910.1450—Occupational Health and Safety Standard for Laboratories using Hazardous and Toxic Substances.
  - Laboratory Safety Guidance OSHA 3404-11R—quick guide summary to the various OSHA Standards for laboratory safety.

As we have demonstrated in the previous sections, there are significant and sometimes costly safety features "baked-in" to the design and construction of a micro/nano fabrication facility. These are considered the "minimum," and best practices or prudent judgment may add to these features in the design of a hazardous-use facility.

ADMINISTRATIVE FEATURES: SAFETY AND EMERGENCY RESPONSE PLANNING

Safety Procedures and Protocols

Administrative safety features are those implemented by personnel in the operation and use of the building. In this article, the features are separated into two categories:

- Standard Operating Procedures: Processes for safe use and handling of materials, operation of equipment, and maintenance of equipment that are developed and defined, which can be taught as part of an introduction to the facility or the hazard. Examples include the use of PPE for everyday handling of chemicals, and the use of fume hoods.
- Emergency Response Procedures: Processes developed prior to an event and established to prepare for a safe and rapid resolution of an emergency. Examples include the use of fire extinguishers, a building exit and rally plan, and the donning self-contained breathing apparatus (SCBA) when responding to a toxic gas leak.

At the highest level safe operations require awareness of potential dangers and eliminating or avoiding these dangers. As mentioned previously, risk management protocols (as documented by NIOSH and the Centers for Disease Control) provide direction for laboratory safety by defining how to control exposure to various chemical, biological, and physical hazards, and most recently nano-materials.

There are a variety of published recommendations and procedures that apply generally, such as *Prudent Practices in the Laboratory*.[5] Additionally, recommended practices available from equipment and materials suppliers can be a source for general safety procedures.

More specific safety protocols are developed in each individual facility and provided to workers as part of training to promote constant awareness of safety techniques and processes. It is critical that the design and construction of the research facility encourage the practice of safety. Customized procedures are tailored to the specific facility and organization and can become ingrained in day-to-day operations. Examples of customized procedures that apply to micro/nano fabrication facilities include, but are not limited to:

- HPM handling, transport training, and chemical hygiene plans: Prescribe how materials are delivered, handled, stored, and distributed in the specific facility, from loading dock to lab bench to waste disposal:
  - Hazardous materials include, but are not limited to, corrosives, toxics, flammables, explosives
  - Procedures include how to deal with spills and clean-up of wet and dry materials
  - Safe disposal of wastes
- Safety equipment locations and use: Eye Wash/Safety Showers (EW/SS), fire extinguishers, fire

alarms, respirators

- Nano materials exposure prevention:
    - Handling protocols– open air in “free particle” state
    - Use of filters and breathing apparatus
- Fume hood, safety cabinet function and use
- Electrical safety: Lock-out/tag-out procedures for modifying electrical systems in the facility for maintenance or research operations
- Laser safety: Interlocks on Class 3B and 4 laser system shutters, protective eyewear, door and curtain interlocks
- Procedures for handling cryogens: Delivery of ‘dewar-type’ tanks, fill and transfer procedures to prevent overpressure, safety equipment to prevent freezer burn, and similar project-specific practices.
- Material Safety Data Sheets (MSDS): These provide the complete technical, hazard, and safety information on all the chemicals located in a facility. MSDS must be readily locatable and available for workers to access.
- Hazardous Material Management Plan (HMMP): As required by the fire code and typically required by local fire marshals and campus environmental health and safety (EHS) departments. The HMMP indicates the presumed hazardous materials to be used or stored at a facility and typically provides a facility site plan designating items such as hazardous material storage and use areas, maximum amount of each material stored or used in each area, range of container sizes, and storage plans showing the intended storage arrangement.
- Hazardous Material Inventory Statement (HMIS): Similar to the HMMP, the HMIS is required by the fire code, and is typically required by local fire marshals and campus EHS departments. An HMIS provides the inventory of the presumed hazardous materials to be used or stored at a facility, including the hazardous materials manufacturer’s name, chemical name, trade names, hazardous ingredients, hazard classification, MSDS or equivalent, chemical abstract service (CAS) identification number, maximum quantity stored or used on-site at one time, and the storage conditions.

Emergency Response Procedures

Unlike Standard Operating Procedures, Emergency Response Procedures are based on the assumption that an “event” has already occurred. At this point during an emergency event actions are aimed toward preventing further exposure and controlling the danger. It is in this area we have observed the building design has the most potential to inhibit a sound, reliable approach to safety, when administrative processes may conflict with engineered features.

Emergency responders, or “first responders,” are trained personnel whose job is to arrive on the scene of an emergency situation. These responders include police and fire department personnel and Emergency Medical Services (EMS) workers. Many facilities also have an Emergency Response Team or Campus Response Team, comprised of researchers and staff who have been specially trained by the institution. First responders are trained to handle all types of emergency situations, such as personal injury emergencies, including rescues; fires; hazardous material (HazMat) events; and earthquakes and disasters.

First responders typically are focused on vehicle response, knowing how and where to approach a facility to facilitate the mitigation procedures needed for the specific emergency. The responders should be informed about the building entry points. Responders should also be aware of the safety training and procedures of the occupants, such as where the occupants are to assemble during the evacuation of a building. As previously mentioned, H-5 Occupancy Nanofacilities are required to have an Emergency

Control Station. Responders should be trained to know where emergency control stations and emergency monitors and alarms are located to determine the emergency type and location. Their arrival at the ECS, and their capabilities of identifying the exact nature of the emergency sets in motion the appropriate response protocols and activities for mitigating the emergency event.

BRIDGING THE GAP

It is vitally important for building owners, lab users, and especially users in nanofabrication facilities to understand the engineering features built into their facility. As shown in this article, the array of safety features provided in technology buildings, including the less-hazardous B Occupancy Laboratory Building, is extremely complex. However, it is important for the holistic approach to safety procedures and activities that laboratory building owners, with the help of the design and construction teams of their facility, integrate the administrative and engineered features. Understanding the engineered features built into the facility will help to ensure the requirements for safe operation and emergency planning are fully utilized.

Example of Integration

The IBC requires an ECS for an H-5 Occupancy such as a large nanofabrication cleanroom facility. However, the code does not specify the size, features, or location. An architect will begin by incorporating an ECS in the building program, and in adjacency diagrams as shown in Figure 2, during the earliest stages of design.

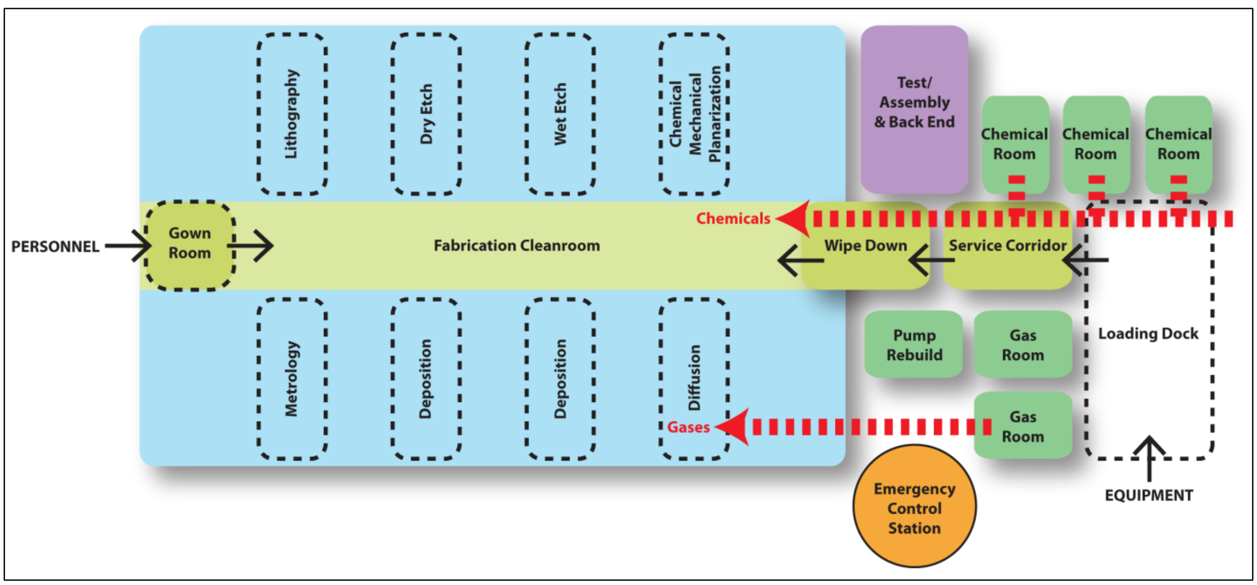

Figure 2. Adjacency diagram of a Nanofab Facility.

Even at this early point in the design process, however, it is recommended that the owner, or assigned lab users, participate in the design of the ERC by answering key questions:

- How can the ECS be manned as required by the code?
- How will the space be used by first responders?
- Where is the optimal location—near the hazards or near the building exit?

- What systems should be provided—emergency shut-down, fire alarm panel, gas monitoring?
- What equipment is required—SCBA, PPE, and a spill cleanup cart?

Most institutions have a basic emergency plan, but the plan must be broad enough to cover all eventualities. This level of detail is needed to ensure safety when dealing with the special hazards associated with micro- and nanotechnology facilities.

Example of Conflict

A three-story micro/nano fabrication facility was designed and constructed in accordance with the users' building program, code requirements, and best professional practice. The facility included a large cleanroom with associated hazardous gas bunkers.

During the design process the local fire authority had asked that the building's fire department connection be placed adjacent to a wide exit stairwell at the rear of the building. Adjacent to this stairwell was a main corridor entering the building, and off to one side was the ECS. The fire marshal had requested these specific locations so he could easily stage fire fighting operations, or hazardous materials response teams, from the alley at the rear of the building and access the upper floors via the stairwell with a standpipe and the fire department connection close at hand.

However, the building manager had not participated in the design or planning of the facility His evacuation plan had the majority of the building occupants exiting and rallying in that same rear alley since they could escape easily from the ground floor corridor and the large exit stairwell. Fortunately, one practice evacuation exercise revealed the conflict and the evacuation plan was modified.

This is a rather simple example, but it illustrates the importance of understanding the big picture—and of conducting safety drills.

Owners and lab users must be aware of the many engineered features to consider, whether the facility is brand new or older. Some of the code-required features to include when designing and building a new facility are as follows. This list is not intended to be comprehensive.

Emergency Planning and Emergency Management Programs

- Chapter 4 of the Fire Code requires an approved fire safety and evacuation plan. Facility owners and managers should be involved in the design and operation of the facility, communicate with the first responders, and understand the code requirements.
- Fire safety plans include the following:
    - Procedure for reporting a fire or other emergency
    - Life safety strategy and procedures for notifying, relocating, or evacuating occupants
    - Site plans indicating occupancy assembly point, locations of fire hydrants, and normal routes of fire department vehicle access
    - Floor plans identifying the locations of exits, primary and secondary evacuation routes, accessible egress routes, areas of refuge, manual fire alarm boxes, portable fire extinguishers, occupant-use hose stations, and fire alarm annunciators and controls.

Safety Features Incorporated into the Design

- Gas monitoring and automatic shutoff valves; manual turn-ons required
- SCBA and respirators' locations and use
- Cleanroom equipment safety features—fire protection, exhaust, emergency manual shut-offs
- Mechanical air systems—supply and exhaust systems, emergency operations, re-startup of shutdown systems following power loss

- Electrical systems—emergency, standby, dedicated, conditioned, UPS

Emergency Health and Safety (EHS) First Responders Processes and Procedures

- Fire, HazMat, personal injury, terrorism, and other emergencies
- Response point entry, activities-including access to the ECS

Code Requirements of the Design

- Seek an Operational Presentation of the building's mechanical and electrical systems, and Engineered Safety Features from site facilities staff, EHS, and designers on building systems
- Systems include Mechanical, Electrical, Process, and Fire Protection and Safety Systems

Code-required Documentation

- Emergency Management Plans
- Material Safety Data Sheets (MSDS) library; location and availability
- Hazardous Material Management Plan (HMMP)
- Hazardous Material Inventory Statement (HMIS)
- Keep updated, distributed, and provide training on code requirements and Allowable Quantities of Hazardous Production Materials (HPMs, Chemicals)

Code Requirements of the Design—The Fire Code

- General precautions for the safe storage, handling or care of hazardous materials.
- Personnel training and written procedures: Persons responsible for the operation of areas in which hazardous materials are stored, dispensed, handled, or used must be familiar with the chemical nature of the materials and the appropriate mitigating actions necessary in the event of fire, leak, or spill.
- Fire department liaison: Responsible personnel should be designated and trained to aid the fire department in planning emergency responses and identifying where hazardous materials are located. These individuals require access to Material Safety Data Sheets and must be knowledgeable about the site's emergency response procedures.

Conclusions

In addition to implementing administrative controls, facility owners and users must be familiar with the engineering safety features built into the facility. Owners and users should actively seek out designers and builders to learn about these features.

Following are some suggestions for micro/nano-fabrication facility owners, managers, and users to bridge the gap between engineering and administrative safety features:

- Become involved in facility design and construction as early as possible.
- Understand how the facility is supposed to operate.
- Develop the Emergency Management Program in concert with the building design team.
- Communicate early and often with the first responders, municipality, or campus concerning policies, processes, procedures.
- Become familiar with the applicable code documents.

- Understand how the built-in safety features should operate during emergency conditions and how to re-set them after the emergency.
- Develop safety procedures and provide training that incorporates the engineered features.
- Following these steps will provide the users with a holistic understanding of safety in the nanofabrication facility.

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IEST Working Group NANO205 is developing a new Recommended Practice (RP), IEST-RP-NANO205.1, *Nanotechnology Safety: Applying Prevention through Design Principles to Nano-technology Facilities.* This RP is targeted for publication in late 2014.