Chapter 21: Exposure Assessment in the Laboratory Environment

By Joseph Damiano, MS, CIH, CSP, FAIHA®, Diana H. Peroni, MS, CIH, Stephen W. Hemperly, MS, CIH, CSP, CLSO, FAIHA® and Timothy E. Roberts, CIH, CSP

A laboratory is a facility dedicated to scientific experimentation or testing. Laboratories reside in research centers, academic institutions, factories, health care facilities and in numerous other workplaces. There are various types of laboratories. There are analytical labs where materials or devices are evaluated to determine selected chemical, physical or biological attributes, for example, the concentration of a metabolite in a blood sample or the presence of a radionuclide in a soil sample. Some laboratories house experimental equipment and others support medical research. Some laboratories perform pilot scale evaluations of industrial processes. The Occupational Safety and Health Administration (OSHA) defines a laboratory as a workplace where relatively small quantities of hazardous chemicals are used on a non-production basis. The textbook by L. DiBerardinis describes the design and engineering features for a variety of common laboratories (e.g., chemistry lab, pilot plant, gross anatomy). Laboratories are as wide ranging as science itself, and often serve as the venue for many chemical, biological and engineering developments.

Why a Chapter on Laboratory Exposure Assessment?

Similar to any workplace, the chemical, physical and biological agents present in laboratories must be assessed in order to differentiate acceptable from unacceptable exposures, and effectively target health hazard controls. Exposure assessment in the laboratory environment is often more challenging than in other workplaces. Laboratories often feature intermittent, short-duration and non-repetitive tasks. When considering these factors, industrial hygienists may inappropriately reject the need for exposure assessment. While laboratories feature smaller quantities of chemical agents and lower exposure levels than commercial scale operations, some investigators have reported significant to unacceptably high exposures to environmental agents. For example, several studies have reported airborne formaldehyde exposures exceeding occupational exposure limits (OELs) in anatomy laboratories, where specimens are closely positioned within breathing zones. Studies have revealed significant exposures to quartz in geotechnical laboratories and lead in mine assay laboratories,
where rock and soil samples were prepared for analysis via grinding, fluxing and other aerosol emitting processes.\(^{(6,7)}\)

There have been reports of illness and disease associated with exposures to chemical, physical and biological agents in the laboratory environment. Fatalities have occurred among laboratory workers exposed to hydrofluoric acid through skin contact and dermal absorption.\(^{(8)}\) A researcher at Dartmouth University exposed to dimethylmercury suffered neurological damage resulting in death.\(^{(9,10)}\) There are reports of eye injuries from exposure to laser radiation in laboratories.\(^{(11)}\) Animal research laboratories have reported cases of allergic sensitization and asthma from exposure to protein allergens present in animal urine, saliva and skin.\(^{(12-14)}\) Additionally, epidemiological studies have reported increased cancer and reproductive risks among laboratory workers.\(^{(15-17)}\)

Many laboratories develop new chemicals, new biological agents, or new devices resulting in the introduction of new or unknown hazards. It is critical in such operations to anticipate the exposures, and apply exposure management strategies to minimize potential health risks.

In view of the potential exposures and associated health risks, the anticipation, recognition, evaluation, control, and confirmation of potential health hazards must be integrated into each laboratory’s general health and safety program.\(^{(18)}\) The challenge is to do this effectively and efficiently. This chapter offers practical strategies for occupational exposure assessment in the laboratory environment.

**Application of the AIHA Exposure Assessment Process to the Laboratory Environment**

In recent years and in many workplaces, the state-of-the-art approach for industrial hygiene has shifted from a compliance-based monitoring strategy to the “comprehensive approach” focusing on the assessment and management of all exposures for all workers on all days.\(^{(19)}\) In many organizations, the comprehensive approach has been integrated into the chemical hygiene programs featured in modern laboratories. In the United States, the adoption of the comprehensive and integrated approach was driven in part by OSHA’s Laboratory Standard.\(^{(1)}\) The need for a comprehensive approach was also driven by the necessity of adequately controlling the numerous and variable hazards often present in labs, the absence of OELs for many environmental agents, and the frequent impracticality of assessing exposures based upon personal monitoring in the laboratory environment.

OSHA’s Laboratory Standard\(^{(1)}\) calls for initial and periodic monitoring of chemical exposures if there is reason to believe the exposure levels exceed an assigned Action Level or Permissible Exposure Limit (PEL). This assessment is intended to be performed by or under the direction of the Chemical Hygiene Officer (CHO), a role often assigned to an industrial hygienist. However, no criteria or guidance is provided in the OSHA standard addressing how to decide whether exposure levels may exceed an Action Level or PEL. An even greater challenge is to fulfill the monitoring requirement in laboratories featuring hundreds or thousands of chemicals where the use of these chemicals is ever changing.

How can the industrial hygienist determine which chemical exposures to monitor in the laboratory? More importantly, how can an industrial hygienist assess all chemical, physical, and biological exposures present in the laboratory environment? The answers to these questions are addressed in this chapter and are based upon the
exposure assessment strategy presented in Chapters 1 through 11. The following is a suggested approach for applying the AIHA® exposure assessment process to the laboratory environment highlighting the basic elements of the strategy illustrated in Figure 21.1. It should be noted that laboratory support operations, such as maintenance or construction, are not addressed in this chapter and are normally evaluated by the general exposure assessment methodology described in Chapters 1 through 11.

1. Start: Establish the Exposure Assessment Strategy

Each organization featuring one or more laboratories should establish a written program addressing how the exposures present in its operations will be assessed, by what criteria, and by whom. The exposure assessment strategy can be a stand-alone program, or it can be integrated into the Chemical Hygiene Plan prescribed by OSHA. Biological and physical agent exposure assessments should be addressed within the scope of the written program or addressed in other administrative procedures.

A stated goal of the written program should be to ensure that all workplace exposures are controlled to levels that will not pose a significant risk for occupational illness or disease.

Figure 21.1 – AIHA® Exposure Assessment Process
The written program should address who is responsible for the exposure assessments. In general, exposure judgments should be performed by or under the review of a professional industrial hygienist, and as noted earlier, industrial hygienists are often assigned to serve as the Chemical Hygiene Officer. This is a logical assignment in view of the industrial hygienist’s training and experience. If the Chemical Hygiene Officer role is not assigned to an industrial hygienist, the CHO should perform his or her duties under the review of an industrial hygienist. While the industrial hygienist is the most qualified individual to perform exposure assessments, he or she should involve all stakeholders with direct knowledge of laboratory operations, including principal investigators, laboratory staff, safety professionals, facility engineers and medical personnel.

The written program (which may be part of the Chemical Hygiene Plan) should address how exposures will be identified, evaluated and controlled. Frequently this will be prescribed within a general process for assessing health and safety hazards in laboratory operations and research projects. Standard control strategies or mitigations are often specified, and augmented by a procedure for systematically identifying exposures that may not be adequately controlled by the standard mitigations – thereby requiring specialized evaluation by the industrial hygienist. Additionally the written program should include a system for anticipating, evaluating and controlling the hazards associated with planned changes in the workplace, workforce, and environmental agents, otherwise known as a management-of-change process.

Finally some laboratory programs have integrated industrial hygiene assessments into the development of new processes, equipment and products. The intent is to ensure the health and safety ramifications of new technologies are identified and addressed at an early stage thereby providing the opportunity to avoid problematic conditions at a commercial scale.\(^{(20)}\)

### 2. Basic Characterization

Basic information describing the laboratory’s workplace, workforce, and environmental agents must be collected in order to proceed with the exposure assessment.

**Workplace:** The industrial hygienist must understand each laboratory as the workplace venue for exposures to environmental agents. Each laboratory should be identified, and information should be acquired addressing the purpose of each lab and services provided to its customers. Some labs may specialize in the analysis of samples, and others may support forensic investigations. There are laboratories that synthesize new compounds and others that perform physical analyses of materials. The basic characterization should identify the operations and equipment present in each laboratory.

**Workforce:** The industrial hygienist must understand how each laboratory is staffed. Are laboratory personnel dedicated to a single lab or do they work in multiple labs? How many scientists, engineers or technicians are present in each laboratory? Is their work similar, or do they have specialized work activities? What are the tasks that may be associated with potentially significant exposures to chemical, physical and biological agents?

**Environmental Agents:** The industrial hygienist must identify the potentially significant environmental agents present in each laboratory, including quantities and other pertinent data. Safety Data Sheets provide key information such as OELs and vapor pressure.\(^{(21)}\) Laboratories often maintain lists of chemicals that have been reviewed from a health and safety perspective, as well as an on-going inventory...
of chemicals stocked in the laboratory. The identification of potentially significant environmental agents should consider chemical samples, test specimens, newly synthesized compounds, intermediates and waste materials.

Industrial hygienists (or the personnel conducting the exposure assessment) must identify the potentially significant physical agent exposures present in each laboratory, including radioisotopes, x-ray generating devices, lasers (and other non-ionizing radiation sources), and ergonomic hazards (e.g., exposure to repetitive motion or awkward postures). Chapters 15–17 provide in-depth discussions of ergonomics, non-ionizing radiation, and ionizing radiation.

Finally, the potentially harmful agents present in microbiology, toxicology and other biological laboratories must be identified in order to assess exposures and determine an effective control strategy.

Laboratory-specific strategies and management systems for assembling and maintaining basic characterization data have been reported in scientific publications. Remarkably, the process of touring laboratories for data collection will likely reveal opportunities to correct unsafe practices and provide an opportunity for educating laboratory workers on occupational health risks and strategies for minimizing exposures.\(^{22,23}\)

### 3. Exposure Assessment

All exposures should be judged acceptable, unacceptable, or uncertain. Those exposures not assessed, may or may not be adequately controlled. However, it is not necessary to identify, evaluate and document each and every exposure scenario individually. One general assessment can be done for groups of activities/materials that have low exposure potential, if performed in a well-defined manner under consistent controls. It is necessary that the exposure assessment process encompass all exposures and serve to identify the specific exposures judged unacceptable – requiring additional control, and exposures judged uncertain – requiring additional information gathering in order to resolve the assessment.

Exposure assessment can be a daunting task in the laboratory environment, and similar to other environments, the process can be made practical by identifying Similar Exposure Groups. A Similar Exposure Group (SEG) is a group of workers having the same general exposure profile for the environmental agents being studied because of the similarity and frequency of the tasks they perform, the materials and processes with which they work, and the similarity of the way they perform the tasks.

If the exposures for each individual worker can be assessed there is no need to establish SEGs. However many labs are staffed with numerous employees, and grouping workers into SEGs is often helpful in order to account for all workers and all exposures. While there are many schemes for creating SEGs as described in Chapter 4, there are several practical strategies that can be successfully applied to the laboratory environment. For example, if all of the workers in a single laboratory perform similar work, the laboratory and its workers are a single SEG. On the other hand, if there is significant specialization in work duties, there can be two or more SEGs within a single lab. Also there may be certain tasks associated with potentially significant exposures, and these tasks should be identified as SEGs. In a research-oriented laboratory all of the scientists serving on a research team may be designated as a single SEG.

Industrial hygienists creating SEGs are encouraged to establish a simplified structure and should keep in mind the SEG concept is intended as a practical vehicle for enabling comprehensive exposure assessments. More often than not, fewer SEGs
initially is better. Subsequent iterations of the exposure assessment process offer the opportunity to refine the SEGs associated with the higher exposure risks.

While the identification of SEGs may serve to link individual laboratory workers with exposures, the industrial hygienist is faced with the need to identify those exposures representing an unacceptable or uncertain health risk. Ideally for each SEG, the industrial hygienist should define the exposure profile, that is, the estimated magnitude and variability of exposures for the SEG. The exposure profile for each SEG and (its uncertainty) is compared to the OEL (and its uncertainty), and the comparison yields the exposure assessment. The exposures associated with each SEG are then judged as acceptable, unacceptable, or uncertain.

Obviously the aforementioned methodology can be difficult to apply in many laboratory environments simply because most labs feature numerous exposures and the exposures present are constantly changing. This may necessitate reliance on control banding schemes as described later in this chapter. However, if a control banding scheme is not available or does not provide for sufficient identification and control of exposures, the industrial hygienist will have to utilize the general exposure assessment methodology. For example, it is unlikely a pertinent control banding scheme will be available for a laboratory pilot scale facility, thus necessitating application of the general AIHA® exposure assessment strategy. It is of interest to note the applicability of the OSHA Lab Standard to pilot plants is subject to interpretation*, and if the laboratory-scale definition is not met, the full requirements of substance-specific standards are applicable.(24)

4. Further Information Gathering

Exposures judged uncertain must be resolved. That is, uncertain exposures should ultimately be judged as acceptable or unacceptable. Further information must be gathered in order to reduce the uncertainty to a point at which the industrial hygienist can complete the exposure assessment. The further information may be monitoring data (providing a measure of the exposure level), or the further information may be health effects data (providing the information needed to establish an OEL.) On frequent occasions and especially in the dynamic laboratory environment, it can be more practical and protective to simply control an uncertain exposure, rather than expend resources on exposure monitoring or a toxicological evaluation of a chemical agent.

Monitoring

The AIHA® exposure assessment strategy recommends a threshold of ten percent (10%) of the OEL as a trigger for beginning to collect exposure monitoring data to support the exposure judgment. In many laboratory environments there is ample reason to believe that exposures will not exceed 10% of the OEL in view of the small quantities of chemicals in use, and the presence of commonly applied engineering and work practice controls. Although few laboratory personal monitoring studies have been published, reports of those studies appearing in the literature generally (but not consistently) show exposures at levels where baseline and periodic monitoring may not be necessary.

In a 1996 study at the Massachusetts Institute of Technology (MIT)(25), 132 air samples were collected to measure airborne exposures for 23 different chemical agents in research and teaching laboratories affiliated with the departments of

Material Science, Chemical Engineering, and Biology. All monitoring results were below OELs. However 5% of samples exceeded 10% of the OEL. The higher exposures were apparently associated with chemical handling on open bench tops rather than within chemical fume hoods.

Another study at MIT\(^\text{26}\) evaluated the use of benzene, formaldehyde, chloroform, methylene chloride, and arsenic compounds. Exposures were measured in the eight (of 88) laboratories featuring the highest exposure potential. Nearly all of the monitoring results were well below 10% of the OEL. One sample representing the methylene chloride exposure associated with a flash chromatography task exceeded the Short Term Exposure Limit. This unacceptably high exposure occurred as a result of inadequate air flow in a chemical fume hood.

Potentially significant airborne exposures to acrylamide were reported for biomedical laboratory personnel using crystalline or commercially available solutions of acrylamide to make polyacrylamide gels.\(^\text{27}\)

Brookhaven National Laboratory (BNL) applied the AIHA exposure assessment strategy in its research operations. Numerous air samples were systematically collected, and without exception the measured exposures did not approach OELs for chemical tasks performed within fume hoods. BNL now focuses their laboratory exposure monitoring on chemicals featuring low OELs (less than 1 ppm), high vapor pressures (greater than 100 mm Hg), and transfer quantities exceeding 100 milliliters.\(^\text{28}\)

Collectively the aforementioned studies suggest that exposure assessments (and personal monitoring to measure exposures exceeding 10% of the OEL) should be focused on tasks involving highly toxic and volatile chemicals handled without the benefit of local exhaust ventilation and in relatively large quantities for bench scale laboratories.

---

**Mathematical Modeling**

A robust laboratory health and safety program will feature the prospective assessment of the exposures associated with newly planned research projects and other laboratory operations. Mathematical models can be used to prospectively estimate the magnitude of exposures associated with normal operations and failure conditions. Mathematical models can be used to provide an initial low cost estimate of the maximum exposure potential possibly obviating the need to conduct more expensive air monitoring.\(^\text{29}\) In one study, the “zero ventilation model” and the “well mixed room model” were used to estimate organic vapor exposures in a university laboratory; air samples were collected to evaluate the performance of the models.\(^\text{30}\) Also mathematical models can be used as a substitute for air monitoring where there are co-existing hazards (e.g., radiological) which may impede personal monitoring. The application of mathematical models in occupational exposure assessments is addressed in Appendix I, and more thoroughly in the AIHA® publication, Mathematical Models for Estimating Occupational Exposure to Chemicals, 2nd edition.\(^\text{31}\)

---

5. **Health Hazard Control**

Health hazard control methods are addressed in Chapter 23, and similar to other workplaces the hierarchy of control strategy underlies the management of unacceptable exposures in laboratories. Primary consideration should be given to hazard elimination, and chemicals replaced with less toxic substitutes where feasible and favorable toward reducing the overall health, safety, and environmental risks.
Generally health hazard control strategies integrate engineering controls, work practice controls and personal protective equipment in comprehensive programs directed at minimizing exposures in the laboratory environment. It is a common practice in laboratories to document research project-specific administrative and work practice controls in Standard Operating Procedures (SOPs). Laboratories feature increased reliance and utilization of standard hazard controls and mitigation strategies frequently based upon control banding schemes as described later in this chapter.

The design of laboratory facilities and key engineering controls are often based upon standards and codes. Engineering resources applied to laboratories include the text by DiBerardinis et al., Guidelines for Laboratory Design – Health, Safety, and Environmental Considerations(2) and American National Standards Institute (ANSI) Z9.5–2012, Laboratory Ventilation.(32) The Centers for Disease Control (CDC) has published guidelines for safe work practices in human and animal medical diagnostic laboratories.(33) Additionally the National Institute for Occupational Safety and Health (NIOSH) has published a comprehensive strategy for managing exposures to engineered nanomaterials in research laboratories. The NIOSH strategy addresses exposure assessment, control banding schemes, and health hazard controls.(34)

Industrial hygienists should consider that the dermal exposure pathway is often the most likely route of exposure for chemical agents in the laboratory environment. For example in chemistry labs, airborne exposures are readily managed by handling volatile chemicals within fume hoods. However, chemicals are frequently transferred by hand through pouring, pipetting, conveying solids by spatula, and other manual techniques. Skin contact can occur either directly or indirectly via contact with contaminated instruments or surfaces. Many laboratory chemicals are corrosive to the skin and others may cause sensitization. Some laboratory chemicals are absorbed through the skin (e.g., sodium cyanide). Consideration should be given to seeking less toxic substitutes for chemicals classified GHS-1 acutely toxic via skin absorption.(21) Laboratory personnel should be encouraged to identify and practice chemical handling techniques that will minimize the likelihood of skin contact. Equipment, tools and work surfaces should be regularly cleaned and good housekeeping maintained to minimize the likelihood of skin contact with contaminated surfaces.

The use of personal protective equipment in laboratory environments is often recommended in view of the inherent uncertainties associated with research activities and as secondary (back-up protection) in the event of a failure condition. For example, single use chemically-resistant gloves are often prescribed as a standard back-up mitigation in chemistry labs where robust work practices directed at precluding skin contact serve as the primary mitigation.

Health hazard controls in bench scale research and laboratory pilot plants can be enhanced by applying the major elements of OSHA’s Process Safety Standard, 29 CFR 1910.119, even if the operation does not have chemicals in quantities that require compliance with the standard.(35) Process failures can result in acute exposures. For example, toxic gases may be used to create controlled test atmospheres, and an accidental release into the laboratory could result in a harmful exposure. A good process safety management program will encourage fail-safe designs, and improve the reliability of engineering and administrative controls. The major elements of process safety management include process hazard analyses, operating procedures, training, pre-start up reviews, management-of-change, employee involvement, incident investigations, emergency planning, and compliance audits.(22,36)
The initial and continuing effectiveness of each health hazard control strategy must be verified. For example, chemical fume hoods are periodically surveyed to confirm their performance. Additionally, chemical fume hoods are often equipped with air flow monitors and alarms to warn users of reduced performance or equipment failure. While these measures provide for a capable facility, chemical fume hood users must know and understand those parameters that contribute to the safe use of chemical fume hoods. Prescribed work practice controls should address the arrangement of equipment within the hood in order to avoid air flow distortions, lowering the sash as much as possible while maintaining a comfortable working posture, transferring chemicals six or more inches into the hood, and avoiding nearby activities that could create turbulence and affect hood performance. While these work practice controls must be conveyed through training, it is equally important to verify implementation through observational inspections and audits.

**Hazard Bands**

Hazard bands may be used to support exposure assessments or provide for standard hazard control strategies in the laboratory environment. Hazard banding is an evolving exposure management tool and at this time there are essentially two hazard-banding tools, OEL-Bands and Control Bands. Chapter 25 provides an in-depth review of various hazard-banding methodologies.

OEL-Bands are used to facilitate the identification of an OEL in the absence of a formal OEL. Presently the National Institute for Occupational Safety and Health (NIOSH) is developing a system for classifying chemical agents, absent OELs, into one of five OEL-bands. Each band represents an OEL expressed as range of airborne concentrations. The NIOSH system features a three-tier methodology and eight standard health endpoints for the classification of a specific chemical into an appropriate OEL-band. Tier 1 is a simple and rapid method utilizing Global Harmonization Standard (GHS) chemical hazard ratings. Tier 2 is a semi-quantitative methodology that produces a more refined OEL-Band. Tier 3 relies on expert judgment and a critical evaluation of dose-response data. The NIOSH decision logic can be applied in laboratories to facilitate the assessment of chemical agents that do not have formal OELs.

**Control Bands**

Control bands associate OEL-Bands (or other hazard criteria) with standard health hazard controls. Control bands were originally developed to manage exposures to new chemical compounds created in the pharmaceutical industry. An example was presented in Chapter 5, Table 5.3 where each band is linked with standard engineering containment levels ranging from “good manufacturing processes” to “no human intervention.” AIHA has published guidance for conducting control banding analyses.

Control banding schemes are sometimes applied in the laboratory environment where it is impractical to apply the general exposure assessment methodology in view of the variable operations present in labs, the absence of OELs for many environmental agents, and the difficulty of performing exposure monitoring in the lab environment. Since operations and associated exposures differ from lab to lab, and possibly from worker to worker, it is often worthwhile and necessary to consider grouping workers into SEGs in order to accurately target the application of control banding schemes to laboratory workers.
Here are several control banding schemes applied in laboratories:

**Prudent Practices**

The National Research Council publication, Prudent Practices in the Laboratory – Handling and Management of Chemical Hazards is a comprehensive resource for chemical laboratory safety. Prudent Practices provides strategies for minimizing exposures via inhalation, skin contact and ingestion. These strategies, if effectively implemented, will control most every chemical exposure to acceptable levels in bench scale chemistry laboratories. The following is a summary of the recommended Prudent Practices:

**Engineering Controls:**

- Use a fume hood for volatile chemicals or aerosol generating tasks.
- Use fume hoods properly (at proper face velocity, work 6 inches back, keep sash at lowest position, minimize items in hood).

**Work Practices:**

- No eating, drinking, smoking, gum chewing, applying cosmetics in the lab.
- Good housekeeping.
- Special care when handling solutions of chemicals in syringes.
- No mouth pipetting.
- Wash hands after working with chemicals regardless of the use of gloves.

**Personal Protective Equipment (PPE):**

- Wear safety glasses with side shields wherever chemicals are stored or used.
- Use tight-fitting chemical goggles when there is danger of splashing – supplemented with a face shield when the splash hazard potential is high.
- Wear a lab coat.

The strategies presented in Prudent Practices have been adopted as standard mitigations in many laboratories. These standard mitigations can be thought of as a single control band however these practices may not provide for sufficient control of exposures in all circumstances. For example, one standard mitigation practice is the prescribed use of volatile chemicals in a fume hood. However there may be scenarios such as the use of a highly toxic and highly volatile chemical in a scaled-up reaction, where a fume hood does not provide adequate protection, necessitating an alternate or enhanced control strategy (e.g., substitution, use of a glove box). Accordingly it is necessary to augment the application of Prudent Practices with a management system that will uncover laboratory activities that may not be adequately controlled by the standard practices.

**OSHA's Laboratory Standard**

OSHA’s Laboratory Standard can be viewed as a control banding scheme. Appendix A of the OSHA Laboratory Standard, while non-mandatory, calls for the implementation of standard health and safety practices and controls in chemistry laboratories as recommended in Prudent Practices. The OSHA Laboratory Standard requires laboratories to consider additional controls for “particularly hazardous substances”, including acutely toxic chemicals (e.g., GHS-1), select carcinogens, and reproductive toxins. Essentially the standard “prudent practices” applied to all chemicals are one control band, and the additional practices that may be applied to particularly hazardous substances are a second control band. The additional practices
include the identification of designated work areas, use of chemical fume hoods or other containment devices, and decontamination procedures.

**Chemical Safety Levels**

A “Chemical Safety Level” (CSL) control banding scheme for use in microbiological and biomedical laboratories was proposed by Hill, Gaunce, and Whitehead. Under this scheme, laboratories using the CSL system are classified into one of four chemical safety levels: they are CSL1 (low risk), CSL2 (moderate risk), CSL3 (substantial risk) and CSL4 (high risk). The classification of laboratories into one of four levels is based upon specific health and safety criteria, including the toxicity of the chemicals in use and the work performed in the lab. Instrumental labs using small vials with septum or screw cap closures generally fall into the CSL1 (low risk) level. Standard chemistry labs featuring chemical fume hoods most often fall into the CSL3 (substantial risk) level.\(^\text{44}\)

The Chemical Safety Level controls are comprehensive and logically graduated. The CSL system includes a set of standard safety practices that apply to all levels; they include engineering features, a chemical inventory, PPE, disallowance of eating, drinking and smoking, good housekeeping, and access to emergency equipment. Additional controls are prescribed for CSL levels 2 through 4. The CSL 4 controls are quite rigorous and include controlled access, independent ventilation systems, and dressing rooms with showers. It should be noted that the underlying toxicity criteria classify confirmed human carcinogens and teratogens into the CSL 4 level. Human carcinogens and teratogens (e.g., dichloromethane, toluene) are commonly used in many chemistry labs but the prescribed CSL 4 controls are likely greater than necessary to effectively minimize exposures and may be viewed as impractical.\(^\text{44}\)

In response to recommendations from the U.S. Chemical Safety Board\(^\text{45}\), the American Chemical Society (ACS) published recommendations for identifying and evaluating hazards in research laboratories. The publication includes a chapter addressing the use of Chemical Safety Levels as a control banding strategy for managing exposures in laboratories.\(^\text{46}\)

**Ventilation Control Bands**

Cornell University developed a control banding scheme used to identify the appropriate general ventilation rates for chemistry laboratories. The ventilation rates, measured in air changes per hour (ACH), are based upon a decision logic and criteria, including GHS health hazard ratings and chemical usage. The control bands use a default rate of 8 ACH when a laboratory is occupied and 4 ACH when unoccupied. When conditions allow, the alternate control band is 6 ACH occupied and 3 ACH unoccupied.\(^\text{47}\)

**CDC Biosafety Levels**

The U.S. Center for Disease Control and Prevention and the National Institutes of Health recommends a control banding scheme described in the publication, Biosafety in Microbiological and Biomedical Laboratories (BMBL).\(^\text{48}\)

The BMBL publication identifies four biosafety levels ranging from 1-Agents not known to cause disease in health adults, to 4-Dangerous exotic agents that pose a high risk. Standard facilities and mitigations (e.g., containment, work practices, PPE) appropriate for the operations and routes of transmission for infectious agents are prescribed for each of the four biosafety levels. Biosafety Levels 1 through 4 are summarized in Table 21.1. Standard microbiological practices include hand-washing,
Table 21.1. Summary of CDC Biosafety Levels for Infectious Agents

<table>
<thead>
<tr>
<th>BSL</th>
<th>Agents</th>
<th>Practices</th>
<th>Primary Barriers and Safety Equipment</th>
<th>Facilities (Secondary Barriers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not known to consistently cause diseases in healthy adults</td>
<td>Standard microbiological practices</td>
<td>- No primary barriers required.</td>
<td>Laboratory bench and sink required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- PPE: laboratory coats and gloves; eye, face protection, as needed</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Agents associated with human disease</td>
<td>BSL-1 practice plus:</td>
<td>Primary barriers:</td>
<td>BSL-1 plus:</td>
</tr>
<tr>
<td></td>
<td>Routes of transmission include percutaneous injury, ingestion, mucous membrane exposure</td>
<td>- Controlled access</td>
<td>- BSCs or other physical containment devices used for all manipulations of agents that cause splashes or aerosols of infectious materials</td>
<td>- Autoclave available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Decontamination of all waste</td>
<td>- PPE: Protective laboratory clothing, gloves, face, eye and respiratory protection, as needed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Decontamination of laboratory clothing before laundering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Indigenous or exotic agents that may cause serious or potentially lethal disease through the inhalation route of exposure</td>
<td>BSL-2 practice plus:</td>
<td>Primary barriers:</td>
<td>BSL-2 plus:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Controlled access</td>
<td>- BSCs or other physical containment devices used for all open manipulations of agents</td>
<td>- Physical separation from access corridors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Decontamination of all waste</td>
<td>- PPE: Protective laboratory clothing, gloves, face, eye and respiratory protection, as needed</td>
<td>- Self-closing, double-door access</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Decontamination of laboratory clothing before laundering</td>
<td></td>
<td>- Exhausted air not recirculated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Negative airflow into laboratory</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Entry through airlock or anteroom</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Hand washing sink near laboratory exit</td>
</tr>
<tr>
<td>4</td>
<td>Dangerous/exotic agents which post high individual risk of aerosol-transmitted laboratory infections that are frequently fatal, for which there are no vaccines or treatments</td>
<td>BSL-3 practices plus:</td>
<td>Primary barriers:</td>
<td>BSL-3 plus:</td>
</tr>
<tr>
<td></td>
<td>Agents with a close or identical antigenic relationship to an agent requiring BSL-4 until data are available to redesignate the level</td>
<td>- Clothing change before entering</td>
<td>- All procedures conducted in Class III BSCs or Class I or II BSCs in combination with full-body, air-supplied, positive pressure suit</td>
<td>- Separate building or isolated zone</td>
</tr>
<tr>
<td></td>
<td>Related agents with unknown risk of transmission</td>
<td>- Shower on exit</td>
<td>- Dedicated supply and exhaust, vacuum, and decontamination systems</td>
<td>- Other requirements outlined in the text</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- All material decontaminated on exit from facility</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Laser Hazard Classes

The American Conference of Governmental Industrial Hygienists (ACGIH®) has established and maintains Threshold Limit Values (TLVs®) for laser radiation. The unit of measure for the TLVs® is generally listed in Joules per square centimeter (J/cm²). According to the ACGIH®, it is not necessary to determine laser irradiances or radiant exposures for comparison to the TLVs because the likelihood of hazardous exposure can be minimized by adhering to ANSI Z136.1, American National Standard for Safe Use of Lasers.

ANSI Z136.1 includes a control-bandng scheme applicable to the use of lasers in the laboratory, as well as other work environments. The ANSI standard is based upon the classification of laser radiation emission sources into one of seven hazard classes (1, 1M, 2, 2M, 3R, 3B, or 4). Under this scheme, a laser or laser system is classified based on its radiant power and potential hazard. Control measures are specified for each hazard class, and the higher the hazard class number, the more stringent the control measures. The laser safety control requirements are summarized in Table 21.2. The control measures are commensurate with the laser or laser system’s capability to injure personnel, the environment in which the laser is used (e.g., access to the laser beam path), and the personnel who may use the laser or be exposed to its emissions (e.g., individuals trained – or untrained – in laser safety).

*A laser system is an assembly of electrical, mechanical, and optical components that includes a laser.*
Control strategies specific to laboratory use of lasers in research, development and testing are described in ANSI Z136.8, American National Standard for Safe Use of Lasers in Research, Development and Testing. The control strategies are based upon the laser beam (e.g., pulse compression or amplification), beam path (e.g., air or vacuum), configuration (e.g., level of enclosure), interaction between the beam and target materials (e.g., generation of air contaminants), the environment in which the laser is used (i.e., level of access and restrictions), and the personnel who may use or be exposed to the laser’s radiation.

### Radiofrequency Safety Program Categories

Control banding principles can also be applied to managing the radiofrequency exposures associated RF generators that may be used as energy sources in laboratory experiments. The ACGIH® Threshold Limit Values® for Radiofrequency and Microwave Radiation reference the Institute for Electrical and Electronic Engineers (IEEE) standard C95.7 Recommended Practice for Radio Frequency Safety Programs. Under IEEE C95.7–2014, RF sources are classified into one of four categories.
hazard categories. The greater the level of exposure, the higher the Radio Frequency Safety Program Category (RFSP). See Table 21.3. Category 1 requires few controls while category 4 requires rigorous controls. Two sets of exposure limits are used to determine into which category an RF source is placed. The upper tier limits apply to controlled occupational environments and are less restrictive. The lower tier limits apply to the general public and are more restrictive.

### Control Banding Limitations

Control banding schemes, although generally practical and effective, will not provide for sufficient control of exposures in all circumstances. The laboratory control banding scheme should be augmented with a management system or administrative procedure that will identify activities that may not be adequately controlled by the standard mitigations, thereby providing notification and involvement of industrial hygiene professionals who will prospectively assess the exposures and recommend alternate or enhanced control strategies. The management system or administrative procedure can be very simple or quite sophisticated depending upon the laboratory operations and organization. At the very least, laboratory staff need to know how to recognize and handle day-to-day process or material changes that require additional review.(22) Ideally laboratory personnel and other stakeholders should be involved in composing the management system or administrative procedure to ensure its practicality and effectiveness.

---

<table>
<thead>
<tr>
<th>RFSP Category</th>
<th>Maximum Potential Exposure Condition*</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operational characteristics of source(s) would not cause applicable RFSPILs (Radio Frequency Safety Program Initiation Levels) or lower tier limits to be exceeded.</td>
<td>None required, unless maintenance or other conditions [e.g., RF interaction with medical devices / implants and/or presence of electro-explosive devices(s)]</td>
</tr>
<tr>
<td>2</td>
<td>Operational characteristics of source(s) may cause the lower tier limits to be exceeded, but the upper tier limits would not be exceeded in accessible areas.</td>
<td>RF exposure control policy / operating procedure · Program administrator (RF Safety Officer) · Use of signs · General RF safety awareness training · RF safety program audits</td>
</tr>
<tr>
<td>3</td>
<td>Lower tier exceeded and potential to exceed the upper tier exposure limit in accessible areas unless mitigating controls are applied.</td>
<td>Category 2 controls and · Inventory of RF sources / exposure situations · Exposure assessment · Safe work practices · Personal and / or area monitors</td>
</tr>
<tr>
<td>4</td>
<td>Exposure will exceed ten times the upper tier exposure limit in accessible areas.</td>
<td>Category 3 controls and · Positive access control barriers · Use of lock-out tag-out procedures · Personal protective equipment</td>
</tr>
</tbody>
</table>

*In assessing the characteristics of an RF environment, consideration should be given to the potential for excessive exposure in the case of an accidental failure of systems that normally preclude excessive exposure such as breaks in waveguides.
Some laboratories have established research project-specific envelopes. These envelopes specify the equipment and chemicals in-use with operating limits and quantities. Researchers are not allowed to work outside of the envelope without acquiring a health and safety review and authorization to modify the operating envelope. The review may reveal the need for new or enhanced mitigations, including engineering controls, administrative controls, or personal protective equipment. Langerman has recommended laboratory-specific quantity limits for chemicals, and if those limits will be exceeded there should be a compulsory procedure to call for assistance.\(^{(36)}\)

Many laboratories require preauthorized acquisition and use of infectious organisms, laboratory animals, recombinant DNA molecules, and radioactive materials. These targeted programs can serve to facilitate the timely involvement of the industrial hygienist, thereby affording the opportunity to apply exposure assessment principles where needed in order to effectively and efficiently identify and control health hazards.

Some institutions have established programs requiring review and authorization prior to commencing use of selected chemicals. The University of Texas Health Science Center at Houston requires laboratory personnel to obtain approval prior to using selected highly toxic compounds, carcinogens, pesticides, unstable compounds, toxic gases, and antineoplastic agents.\(^{(53)}\)

Many private and public-sector laboratories and especially research-oriented universities are complex organizations and the deployment of administrative procedures can be challenging. Consideration should be given to training laboratory staff in order to improve their understanding of the standard mitigation strategies and when to contact health and safety professionals for assistance.

**Summary**

Similar to any workplace, the chemical, physical and biological exposures present in laboratories must be assessed in order to effectively target appropriate health hazard controls. The laboratory exposure assessment process must be comprehensive in order to determine the acceptability of each hazard. Those exposures not assessed may or may not be adequately controlled.

Here is a summary of the exposure assessment practices recommended in this chapter:

- Each organization featuring one or more laboratories should establish a written exposure assessment program addressing how exposures in its operations will be assessed, by what criteria, and by whom. The exposure assessment program can be integrated into the Chemical Hygiene Plan prescribed by OSHA.
- Exposure assessments should be performed by an industrial hygiene professional or other properly trained laboratory personnel (e.g., Chemical Hygiene Officer) operating under the review of an industrial hygienist.
- Exposure assessments in complex laboratories or large facilities can be made practical by identifying Similar Exposure Groups.
- In many laboratory environments there is ample reason to believe that exposures will not exceed 10% of the OEL in view of the small quantities of chemicals in use, and presence of commonly applied engineering and work practice controls. Although few laboratory personal monitoring studies have been published, reports of those studies appearing in the literature generally (but not consistently) show exposures at levels where baseline and periodic monitoring may not necessary.\(^{(25–28)}\) The exposure assessment process
may reveal some SEGs that should be monitored in order to complete the exposure assessment and if needed, target health hazard controls and medical surveillance.

- Industrial hygienists should consider that the dermal exposure pathway is often the most likely route of exposure for chemical agents in the laboratory environment. Consideration should be given to seeking less toxic substitutes for chemicals classified GHS-1 acutely toxic via skin absorption. Laboratory personnel should be encouraged to identify and practice chemical handling techniques that will minimize the likelihood of skin contact. Single use chemically resistant gloves are often prescribed as a standard back-up mitigation in chemistry labs where robust work practices directed at precluding skin contact serve as the primary mitigation.

- Laboratories should adopt standard control strategies and mitigations if available and effective (e.g., National Research Council’s Prudent Practices). Standard control strategies are often applied as control banding schemes.

- Standard control strategies (e.g., control banding schemes) should be augmented by a management system or administrative procedures to facilitate the identification of exposures that may not be adequately controlled by the standard mitigations, thereby requiring specialized evaluation by the industrial hygienist. These management systems can be simple or quite sophisticated depending upon the needs of the organization. They may include lab-specific quantity limits for chemicals, additional mitigations for particularly hazardous substances, requirements to obtain authorization to use selected chemical, physical or biological agents, or chemical envelopes embedded in a research project permitting system.

- If a standard control strategy is not available for a laboratory operation, consideration should be given to developing a new strategy perhaps based upon control banding. A new control banding scheme could be based upon OEL-bands or a tiered categorization of hazards, and each band linked to standard controls. The scheme should be validated through monitoring or modeling to verify that the standard mitigations will indeed effectively control exposures below OELs. In the absence of a standard control strategy, the industrial hygienist must utilize the general exposure assessment methodology described in Chapters 1 through 11.

- Laboratory health and safety programs should include a management-of-change process to enable the prospective identification of hazards associated with modifications to the workplace, workforce or environmental agents.

Acknowledgements: Thank you to the AIHA® Laboratory Health and Safety Committee including Diana Peroni, Joe Damiano, Steve Hemperly and Tim Roberts. A Special thank you to Ken Kretchman who authored the previous version of this chapter and contributed to the update. Additional thanks are extended to Bill Galdenzi, Michael E. Miller, Sherolyn Bishop and Demetra Barlas who contributed as well.

References


49. **American Conference of Governmental Industrial Hygienists (ACGIH®):** *Documentation of Threshold Limit Values for Physical Agents (TLV®-PA).* Cincinnati, OH: ACGIH®.


