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HEALTHIER WORKPLACES | A HEALTHIER WORLD

Hierarchy of Controls

White Paper

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TABLE OF CONTENTS

Executive Summary

The hierarchy of controls (HoC) is a fundamental model utilized by industrial hygienists to select and recommend one or more control strategies offering reliable worker health protection and practical deployment. This white paper is a high-level discussion of the application of the hierarchy of controls, providing resources to take this key approach for a variety of professionals and to apply it consistently to many different occupational and environmental health and safety (OEHS) issues facing the public and workers today.

The use of the word *hierarchy* (of controls) dates to the 1950s as an historic and common convention for principles of control and thereby generally applied as a means of rank ordering types of control regarding accessibility and effectiveness. As the various iterations of the HoC evolved alongside business management practice, elimination of the hazard has been maintained as best practice for safety and health.

The variety of models presented in this document provides a systematic approach to priorities and implement control measures to eliminate or minimize workplace hazards and risks. Some are simple and some are complex, but each one of them begins with elimination of the hazards using Prevention through Design (PtD). For example, the NIOSH *Total Worker Health* (TWH) model integrates protection from work-related hazards with efforts to promote worker well-being. The TWH HoC is designed to be used iteratively with the traditional HoC and is particularly applicable in managing risks of psychosocial hazards. Ultimately, the plan to reduce risk can be presented to management decision-makers for their approval by selecting the appropriate model for an organization.

The layers of the HoC range from elimination, or deciding against the introduction of the hazard at the outset, to controls that may well introduce the most burden on production personnel, administrative controls, or the use of personal protective equipment (PPE). Certain levels of control, such as engineering controls like enclosure or local exhaust ventilation (LEV) may not be sufficient in achieving the desired level of risk control. Administrative controls, PPE, or other tools may be used in combination (a layered approach) to achieve the risk reduction target.

Additional guidance on appropriate implementation of the HoC, as well as valuable insight and tools to promote efficient and cost-effective risk mitigating control measures within the process of workplace risk management is offered in this document. In addition to detailed coverage of various HoC models as described in the literature, case study examples further illustrate useful tools and appropriate considerations in the innovative and sustainable application of effective controls.

The business case tool is an asset in implementing the HoC and should become a customary part of managing change within an organization. Readily available and accessible tools and strategies are shared to assist with making the business case for control improvements, supporting the concept that control improvements are often justified from both a health and economic perspective. There are always costs associated with administrative and PPE controls that should not be overlooked.

Confirming the effectiveness of control measures is a crucial step in risk management. It involves monitoring and reassessing the functionality of controls to ensure they are reducing exposure levels and risks within acceptable parameters. By reassessing control measures, valuable data can be obtained for prioritizing resource allocations and justifying improvements to the hierarchy of controls.

A risk management plan reflecting these principles should be developed and implemented as early as possible in the planning of new and reassessment of existing processes. Integration and harmonization of the risk management plan with the organization's culture is critical to success.

Introduction

The HoC has long been recognized as a method of identifying and ranking safeguards to protect workers faced with OEHS hazards and risks. Many versions of the well-known HoC pyramid have been described in the OEHS literature over the past 50 years. At its core, this risk management framework provides a structured methodology aimed at instituting the most effective means of risk reduction first.

In order to establish safety and accountability in modern risk management, it is important to develop a strategy that takes into consideration specific hazards and system needs. However, the fundamental premise of the HoC is that risk management by design, or Prevention through Design (PtD) (i.e., not introducing a hazard into the workplace from the start), is the most effective way to manage risk, and that the use of PPE is the least effective method to eliminate or reduce risks.

While the most effective controls will vary by workplace and hazard, using the HoC is a good starting point for identifying goals and continuously pursuing effective risk prevention and mitigation. To effectively move up the HoC, a well-planned, prioritized approach is necessary. This involves identifying and justifying the benefits of higher-level controls and providing a systematic approach to their implementation.

Every stakeholder from upper management, engineering, supervision, and hourly production workers should know and understand the trade-offs and timelines when this model is effectively applied to preventing and mitigating risk. Overall, using the HoC can help organizations develop a more robust and effective risk management strategy.

Ultimately, with effective use of the HoC, organizations can create a foundation for continuous improvement, foster a shared understanding and appreciation for risk management among all stakeholders, and ultimately cultivate a workplace environment that prioritizes the well-being and protection of its workers. The impact of implementing the HoC extends far beyond mere risk reduction: it has the potential to transform organizations into safer, more efficient, and more sustainable entities.

In 2023, AIHA conducted a State-of-the-Art/ Continuous Improvement: Airborne Chemical Exposure Assessment Survey, which included questions regarding the HoC. Nearly half of respondents reported gaps in applying the HoC in managing risks. They blamed the lack of resources and deficits in objectively supporting the business case for applying more effective controls such as elimination and engineering controls.

This white paper is provided for the management of OEHS risks, in context with management, labor, and regulatory stakeholder needs and constraints. Recommendations are made for its continued use in a variety of settings as best practice in the risk management process.

Effective implementation requires a concerted, coordinated effort accounting for costs, benefits, and stakeholder input. But an investment in robust life-cycle planning with the HoC leads to appreciable short- and long-term dividends. Before diving into the various hierarchy of controls models used today, it helps to understand where the concept originated.

History

A hierarchical sense of workplace leadership was in vogue during the mid-20th century. The origin of the word hierarchy comes from combining the Greek *hieros* (supernatural or holy) and *archos* (ruler) in reference to the ranks of angels (Merriam-Webster, n.d.). Thus, the use of the word *hierarchy* in this description of hazard controls infers a ranking by consensus, in which various categories of control are ranked superior or inferior to other categories.

In the extension of this language to risk management, the term hierarchy was established in association with the variety of accident control or preventive measures that reflect the consensus of experience at the time.

Barnett and Brickman (1986) published an historical account of published hierarchies of controls including 39 different safety hierarchies dating back to the American Standards Institute's (1953) *Safety Color Code for Physical Hazards* Z53-1, while noting that, by 1985 the general consensus on priorities for control of hazards) was:

1. Eliminate hazard or risk
2. Apply safeguarding technology
3. Use warning signs
4. Train and instruct
5. Prescribe personal protection

In this and a second paper, the authors caution that hierarchy should be understood as just "general consensus" that may not be valid in every circumstance. In fact, the five priorities have also been referred to as *principles of control*, thereby circumventing the determinative meaning of hierarchy (Barnett, 2020). Over time, however, hierarchy became the dominant concept and the term *hierarchy of control* is now widely used. The pyramid has become a well-recognized image listing elimination, substitution, engineering, administration, and PPE in rank order regardless of orientation. It is found in occupational health and safety textbooks (Frumkin, 2016) and is prominent on both NIOSH and OSHA websites.

Hierarchy Model Figures

Visual metaphors are critical to communication in the current milieu of websites, branding and logos, and video displays. They are especially important in accurately conveying complicated science (Mnguni, 2014) and helping learners apply knowledge to new situations (Ziemkiewicz & Kosara, 2008). The word *metaphor* carries the idea that well-recognized images can convey better understanding of new concepts.

Visually, pyramids are the classic metaphor describing the rank-order chain-of-command concept, rising to the pinnacle nearest “the god(s).” The various pyramidal iterations of the HoC have influenced generations of OEHS professionals for more than half a century.

The Classic Inverted Pyramid

The conventional representation of the hierarchy of controls is an inverted pyramid structure conveying prioritization of strategies. Current versions orient the pyramid differently, depending on the agency or application of the controls. The clearest conflict in visual representation between the inverted and typical pyramid is found in the differing images offered by NIOSH (2023) and OSHA (n.d.-a) (Figure 1).

NIOSH elevates elimination to the highest, most effective option for controlling workplace risk, situated at the top vertex, while PPE resides at the base. By contrast, OSHA orients the apex of its pyramid model to convey elimination as an aspirational level, with PPE representing the most readily accessible control. (Figure 1).

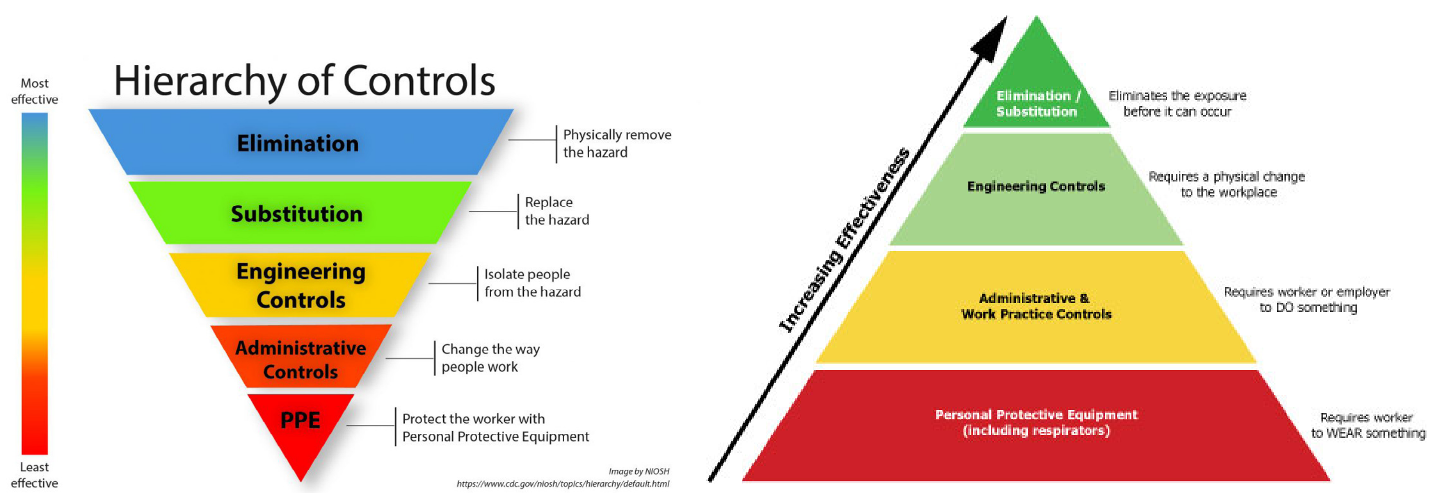


Figure 1. Hierarchy of Controls: Comparison of NIOSH and OSHA
Note. From *Hierarchy of Controls* by NIOSH, 2023 (https://www.cdc.gov/niosh/topics/hierarchy/default.html), and *Chemical Hazards and Toxic Substances*, by OSHA, n.d.-a. (https://www.osha.gov/chemical-hazards/controlling-exposure)

Alternatives to the Classic Model

Seeking to build on the inverted pyramid paradigm, alternate standards' bodies and agencies have since published adapted models. Another risk reduction approach used for chemical risk management is the safer technology and alternatives analysis (STAA) concept promoted in the U.S. EPA's Risk Management Plan (RMP) standard and OSHA's Process Safety Management standard (USEPA/OSHA, 2015). The STAA concept (Figure 2) integrates various strategies to maximize process safety and chemical risk reduction (OSHA, 2017). Additional variations of control hierarchies from ANSI standards are presented in Tables 1 and 2 and Figure 3.

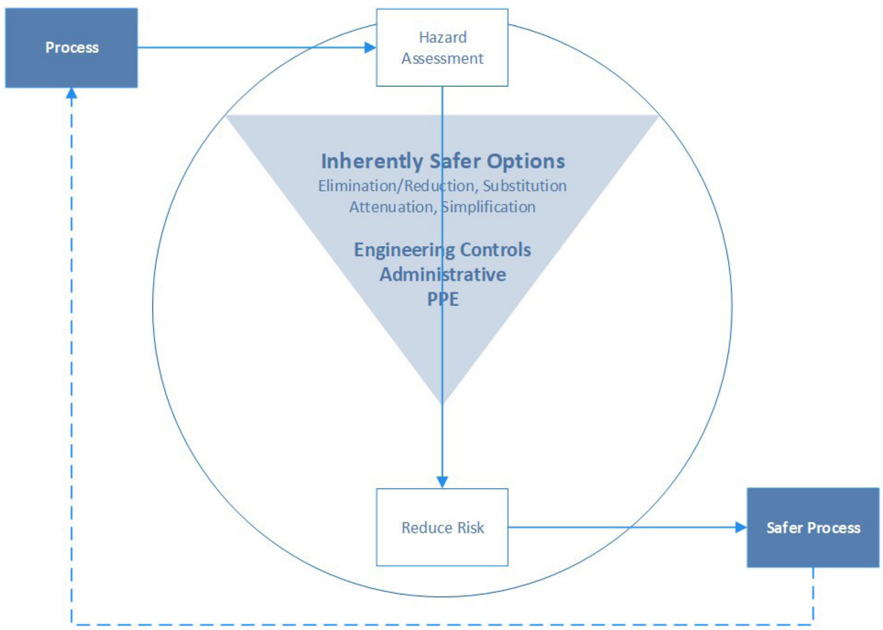


Figure 2. Safer Technology and Alternatives Analysis Concept (STAA)
Note. From *Process Safety Management for Petroleum Refineries: Lessons Learned from the Petroleum Refinery Process Safety Management National Emphasis Program*, by OSHA, 2017. (https://www.osha.gov/Publications/OSHA3918.pdf)

Most Effective

Hierarchy of Health and Safety Controls

CONTROLS	EXAMPLES
1) Elimination	• Design to eliminate hazards, such as falls, hazardous materials, noise, confined spaces, and manual material handling.
2) Substitution	• Substitute for less hazardous material. • Reduce energy. For example, lower speed, force, amperage, pressure, temperature, and noise.
3) Engineering Controls	• Ventilation systems • Machine guarding • Sound enclosures • Circuit breakers • Platforms and guard railing • Interlocks • Lift tables, conveyors, and balancers
4) Warnings	• Signs • Backup alarms • Beepers • Horns • Labels
5) Administrative Controls	Procedures • Safe job procedures • Rotation of workers • Safety equipment inspections • Changing work schedule Training • Hazard Communication Training • Confined Space Entry
6) Personal Protective Equipment	• Safety glasses • Hearing protection • Face shields • Safety harnesses and lanyards • Gloves • Respirators

Least Effective

Table 1. Hierarchy of Health and Safety Controls
Note. From *ANSI Z10-2012 (R2017) Hierarchy of Controls Model*, by ANSI/ASSP, 2017. Reprinted with permission of the American Society of Safety Professionals.

	Risk Reduction Measures	Examples	Influence on Risk Factors	Classification
Most Preferred	Elimination or Substitution	• Eliminate pinch points (increase clearance) • Intrinsically safe (energy containment) • Automated material handling (robots, conveyors, etc.) • Redesign the process to eliminate or reduce human interaction • Reduced energy • Substitute less hazardous chemicals	• Impact on overall risk (elimination) by affecting severity and probability of harm • May affect severity of harm, frequency of exposure to the hazard under consideration, and/or the possibility of avoiding or limiting harm depending on which method of substitution is applied.	Design Out
	Guards, Safeguarding Devices, and Complimentary Measures	• Barriers • Interlocks • Presence sensing devices (light curtains, safety mats, area scanners, etc.) • Two hand control and two-hand trip devices • Enabling devices	• Greatest impact on the probability of harm (Occurrence of hazardous events under certain circumstance) • Minimal if any impact on severity of harm	Engineering Controls
	Awareness Devices	• Lights, beacons, and strobes • Computer warnings • Signs and labels • Beepers, horns, and sirens	• Potential impact on the probability of harm (avoidance) • No impact on severity of harm	Administrative Controls
	Training and Procedures	• Safe work procedures • Safety equipment inspections • Training • Lockout / Tagout / Verify	• Potential impact on the probability of harm (avoidance and/or exposure) • No impact on severity of harm	
Least Preferred	Personal Protective Equipment (PPE)	• Safety glasses and face shields • Ear plugs • Gloves • Protective footwear • Respirators	• Potential impact on the probability of harm (avoidance) • No impact on severity of harm	

Table 2. Safety of Machinery Hazard Control Hierarchy
Note. From *ANSI B11.0-2020 Safety of Machinery*, by ANSI, 2020. Reprinted with permission from B11 Standards Inc.

A well-reasoned, two-step approach to applying controls is presented in an annex to the ANSI B11 standard shown in Figure 3 (ANSI, 2020). The theory presented is that risk treatment should first attempt to eliminate or substitute the hazard, and then consider, in descending order, engineering controls, awareness devices, safe operating procedures, training, and PPE (lower-level controls) to reduce residual risk.

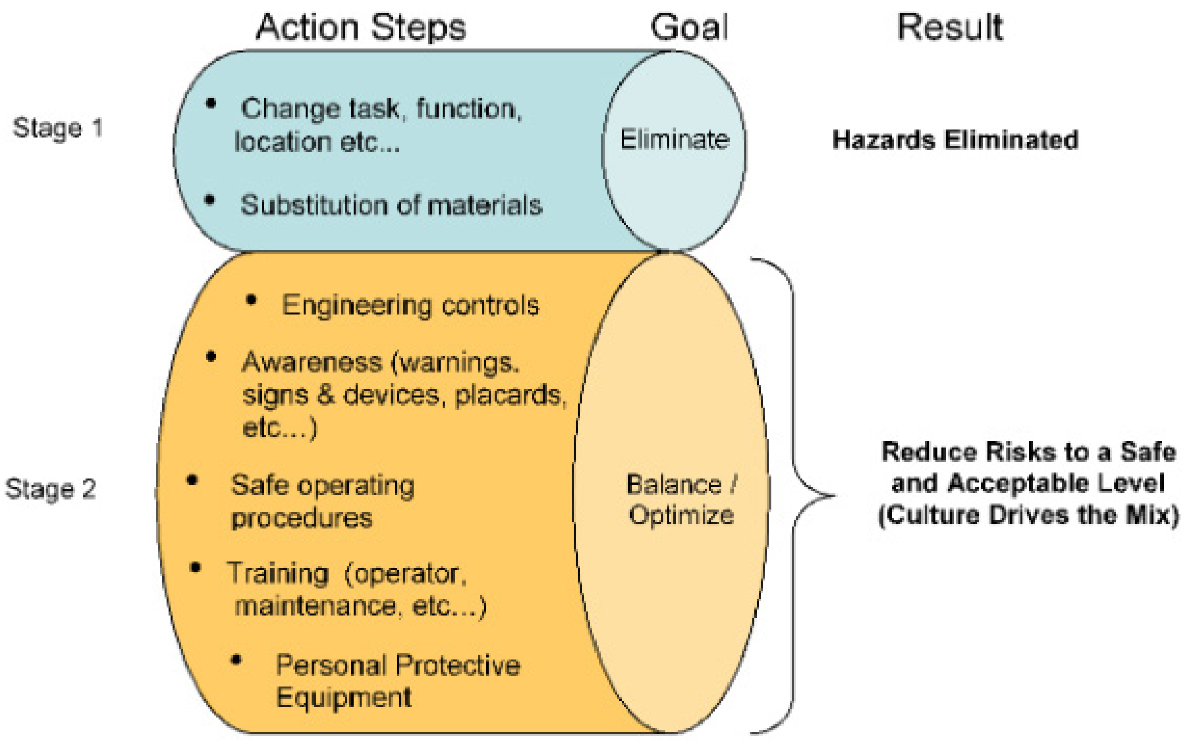


Figure 3. Two-Stage Iterative Approach to the Hierarchy of Controls and Risk Reduction
Note. From *ANSI B11.0-2020 Safety of Machinery*, by ANSI, 2020. Reprinted with permission from B11 Standards Inc.

Among the established models, the ANSI Z590.3 PtD model (Table 3) is a more comprehensive HoC model, since it also includes risk avoidance and warning systems.

Most Preferred	**Risk Avoidance:** Prevent entry of hazards into a workplace by selecting and incorporating appropriate technology and work methods criteria during the design processes.
	Eliminate: Eliminate workplace and work methods risks that have been discovered.
	Substitution: Reduce risks by substituting less hazardous methods or materials.
	Engineering Controls: Incorporate engineering controls/safety devices.
	Warning: Provide warning systems.
	Administrative Controls: Apply administrative controls (the organization of work, training, scheduling, supervision, etc.).
Least Preferred	**Personal Protective Equipment:** Provide Personal Protective Equipment (PPE).

Table 3. Prevention through Design Risk Reduction Hierarchy of Controls Model
Note. From ANSI/ASSE Z590.3-2011, *Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes* (R2016), by ANSI/ASSE, 2016. Reprinted with permission of ASSP.

The Canadian Safety Association (CSA) Standard 1002-12, *Occupational Health and Safety—Hazard Identification and Elimination and Risk Assessment and Control* (CSA Group, 2022) states that measures to control risk should be determined and implemented according to the following hierarchy:

1. elimination
2. substitution
3. engineering controls
4. systems that increase awareness of potential hazards
5. administrative controls
6. PPE

This control labeled "systems that increase awareness of potential hazards"—for example, visual or audible alarms or warning signs—is placed in between engineering controls and administrative controls, much like ANSI Z590.3 (ANSI/ASSP, 2021). In other hierarchies, like the traditional NIOSH (2023) hierarchy, warnings are included in the category of administrative controls.

For risks associated with ergonomics, Lyon et al. (2013) developed a hierarchy of ergonomic risk controls model based on the PtD hierarchy identifying application phases and control examples to aid the user (Table 4).

Hierarchy of Ergonomic Risk Controls			
Control Method	**Stage/Application**	**Control Examples**	**Effectiveness**
Avoidance	Conceptual Stage New Design	Prevent entry of hazard into workplace by design, selection of technologies, equipment and work methods	High
Elimination	Operational Stage Existing Processes Redesign	Eliminate existing hazard by changes in design, technologies, equipment and methods	High
Substitution	Conceptual Stage Operational Stage Existing Processes	Substitute materials, sizes, weights and other aspects to a lower hazard severity or likelihood	Moderately High
Engineering Controls	Conceptual Stage Operational Stage Existing Workstations Redesign	Reduce hazard by changes to workplace, tools, equipment, fixtures, adjustability, layout, lighting, work environment	Moderate
Administrative Controls	Operational Stage Practices and Procedures	Reduce exposure to hazard by changes in work practices, training, job enlargement, job rotation, rest breaks, work pace	Moderately Low
Personal Protective Equipment	Operational Stage Workers	Reduce impact of hazard to employee by use of protective equipment and materials such as vibration attenuation gloves	Low

Table 4. Hierarchy of Ergonomic Risk Controls
Note. Adapted from "Improving Ergo IQ: A Practical Risk Assessment Model," by BK Lyon, G Popov, & K Hanes, 2013, *Professional Safety*, 58(12), p. 26–34.

To provide OEHS professionals with a broader range of risk reduction strategies that include "inherently safer design" concepts, a hierarchy of risk treatment (HoRT) strategies model was included in the 2021 ANSI/ASSP Z590.3 PtD standard.

The objective of OEHS risk management is to implement appropriate risk reduction plans to reduce risks associated with each decision made to achieve an acceptable risk level. OEHS professionals should be able to effectively lead risk assessments, develop appropriate risk reduction strategies, and advise decisions makers in making appropriate decisions.

Risk treatments (i.e., risk controls) are designed to reduce the risk of a hazard's effects and/or reduce the likelihood of its occurrence (i.e., through exposure reduction). A risk treatment plan should include options and alternatives that eliminate the hazard or reduce its risk. The HoRT model (Figure 4) includes 10 risk treatment strategies or tiers, divided into three categories: (1) design/redesign, (2) engineering, and (3) administrative controls.

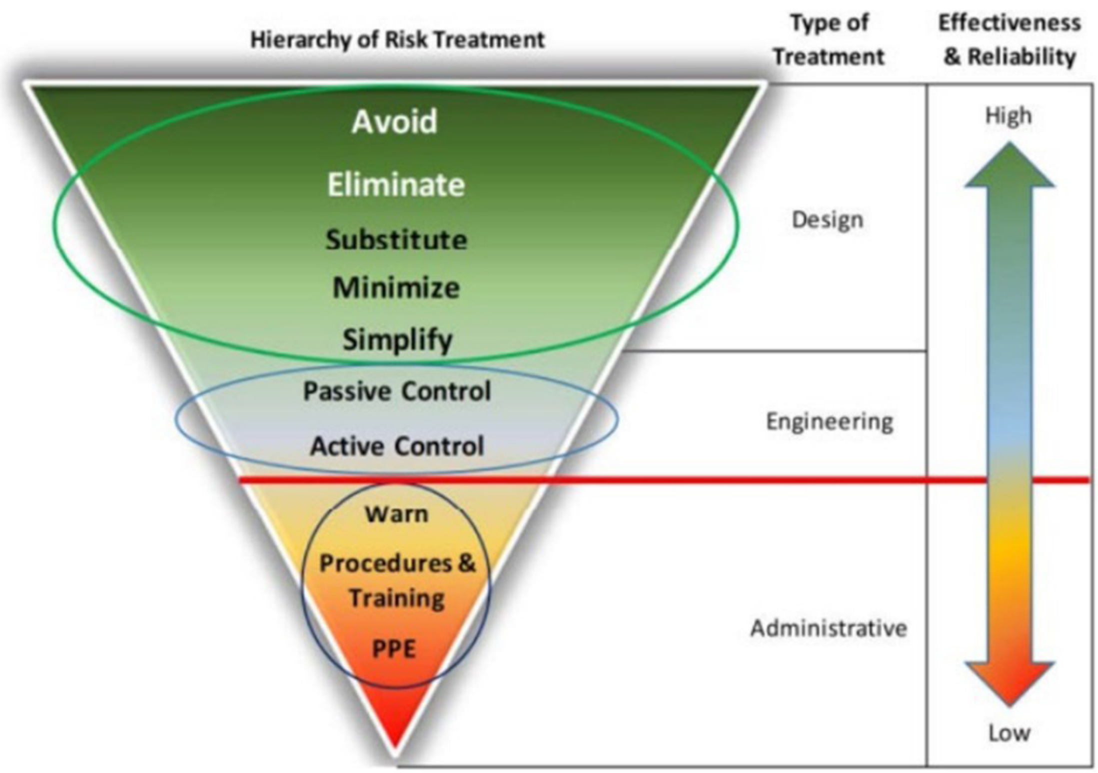


Figure 4. Hierarchy of Risk Treatment (HoRT) with Inherently Safer Design Concepts
Note. Adapted from *Risk Management Tools for Safety Professionals* [ASSP Webinar], by BK Lyon & G Popov, 2018.

An alternative to the "inverted pyramid" model, a modified risk reduction hierarchy model, appears in Figure 5.

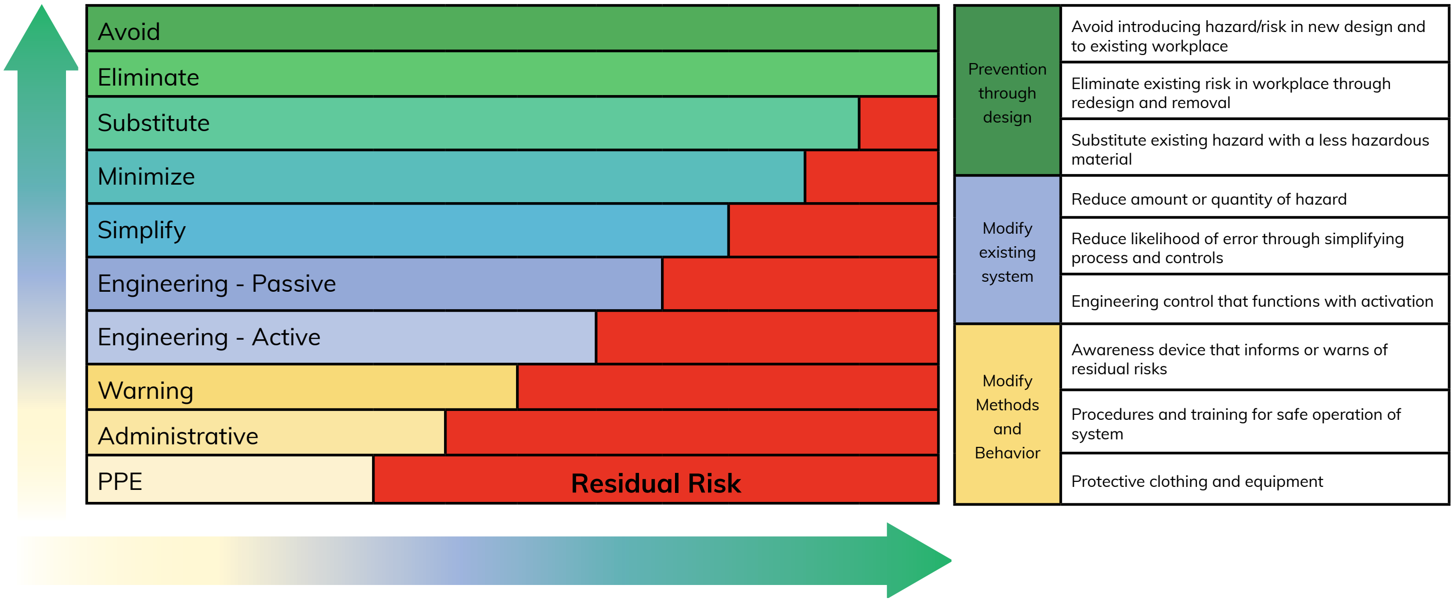


Figure 5. Risk Reduction Hierarchy Model

Note. Adapted from "Risk Treatment Strategies: Harmonizing the Hierarchy of Controls and Inherently Safer Design Concepts," 2019, by BK Lyon & G Popov, *Professional Safety*, 64(5), p. 34–43.

Comparison of Models

A comparison of six of the HoC models and their listed risk treatment strategies is presented in Table 5. The rows represent the various models, while the numbered columns signify the stratification from 5 to 10 risk management strategy levels or tiers within each respective model framework.

Darker shades visually imply techniques considered most favorable and effective for reducing risk reduction within that model. OEHS professionals should evaluate and consider which models and risk reduction strategies best serve the needs of their organizations and applications to reduce residual risk to as low as reasonably practicable (ALARP).

	Risk Treatment Strategies	NIOSH PtD	ANSI Z10	ANSI B11	ANSI Z590.3	HoRT
Most Effective	Avoid				1	1
	Eliminate	1	1	1	2	2
	Substitute	2	2	2	3	3
	Minimize					4
	Simplify					5
	Engineer - Passive					6
	Engineer	3	3	3	4	
	Engineer - Active					7
	Warn		4	4	5	8
	Administrative	4	5	5	6	9
Least Effective	PPE	5	6	6	7	10

Table 5. Hierarchy of Control Models

Note. Adapted from "Risk Treatment Strategies: Harmonizing the Hierarchy of Controls and Inherently Safer Design Concepts," 2019, by BK Lyon & G Popov, *Professional Safety*, 64(5), p. 34–43.

A comprehensive risk assessment should be in place to characterize, evaluate, and prioritize risks across all functions. This allows decision-makers to consider all identified risks in context, weigh them against one another, and determine where resources for risk management are most critically needed.

The highest priority risks should be addressed first through avoidance, elimination, reduction, or control measures. For more complex risk management situations with multiple competing priorities, a risk treatment or implementation plan may be required to document the reasons for selecting control options, their expected benefits, and the methods of implementing the controls.

Selection of the most appropriate risk reduction strategies to achieve ALARP can be achieved by using a decision tree. Figure 6 illustrates such a risk reduction strategy decision tree (Lyon & Popov, 2018) that can be used in the risk treatment planning process.

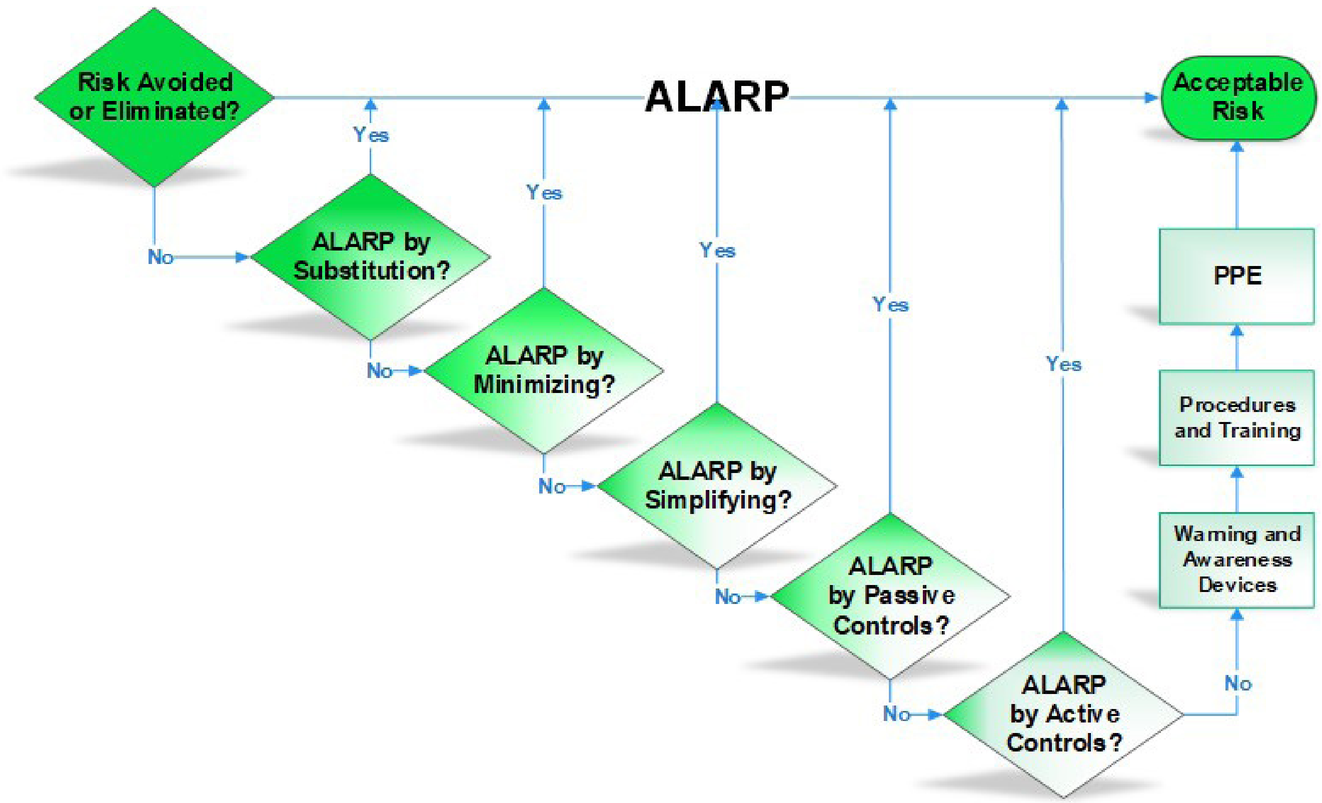


Figure 6. Risk Reduction Strategy Decision Tree
Note. From *Risk Management Tools for Safety Professionals* [ASSP Webinar], by BK Lyon and G Popov, 2018.

It is critical that OEHS professionals begin with the highest level risk reduction strategy, avoidance/elimination, and test its feasibility. One should consider the risk level, what is possible, the anticipated costs and potential trade-offs. If avoidance/elimination is not possible, the OEHS professional should formally consider substitution with a less hazardous material or method.

OEHS professionals should evaluate alternative materials, chemicals, or methods for their respective risk levels, perceived benefits, costs, ability to satisfy operational objectives, and decide whether ALARP can be achieved. If further risk reduction is required, the OEHS professional should look at the next strategy of minimizing the "quantity" of the hazard. Certain materials, weights, sizes, chemicals, or energy forms (e.g., voltage, pressure, temperature) can be reduced to ALARP.

For risks that can be reduced through simplified designs, controls, or methods, the OEHS professional should identify acceptable solutions.

The OEHS professional should consider engineering controls based on their effectiveness as well as their reliability, beginning with passive devices followed by active-type controls. The risk reduction strategies at this stage are considered higher-level controls. If process risk cannot be reduced to an acceptable level, it will then be appropriate to incorporate additional tools such as administrative controls and PPE. These will include administrative controls such as warning devices, job hazard analyses, inspections, work procedures, training, and PPE into the risk reduction plan.

The agreed-upon risk reduction plan should be presented and discussed with management decision-makers for approval, modification, and implementation.

Total Worker Health®

Traditionally, occupational safety and health protection programs have primarily concentrated on ensuring that work is safe and that workers' risks of harm arising from the work itself are reduced. The *Total Worker Health* (TWH) approach has been defined by NIOSH (2020b, para. 1) as "policies, programs, and practices that integrate protection from work-related safety and health hazards with promotion of injury and illness-prevention efforts to advance worker well-being."

Building on traditional health and safety protection programs, the TWH approach recognizes that the work environment is one of many social determinants of health, that is, one of many nonmedical factors that influence respective health outcomes (CDC, 2022).

The NIOSH TWH approach is a prioritized strategy to reduce hazards in the work environment, bringing together all aspects of work and nonwork domains in integrated interventions to cooperatively address and advance worker well-being (NIOSH, 2020a).

The NIOSH TWH Hierarchy of Controls (Figure 7) emphasizes organizational-level interventions and employee engagement to protect workers' safety, health, and well-being in the order of:

1. Elimination of workplace conditions or behaviors that threaten health and safety and worker well-being. For example, removing workstations that create an ergonomic hazard, such as improper worker positioning.
2. Substitution or modification of traditional policies, programs, and management practices with safer, health-enhancing policies, programs, and management practices that promote an interdependent culture of safety and health in the workplace. For example, creating management policies that provide workers with increased flexibility over their work and schedules.
3. Redesign of the work environment for improving safety, health, and well-being. This may be accomplished through removing organizational barriers to improving well-being, improving access to employer-sponsored benefits, and providing more flexible work schedules and arrangements.

4. Education and training to enhance worker safety and health education and knowledge for advancing worker well-being. This may be accomplished through supervisor training on effective strategies to reduce stressful working conditions.
5. Encouragement of worker behavioral change to adjust lifestyle habits for the improvement of worker safety and well-being. This may include worker assistance and support to address individual risks, while promoting healthier choices, such as smoking cessation programs or resiliency training for workers to promote stress management and reduction (Nelson et al., 2020; NIOSH, 2020a).

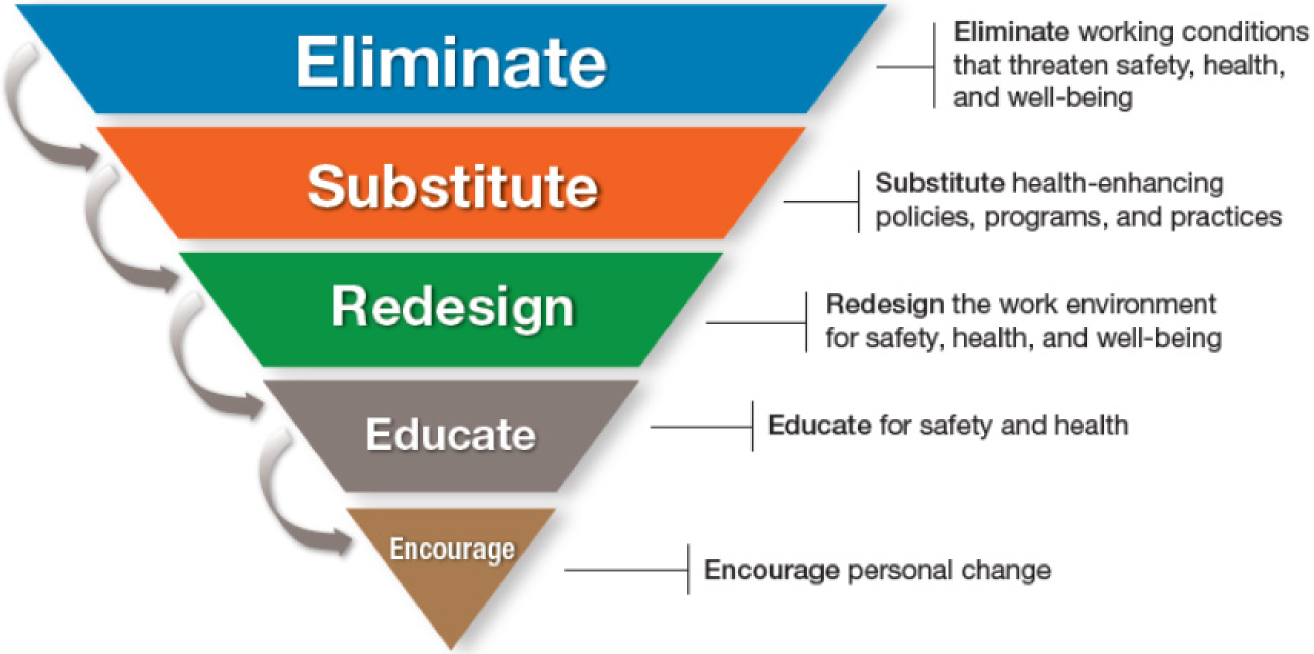


Figure 7. Hierarchy of Controls Applied to NIOSH Total Worker Health®
Note. From *Fundamentals of Total Worker Health® Approaches: Essential Elements for Advancing Worker Safety, Health, and Well-Being*, by NIOSH, 2017.

This companion to the traditional NIOSH HoC of (1) elimination, (2) substitution, (3) engineering controls, (4) administrative controls, and (5) PPE (Figure 1) does not replace the existing model but expands on it to include strategies that advance worker well-being (NIOSH, 2020a). Like the NIOSH HoC, implementation of the TWH hierarchical approach emphasizes elimination as the most effective means of prevention, while addressing overall environmental determinants, rather than focusing on individual-level determinants of health, as a hallmark of TWH programming (Nelson et al., 2020; NIOSH, 2020a; Redinger et al., 2020).

It should be noted that the layer titled "substitution" in the TWH pyramid connects well with the "administrative controls" layer in the NIOSH pyramid, since policies, programs, and practices are administrative activities. However, the first step is always to "eliminate workplace conditions that cause or contribute to worker illness and injury, or otherwise negatively impact well-being" (NIOSH, 2020a).

The TWH HoC is meant to be used in conjunction with the traditional HoC, and it is more applicable than the traditional HoCs in managing risks of psychosocial hazards such as bullying.

The AIHA PR(IH)DE Special Interest Group (SIG) adopted the NIOSH TWH inverted pyramid to address risk management for LBGTQ+ workers. The structure is shown in Figure 8.

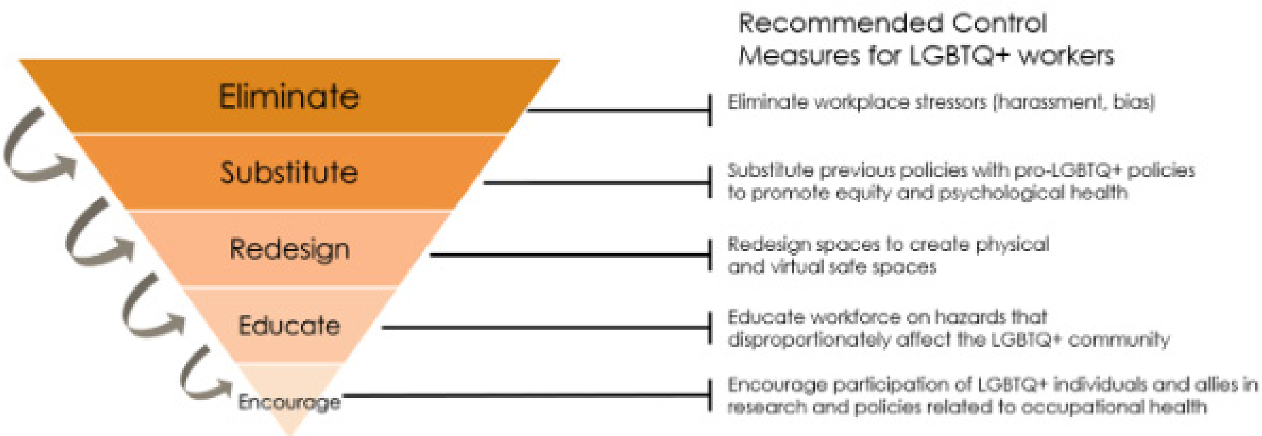


Figure 8. Modified Total Worker Health®
Note. "Importance of LGBTQ+ Ally Training for Advancing Total Worker Health," 2023, by M Ierardi, Pop-up Education Session, AIHce 2023.

As with all approaches to the HoC, the objective is to create a healthier and safer workplace for all workers. The PR(IH)DE approach focuses on those stressors that impact psychosocial as well as physical safety.

Implementation of the TWH approach emphasizes employee engagement and integration of hazard protection with injury and illness prevention efforts (e.g., combining a traditional occupational safety and health program to control airborne contaminants with a smoking cessation program; Lee et al., 2016). Note that the control category titled "substitute" in the TWH pyramid also connects with the "administrative controls" category in the NIOSH and ANSI Z590.3 PtD pyramid, because policies, programs, and practices are administrative activities.

Use of Hierarchy of Controls and Control Strategies

OEHS professionals have long advocated the use of a hierarchical strategy to select hazard controls (Stenzel et al., 2015). Successful implementation of controls starts with planning from the genesis of the process, particularly with raw materials and making the right decisions about controls from the beginning (J. Mulhausen, personal communication, February 15, 2023).

HoC implementation should be considered and used in conjunction with a well-conducted risk assessment process and an evaluation of a business case to justify appropriate controls (AIHA, n.d.). The AIHA Business Case Tool provides a strong approach for estimating the overall impact of proposed improvements and a clear presentation for management and other stakeholders.

The worker health exposure risk assessment process can use AIHA Guideline 9-2007, Guidance for Conducting Control Banding Analyses to select appropriate controls for circumstances that often involve selecting multiple layers of controls (AIHA, 2023). The AIHA exposure risk assessment/management flow process and the ISO 31000 risk management process flow for conducting risk assessments are presented in Figure 9.

The risks should be rated without controls to provide a raw risk rating (i.e., prior to risk mitigating treatment), then controls should be considered and a residual risk rated. If the residual risks are not acceptable, appropriate control measures should be considered and implemented according to the HoC to lower the risk rating to a safe and manageable level.

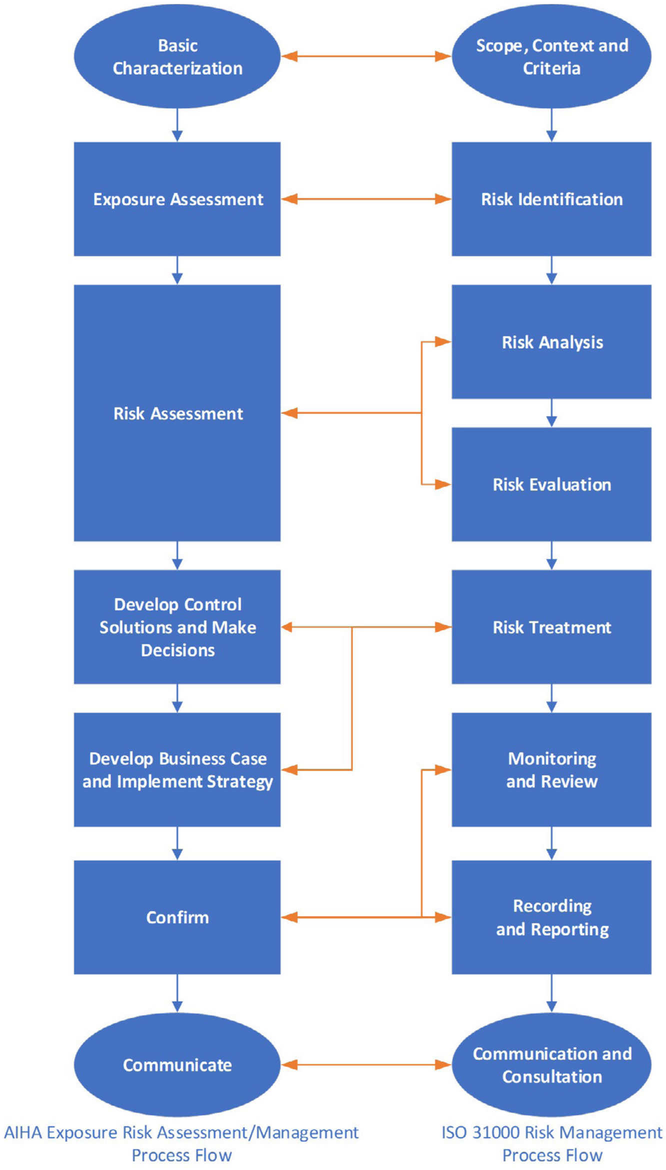


Figure 9. Occupational Exposure Risk Assessment/ Management Processes

Note. From ANSI/ASSP Z590.3-2011 *Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes*, by ANSI/ASSE, 2016. Reprinted with permission (courtesy of the American Society of Safety Professionals).

In the case of carcinogens (and other agents without a threshold toxicity, such as endocrine disruptors), the risk of exposures should be controlled to ALARP.

The HoC scheme that will be used for this white paper, consistent with AIHA's *A Strategy for Assessing and Managing Occupational Exposures* (Stenzel et al., 2015), includes the following levels in order of priority and effectiveness:

- Elimination of the process, equipment, or materials giving rise to the hazard
- Substitution with a less hazardous process, equipment, or material
- Engineering controls (e.g., process modification, enclosure, ventilation, shielding)
- Administrative controls, including work practice controls and employee training
- PPE

Each control scheme may stand alone as a successful way to reduce risk to an acceptable level. More commonly, implementation of a combination of categories, levels or strategies, and controls may be needed to achieve the desired level of risk. For now, each control category in the HoC will be discussed individually.

Elimination Controls

The most efficient way to achieve elimination of hazards and risks is to prevent their introduction into the workplace. This prevention should occur as early as possible in the planning process and the product development tree (see Figures 6, 11, and 13). PtD approaches apply this principle to avoid, eliminate, control, or reduce safety and health hazards and risks in the design and redesign processes (Manuele, 2020; NIOSH, 2013; ANSI/ASSP, 2021). By eliminating hazards at the design stage, employers can prevent hazards and associated risks from occurring in the first place.

Elimination Vignette

Situation

An agricultural supplier packages product for regional markets. A packer, facing a roller conveyor, repetitively moves 5-lb rectangular product boxes (6 in. x 12 in. x 12 in) from the right 18-in. cross-body to a larger box on the left, eventually fitting four product boxes side-by-side into each shipping box, 8 hours or more per day. Line speed adjusts to production schedule.

Hazard

Repetitive movements/awkward postures including elevated elbow, shoulder abduction, head tilting, bent wrist/gripping, and upper body bending/flexing/twisting.

Application of HoC

Automation would eliminate the hazard at an estimated automated cost of $755,000. Benefits-costs analysis, including costs associated with administration, loss of productivity, new employee hiring, and training is pictured, including legal costs, failure to complete orders, loss of clients, and other conceivable costs as appropriate.

A conservative dollar estimate for preventing one De Quervain's disease case and one rotator cuff tendinitis case was presumed. **Figure 10** illustrates how the investment would lead to break even by the 3rd year and add to the cost savings thereafter.

Key Takeaway

Reengineering existing processes can be challenging. The use of business case calculations is invaluable in making your case. Downloadable tools and instructional videos are available at AIHA Business Case Tool.

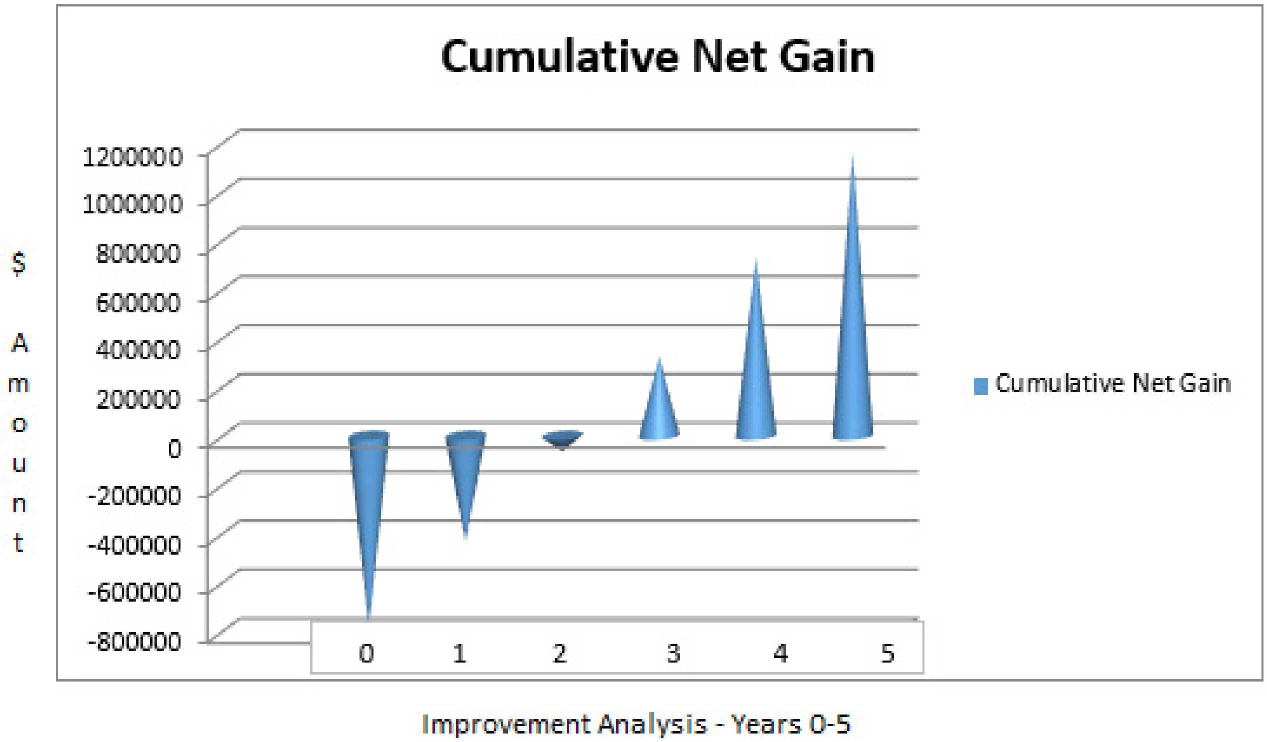


Figure 10. Cumulative Net Gain Generated by the Business Case Tool

Note. This graph illustrates the calculated approximate cost benefits in dollars over time, automating the process described in the Elimination Vignette. By AIHA, n.d.

To successfully implement elimination at the design level, a hazard analysis to identify all hazards and risks should be performed in the conceptual design phase (Manuele, 2020). However, it is important to also consider hazards and risks that may occur during the construction, operations, and maintenance phases of a project. For example, architects may design parapet walls on rooftops for building code, decorative, or other purposes, such as to hide mechanical equipment. For any worker having to access the rooftop or equipment, fall protection may be needed. A simple solution is to design parapet walls of sufficient height such that the fall hazard does not exist, and as a result, fall protection is not needed.

While some hazards can be eliminated, others are more difficult or even impossible to eliminate, leading to further hazard management through engineering, administrative, or individual-level interventions (NIOSH, 2020a). Even with optimal hierarchical designs, no worksite will successfully reduce its risk to zero; some residual risk assigned to the worker will always remain (Redinger et al., 2020).

Substitution Controls

The process of substituting a less hazardous substance or process should include an informed comparative analysis of chemicals and substitutes considering all aspects of human health and environmental hazards during production, use, and disposition of the chemical compounds (AIHA, 2011).

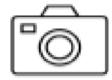
The evaluation should not focus only on a chemical's inherent hazard and its relative hazard(s) as compared with the original chemical. It also should evaluate exposure levels throughout the entire life cycle of the use of the chemical (Committee on the Design and Evaluation of Safer Chemical Substitutions, 2014). In addition, an evaluation of whether the chemical can appropriately perform the same functional use should be included (Hester & Harrison, 2013). It is also possible that substitution may increase risks not associated with that material but in the process itself.

To select an appropriate substitute material or process, there are several alternative assessment frameworks available to follow. For example, OSHA (n.d.-d) has a *Transitioning to Safer Chemicals* toolkit; the Committee on the Design and Evaluation of Safer Chemical Substitutions (2014) has a *Framework to Guide Selection of Chemical Alternatives*; and the European Chemicals Agency (2021) has guidance on analysis of alternatives in developing a substitution plan.

Most alternative assessment frameworks (Jacobs et al., 2016) typically include the following components:

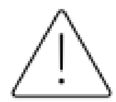
1. hazard assessment
2. exposure characterization
3. life-cycle impacts consideration
4. technical feasibility evaluation
5. economic feasibility assessment
6. established criteria for decision-making

Substitution Vignette



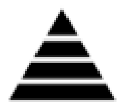
Situation

Sulfur dioxide is a natural byproduct of winemaking. Enhancement with additional SO_2 inhibits spoilage. A large winery with annual production of more than a million gallons of wine using liquefied sulfur dioxide (SO_2) had a minor outdoor release of pure liquefied SO_2, which sent an employee to urgent care. Meanwhile a chemical dosing machine in the bottling line had a minor release during a change-out of dimethyl dicarbonate (DMDC) used to sterilize finished wine. The employees were evacuated without injuries and health effects.



Hazard

Chemical inhalation hazards for both SO_2 (TLV 0.25 ppm) and DMDC (flammable and fatal if inhaled) are significant even in the event of small releases.



Application of HoC

Both food additives were essential to production, so the company focused on substitution and engineering controls. Liquid SO_2 was replaced with potassium metabisulfite tablets, virtually eliminating the risks associated with handling the pure liquid. Without a viable substitute for DMDC, the change-out segment of the bottling line was relocated to a more open area, making the maneuver easier with increased dilution ventilation.thereafter.

Key Takeaway

Substitution of one chemical for another is not always wise or feasible. Substitution of the same chemical in a different state (gas, liquid, solid) may improve control without altering the product. Process layout changes in space and configuration can control the risk of hazardous tasks.

This evaluation is necessary to ensure that an "informed substitution" occurs and assures that hazards are not simply shifted or result in unintended consequences ("regrettable substitutions") when decisions are based solely on chemical toxicological properties without consideration of the product life cycle and application (Committee on the Design and Evaluation of Safer Chemical Substitutions, 2014).

Chemical product substitution can be an effective way to manage employee exposure to hazardous materials, but it must be conducted judiciously to ensure that one hazard is not exchanged for another. An initial risk assessment should be conducted to identify and evaluate employee exposure potential for all chemical products that employees might use in the workplace.

An example of an informed substitution process is the evaluation and selection of benzyl alcohol or dimethyl adipate in place of methylene chloride as a paint stripper (Burnes et al., 2016). Other examples are provided in EPA's safer chemical ingredient list, which is sorted by functional use (USEPA, 2022).

Two examples of "regrettable substitution" commonly cited include the use of bisphenol S (BPS) to replace bisphenol A (BPA) and 2,3-pentanedione as a flavoring substitute for diacetyl (Maertins et al., 2021; Zimmerman & Anastas, 2015). Because of BPA's endocrine-disrupting effects and biopersistence, public pressure resulted in BPA being replaced with BPS (Maertins et al., 2021). However, BPS appears to have similar metabolism, potencies, and mechanisms of action to BPA, but also has additional hormonal disruptive effects that have not been detected with BPA (Rochester & Bolden, 2015). While respiratory exposure to diacetyl can cause bronchiolitis obliterans (Kreiss et al., 2002), similar health effects have been reported in laboratory animals from respiratory exposure to 2,3-pentanedione, including necrotizing rhinitis, tracheitis, bronchial lesions, mucosal inflammation, and bronchitis (Hubbs et al., 2012; Morgan et al., 2016). In the case of both BPA and diacetyl, the substitute chemical displayed similar toxicological properties. While manufacturers of products using these substitutes could say the product was BPA- or diacetyl-free, the potential health risks remained unchanged.

It should be noted that elimination or substitution may not always be possible. The medical device, pharmaceutical, and defense industries have strict requirements regarding the qualification and authorization of materials and products. It is not possible to simply remove beryllium from parts of an airframe, nor to replace it with a different chemical. A new airframe crafted without beryllium is likely a completely new product and, as such, must go through complete qualifications.

Similarly, modification of the way in which medical battery powders are processed, even when the materials are the same, requires the requalification of the entire medical battery. Additionally, in the pharmaceutical industry, many chemicals (known as "molecules" within the industry) are still in experimental stages and all human health hazards may not be known. Many of these products are chemically banded (e.g., NIOSH's occupational exposure banding), classifying the new structural elements against known chemical substances.

Engineering Controls

Well-designed engineering controls can offer effective control of worker risks associated with various production and construction processes (Burton, 2011). Engineering controls do not eliminate hazards, but rather isolate workers from the hazard by creating a physical barrier between personnel and hazards.

The capital costs of engineering controls tend to be higher than less effective controls in the hierarchy; however, they may reduce future costs. For example, a crew might build a guardrail for the open end of a platform rather than purchase, replace, and maintain fall-arrest equipment.

Once engineering controls are implemented, either qualitative or quantitative performance evaluation is warranted in order to understand whether the control solutions are continuously effective in mitigating or eliminating the occupational exposure risk. For example, procedures of pre- and post-start performance testing of ventilation systems are available from ACGIH (2020) and ANSI/ASHRAE (2016).

Essential methods for performing a validation study of industrial ventilation systems include field sampling and testing, laboratory testing, and model evaluation (Chen, 2023). In addition, engineering controls can provide desired protection and reduce the pertinent risk only when their designated functions are not bypassed. Preventive maintenance, instead of corrective maintenance, should be prioritized and conducted to maintain the high quality of the whole ventilation system components, including but not limited to blowers, motors, valves, dampers, and filters.

Lastly, adequate professional training is necessary in the complete life cycle of engineering controls (i.e., design, implementation, validation, and maintenance). Oftentimes within industry, the implementation and maintenance of engineering systems are a partnership between the functions of engineering, facilities, maintenance, and safety and health.

Engineering controls require administrative controls (training, preventive maintenance schedules) to improve the likelihood of successful implementation. This is why they fall somewhat lower in the effectiveness continuum in the HoC.

Ventilation

If designed and implemented properly, ventilation can play a critical role in reducing workplace airborne contaminants. Two main types of ventilation are general (dilution) ventilation and local exhaust ventilation. In dilution ventilation, uncontaminated outside air mixes with inside air, diluting and reducing the concentration of air contaminants.

Dilution ventilation should be considered only for small quantities of low toxicity or low flammability chemical hazards, when contaminants are released at a fairly uniform rate, if there is sufficient mixing to allow for dilution. Dilution ventilation should not be used for biological hazards (ACGIH, 2021). Local exhaust ventilation involves the removal of contaminants using capture devices at the source of exposure.

Another consideration with dilution ventilation is that it can be expensive to install and run because of the relatively large amounts of (conditioned) air that must be introduced. Ventilation best practices are available in the ACGIH Ventilation Manual (ACGIH, 2023b).

Isolation

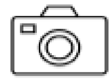
Sometimes, potentially hazardous operations can be isolated to minimize exposure to employees. Isolation can be in terms of distance or shielding. Isolation is also good for jobs requiring few workers, when control by other methods is difficult or not feasible. Examples of isolation include enclosing the operation that generates hazardous exposures, remotely controlling equipment so that the worker does not have to be near the equipment to operate it, or placing the worker in an enclosed and/or soundproof control booth with a clean air supply.

Enclosures have been successfully used to reduce lead exposures during abrasive blasting and vacuuming operations used in bridge lead paint removal (Guth et al., 2022). In addition, Stanton et al. (2022) demonstrated the success of an enclosure with local exhaust installed on a coffee grinder to reduce worker exposures to diacetyl and 2,3-pentanedione.

Wet Methods

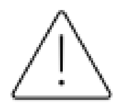
Engineering controls can also include process controls such as the use of wet methods to minimize or reduce airborne dust when drilling, grinding, sanding, or sweeping. For example, the use of wet methods is one of the primary means of reducing exposure to crystalline silica dust. The use of wet methods that are not integrated directly into a system or equipment may be considered administrative controls.

Engineering Vignette



Situation

Automatic high-speed braiding machines are governed by programmable logic controllers with automatic mass-adjusting and motor-driven yarn feeders, saving time, labor, and electricity. In a major upgrade, nine mechanical braiding machines were installed in a central area of the facility to maximize production. Unfortunately, this configuration generated ambient noise levels in excess of 95 dBA in the general vicinity, resulting in employee exposure in adjacent departments over the ACGIH TLV for 10-hour shifts.



Hazard

Ambient noise exposure in excess of 95 dBA presents a serious health risk for hearing impairment, tinnitus, hypertension, ischemic heart disease, and other health effects.

Application of HoC

Sound-absorbing curtains were used to enclose the braiding area. The resulting noise reduction took employee exposure levels below the TLV. This eliminated the need for a hearing conservation program, the use of hearing protection, and serious health risks for employees who worked in the vicinity.

Key Takeaway

Properly engineered enclosures can be effective tools in reducing the risk of ill health effects. The curtains used here enable maintenance access and future changes in process configuration.

Administrative Controls

Administrative controls are steps taken that result in reduced workplace risk by influencing changes in the way people work. Examples include warning signs, placards and labels; changes in process tasks or work instructions; and employee training and oversight.

With administrative controls, the hazard itself is not actually removed or reduced, and risk reduction for the worker is dependent on the worker following the required work practices.

Administrative controls can include the following:

- **Reduction of work periods and job rotation.** Reduction of work duration, job rotation, and scheduling work when other environmental hazards will be less present are all examples of effective administrative controls. ACGIH (2023a) offers work-rest schedules that are dependent on heat stress risk levels. Rotation of cross-trained workers to and from high-risk tasks is common regardless of the hazards. Scheduling road construction so it is performed at night when fewer people are driving is another example. However, job rotation should not be used for work involving highly toxic or carcinogenic materials and in some cases is specifically prohibited by law (Plog & Quinlan, 2012).
- **Training.** Training workers on the potential hazards encountered in the workplace is critical to helping to prevent exposure or injury. For some hazards, such as highly hazardous or carcinogenic agents, the use requires a "designated area" (OSHA, 2012) or "regulated area" (OSHA, 2019a) that restricts access by those who are not trained on the potential hazard. However, it is not enough to simply provide training. For training to be effective, the employer must also verify that employees can demonstrate competency, and that the knowledge and skills acquired in training can be transferred to performing the job safely (OSHA, n.d.-b).

Administrative Vignette

Situation

Synthesis of antibiotics involves multiple steps that can be hands on, especially during the drug development process. Benzene is frequently employed to break a specific bond when introducing a new functional group or modifying the structure of the molecule. Ventilated hoods and glove boxes are standard in most pharmaceutical research labs. Because benzene is highly toxic and can cause cancer and genetic damage at very low levels of exposure, administrative controls are essential to further reduce exposure.

Hazard

Use of benzene and other benzene derivatives in pharmaceutical synthesis must be carefully controlled due to the toxicity and carcinogenicity associated with benzene.

Application of HoC

Video exposure monitoring (VEM) was used to evaluate benzene exposure during routine tasks. Gloves with residual benzene contamination in contact with face-touching were found to be the most significant source of exposure. Typically, controls may include increasing hood ventilation, restricting the opening of the laboratory hood sash, and placing the laboratory equipment further back in the hood. In this example, training, frequent glove changes and barriers such as face shields were most effective in reducing scientists' exposure.

Key Takeaway

Proper assessment of exposure including skin absorption using a variety of technology, including VEM as well as airborne and biological monitoring, will better characterize the hazard and suggest controls that work.

- **Good housekeeping and maintenance.** Examples in which good housekeeping can reduce exposures include removing dust on overhead ledges or on the floor before it can become airborne, avoiding dry-sweeping, immediately cleaning up spills, and keeping equipment properly maintained. Equipment failure can result in chemical release, heating failure, and overheating, among other concerns.
- **Personal hygiene.** Good personal hygiene as a means of reducing exposure to hazardous materials has been promoted even before Alice Hamilton's time (Hamilton & Verrill, 1917; Hamilton, 1948). Handwashing practices are also effective in reducing transmission of infectious diseases (CDC, 2002; Gozdzielewska et al., 2022). Prohibiting eating, drinking, smoking, and applying cosmetics or contact lenses in areas where hazardous or biological materials are in use has become standard practice for laboratories (National Research Council, 2011; CDC, 2020). As a hazard control, enabling hygiene practices typically requires some degree of additional nonproduction infrastructure ranging from showers and locker rooms to cafeterias and common eating areas. The cost of this additional infrastructure will be proportional to its capacity, such as the number of workers exposed.
- **Distance.** Distancing an individual has been successfully used for hazards such as heat, noise, or radiation sources, and it has been incorporated for use against potential biological sources (Prakash & Digumarthi, 2021). When distancing within the workplace, the associated movement of materials and personnel into and out of restricted areas can represent additional operating cost. Additionally, facility size can impact indirect costs ranging from the lost space for production and transportation to increasing utilities such as conditioned air, light, and power transmission. Working from home is another example of administratively distancing workers from potential exposures (Persad et al., 2021).
- **Access restriction.** Signage is a standard tool to warn workers or identify high-risk areas where specific PPE or prohibitions are in place (Canadian Centre for Occupational Health and Safety [CCOHS], 2022; Prakash & Digumarthi, 2021). Access restriction is distinct from containment insofar as it is an added necessary administrative layer associated with the success or failure of other controls (PPE, task-based qualifications) and has multiple failure modes and motivations. While restricting access may serve other purposes in reducing security risks to an organization, it comes with potentially significant costs for surveillance.

Personal Protective Equipment

PPE is a way of reducing the risk by placing a protective barrier between the person and hazard (New York Committee for Occupational Safety & Health, n.d.). PPE includes, but is not limited to: gloves, respirators, hard hats, eye and face protection, high-visibility clothing, chemical protective clothing, hearing protection, respiratory protection, and safety footwear.

PPE is the least effective method for protecting an individual from hazards and should be used only after all other effective mechanisms to control the risk from the hazard have been exhausted. Caution is advised in using PPE for risk control for these reasons:

1. The hazard itself is not eliminated or changed.

2. Improper PPE may be inadequate or fail.
3. PPE is not 100% effective in managing risk.
4. Some PPE may be uncomfortable and places additional physical stress on an individual by increasing the physiological effort required to complete a task.

Therefore, if PPE is to be deployed, medical examinations may be required to ensure workers can use the PPE without risking their health (Niland & Elam, 2020).

Some circumstances mandate the use of PPE: when the hazard cannot be eliminated, while other controls are being planned/installed, or in emergency or temporary situations (OSHA, n.d.-c; CCOHS, 2022). Smith et al. (2020) identified firefighting operations as a prime example of a work environment employing PPE as a primary means of hazard and risk control.

PPE can reduce the exposure risk found in some work environments; however, in some instances, it will negatively impact human senses and decrease user performance (Morris & Cannady, 2019). Additional issues related to PPE include individual compatibility, use with multiple hazards, limited mobility, reduced dexterity, restricted vision, fatigue, and the possible addition to already established heat stress load (Cox et al., 2019; World Health Organization, 2020; Taylor & Orlansky, 1993).

PPE selection must involve multiple decision-making criteria, accounting for limitations, preferences, and priorities, to provide suitable worker protection (Darko et al., 2019). Ineffective PPE is roughly equivalent to failed or no PPE use, with potentially severe consequences (Cox et al., 2019; Morris & Cannady, 2019; Barro-Torres et al., 2012).

There is a long-standing need for continuous education and training programs to address worker perceptions and behaviors for PPE use sustainability (Sapbamrer & Thammachai, 2020). A positive safety climate and "lead by example" cultures can help increase the success of PPE use (Cavazza & Serpe, 2009). Management should know the required PPE, ensure its availability, and support its use (Floyd & Floyd, 2017).

Respiratory Protection

Respiratory protection has long been used to reduce worker exposure to hazardous agents. OSHA (2011), NIOSH (2018; 2019), AIHA (2022), and several other bodies and organizations have published guidance documents on the management of respiratory protection and the administrative programs that should be put in place to assure that the equipment is used effectively. Respirator effectiveness is partly dependent on the user, who must have the ability to discern the adequacy of the respirator's face seal, effectiveness of field seal checks, consistent adjustment of straps, and consistency in performance over time (Kalsbeek et al., 2007). As with other PPE, consistent use is dependent on comfort, ease of use, training to understand the importance of consistent use, and so on. However, one key issue surrounding the use of respiratory protection is the impact it has on the person's ability to work under various physiologic loads. In addition, the length of work time is shorter, and the accomplished work rate is lower while wearing a respirator (Rebar et al., 2010). Lastly, respirator effectiveness depends on the proper selection of the respiratory protection device, based on the potential hazards, risk, and type of work being performed.

Gloves and Coveralls

Augmenting the natural defenses of the skin can mitigate the damage associated with contact hazards, but this comes with a significant number of limitations and indirect costs. The initial investment should include a needs assessment based on qualified objective expertise and participation from production and hazard experts. Limitations to be considered should include, but are not limited to:

- Productivity: Loss of sensory perception, dexterity, and natural cooling capacity
- Human factors: Comfort, perception of the need, change management processes
- Environmental: Durability, compatibility across all potentially exposed chemicals and conditions
- Economic: Forecast replacement rate, associated training and oversight, waste management (Nelson & Phalen, 2022)

Protective clothing manufacturers use a myriad of test methods to challenge their clothing to a suite of hazards. However, there may be limitations in the overlap of different individual chemicals, chemical mixtures, physical protections, and the effect of chemical mixtures. Additionally, testing labs are available to help validate assumptions for specific products.

Physical, Physiological, and Psychosocial Impacts of PPE Use

Potential physiological impacts of respirator and PPE use have long been concerning (Raven et al., 1979; Louhevaara, 1984; Harber et al., 1989), which is one reason that OSHA requires a medical evaluation of a worker prior to issuance of a respirator (OSHA, 2019d). For example, an elevated risk of heat stress from working in protective clothing and respiratory protection has been reported in numerous studies (Martin & Callaway, 1974; Fletcher et al., 2014; Lin & Chen, 2019; Dorman & Havenith, 2009).

Complaints of headaches, lightheadedness, perceived exertion, and perceived resistance to flow have been reported with extended use of filtering facepiece respirators (FFRs) (Rebmann et al., 2013). Respirator use can also impact visual acuity (Johnson, 2016). These physiological impacts can reduce worker productivity (Johnson, 2016). Protective clothing can also create ergonomic issues associated with the added load on the body from the weight of the clothing, but also from reduced mobility (Dorman & Havenith, 2009).

In addition, protective clothing can increase metabolic rates and energy consumption, thus affecting exertion and productivity (Dorman & Havenith, 2009).

Leung et al. (2022) concluded that while use of some hearing protection may have the potential to reduce anxiety and improve speech intelligibility, respirator use may lead to an increase in work-related stress. Respirator use can impact social interaction (Freud et al., 2020) and communication capabilities (Randazzo et al., 2020); can cause fatigue, which can reduce performance and cognitive function, and can increase anxiety (Wu et al., 2011).

A considerable amount of discomfort can result from wearing respirators, gloves, boots, and protective suits (Akbar-Khanzadeh et al., 1995; Johnson, 2016), which can also increase worker anxiety.

Cost of PPE Use and Environmental Impact

In addition to the human capital costs, there is a significant cost associated with the use of PPE. This includes the cost of the actual equipment, cost and lost time for employee medical surveillance, lost time due to cleaning and maintenance of the equipment, and lost time required for training.

Additional costs and time factor into program management. They include periodic assessment of the workplace to ensure that appropriate PPE is selected and provided. Second, evaluations of the program are necessary, both to ensure that the provisions of any written programs are being properly implemented and to ensure the continued effectiveness of the program (including whether the correct PPE is being used and worn properly and whether the training program is effective).

An employer also must set aside space for proper storage of the PPE. Consideration must also be given to the generation of PPE waste in health and other industries and environments, adding to the hazardous and regulated waste burden.

Yet another factor: using PPE can generate waste and have negative environmental impacts. Individuals and companies should consider using PPE in an environmentally friendly manner to reduce the environmental impact. The recent COVID-19 pandemic has highlighted PPE disposal problems, causing the need for further research for sustainable PPE management (Singh et al., 2020). Alternative ways of using PPE, such as modified testing methods that allow for multiple uses of disposable N95 masks, can be explored to minimize waste (Popov et al., 2022).

PPE Vignette

Situation

A researcher at a major university forgot his safety glasses in his office while leaving for the day (Sharpless, 1992). On his way out, he stopped by a graduate student's desk, where the student was working on flame-sealing a nuclear magnetic resonance (NMR) tube. Because the sealing procedure was incorrect, the NMR tube exploded, and glass fragments shredded the researcher's cornea and penetrated the iris, causing him to lose sight in one eye.

Hazard

University research laboratories customarily handle numerous hazardous materials while conducting processes that increase the risk of exposure. Student personnel and the prevailing work culture may minimize the perception of the severity of hazard exposure.

Application of HoC

Safety glasses were required for use in the lab, and there was an established, safe procedure for flame-sealing the NMR tube, but neither was applied at the time of the incident. Effective and documented training and insistence on safe procedures as part of performance reviews might have prevented the occurrence. Arranging mandatory donning of PPE before entry and doffing after exit could also have mitigated the results.

Key Takeaway

Though the least desired control strategy, PPE should be readily available and worn effectively when required.

Managing Risk Through Layers of Control

Throughout human history, individuals have designed systems with multiple layers of defense. Historical examples include the walls of Constantinople, which featured moats, stone walls, and trenches (Lyon & Popov, 2020). In many industries today, layers of control are deployed to ensure risk control. Relying on a single guard or training class to control known occupational risk factors is less than ideal.

A comprehensive approach to reducing risk to an acceptable level often requires layers of controls or defenses—or a combination of preventive, protective, mitigative, and control measures (Lyon & Popov, 2020). An example appears in a bow-tie analysis diagram (Figure 11) that identifies the "preventive" measures on the left side of the bow tie (barriers positioned between the hazard-causes and the event) and the "mitigation" measures on the right side of the bow tie (reactive measures between the hazardous event and the consequences). Both preventive and mitigative measures are risk reduction treatment strategies.

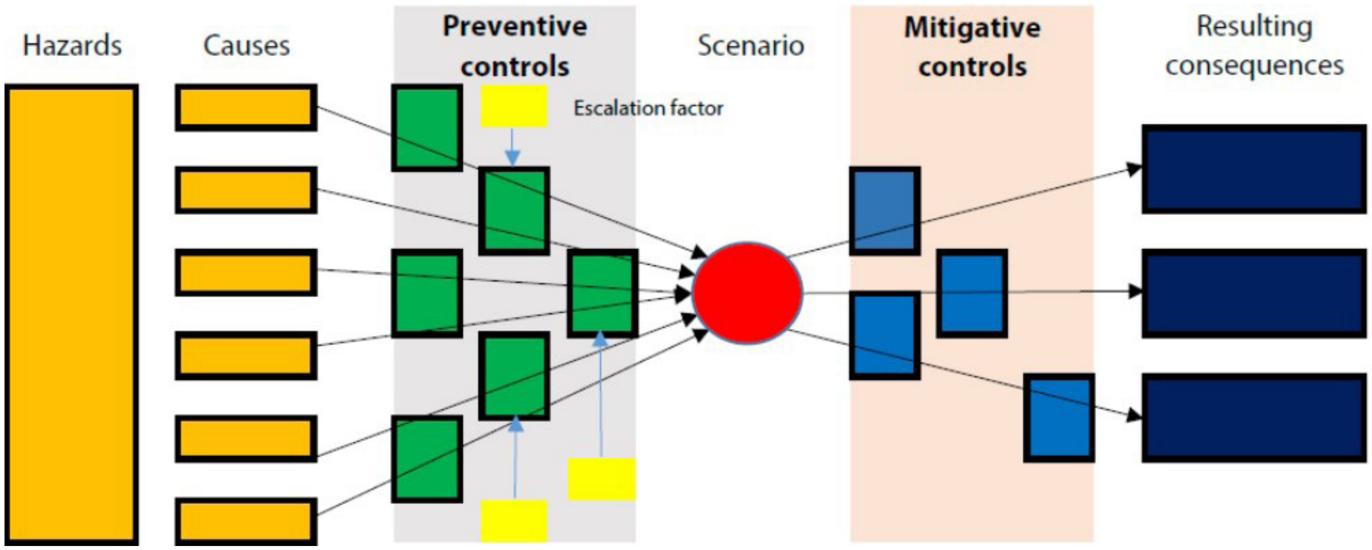


Figure 11. Bow-tie Analysis Example
Note. Adapted from "Managing Risk through Layers of Control," by BK Lyon & G Popov, 2020, *Professional Safety*, 65(4), p. 25–35.

OEHS professionals should understand these differences and make use of all the available risk reduction strategies to properly manage operational risk. Therefore, we should use proper terminology. Common terms used to describe operational risk treatment/HoC include prevention, mitigation, protection, control, and reduction are:

- *Risk prevention* is the act of keeping something from occurring that would otherwise cause risk or harm. This concept is outlined in the ANSI/ASSP Z590.3 (2021), which states that the first four control levels of the hierarchy are more effective because they are preventive actions that eliminate risks through design, elimination, substitution, and engineering measures.

- *Mitigation* is generally defined as the act of reducing the severity or seriousness of something, making the consequences less severe. The Federal Emergency Management Agency (FEMA, 2023) defines mitigation as "the effort to reduce loss of life and property by lessening the impact of disasters."
- *Protection* is similar to mitigation and is the act of shielding, covering, or keeping an asset from harm. It is designed to limit the severity of harm or impact rather than prevent the event from occurring. Insurance risk transfer can also be considered a financial protection measure for the insured parties or properties.
- *Risk control* is a more encompassing term and refers to the management of risk by reducing the likelihood and severity of an exposure.
- *Risk reduction* minimizes or reduces the likelihood and severity of unwanted risk. Reduction refers to making something smaller in size, amount, or number.

In order for risk to be reduced to an acceptable level, a comprehensive approach is required. This approach considers layers of controls, or defenses, including a combination of preventive, protective, and mitigative strategies. Risk treatment plans can involve a single control or multiple controls to accomplish the desired risk reduction. Implementing an inherently safer design has been recognized and accepted as a good engineering practice.

Hazard and risk control measures vary in their degree of risk reduction, effectiveness, and reliability. The HoC concept should be designed with the most effective and reliable risk reduction options at the top, descending to the least preferred option.

As stated earlier, the hierarchy model generally starts with avoidance of risk, followed by elimination of risk, then substitution of risk. From there, known risks are controlled using engineering controls, warning systems, administrative controls, and PPE. It is important to first eliminate the hazard, followed by moderation of the hazard, avoidance of exposure (releasing the hazard), or separation of hazard from what must be protected. Use of PPE is last on the list.

Analyzing the effectiveness of the risk control strategy is a critical aspect of risk assessment. The management of risk is affected by the overall effectiveness of any control. Consider four variables:

1. whether the controls in place are capable of operating as intended and are achieving the expected results
2. whether shortcomings exist in the design
3. whether any other vulnerabilities or circumstances may sabotage the controls
4. whether the controls themselves introduce additional risks

Mechanisms to analyze the effectiveness of controls include bow-tie analysis, hazard analysis/critical control points, event tree analysis and layers of protection analysis (LOPA), layers of control analysis (LOCA), and layers of mitigation analysis (LOMA), estimating the reduction in risk associated with the proposed risk control treatments and systems (Popov & Lyon, 2021).

Other tools include risk matrices designed to consider the incident outcome, severity of the outcome (ranked on a scale of 1 to 5), and the likelihood of occurrence (ranked on a scale of 1 to 5) (Popov & Lyon, 2021). Barrier analysis, often used in incident investigation, can be used to identify and analyze all existing controls related to the hazards of a system or conditions of an incident (Popov & Lyon, 2021).

Whole-system risk factors should also be considered. This type of assessment considers the potential effect of a combined or whole-system set of risk factors. Tools can catalog individual hazards as line items (although this method may miss synergistic effects).

A combined layers of prevention and layers of mitigation model, also known as layers of controls analysis, or LOCA, is presented in Figure 11. In this model, there are multiple independent protection layers (IPLs).

LOCA considers the layers of preventive measures along with the layers of mitigative measures and their risk levels. To effectively reduce risk, both preventive and mitigative measures must often be used. Research has shown that it is more beneficial to invest in layers of prevention versus layers of mitigation (AIHA, n.d.).

Layers of defense have been used throughout human history to reduce known risks from multiple threats. It is important that OEHS professionals consider this approach when analyzing and designing risk reduction treatments. It is also important to include preventive measures as well as mitigative measures. Relying on one control measure is rarely adequate to prevent and protect people, property, or the environment.

Figure 12. Layers of Controls Analysis (LOCA)
Note. Adapted from "Layers of Controls Analysis," by G Popov & BK Lyon, in *Risk Assessment: A Practical Guide to Assessing Operational Risks* (2nd ed.), 2021, p. 201–226.

A conceptual model presenting layered preventive and mitigation measures appears in Figure 13.

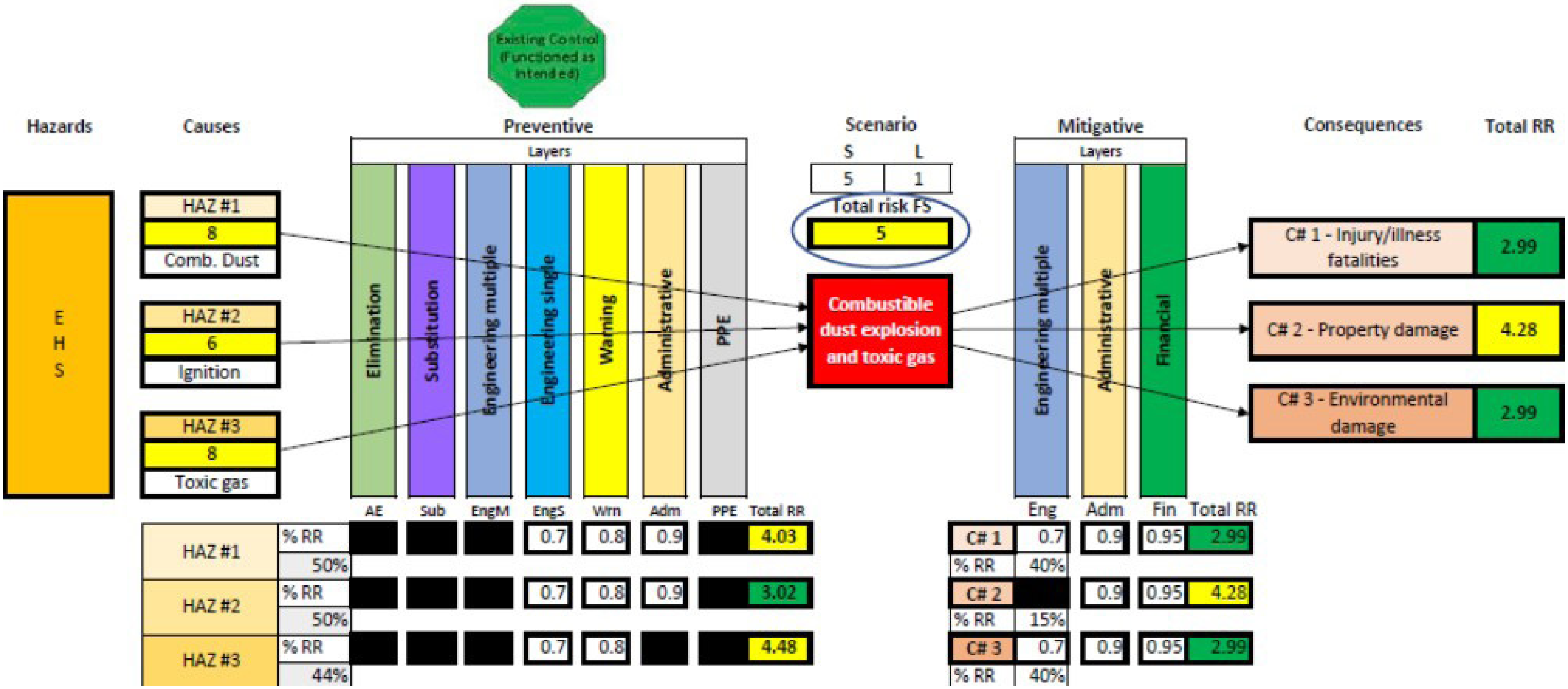


Figure 13. Striped Bowtie Analysis

Note. ANOVA = analysis of variance; SMT = series management training group; Control = wait-list control group. Adapted from "Layers of Controls Analysis," by G Popov & BK Lyon, in *Risk Assessment: A Practical Guide to Assessing Operational Risks* (2nd ed.), 2021, p. 201–226.

Layered controls can be further visualized in the striped bow-tie model. The presented striped bow-tie model visualizes the layers of prevention and the layers of mitigation concept. This model considers both the preventive measures for existing hazards on the left-hand side of the top event, and the mitigating or reactive measures for reducing the impact of the event on the right-hand side (Figure 13).

All three hazards are analyzed as a whole for their severity and likelihood to determine their combined or total risk, which is entered above the top event in Figure 13. Then, the mitigating measures, such as the administrative controls, water spray, and visual inspections, are analyzed together to estimate the residual risk (RR), which is displayed below the top event.

Management of Change

Management of change is a systematic approach used in businesses and organizations to ensure that changes are implemented smoothly and efficiently. Helpful descriptions appear in the ANSI/ASSP Prevention Through Design standard (ANSI/ASSP, 2021); ANSI/ASSP Z10.0-2019 OSH Management standard; and OSHA's Process Safety Management standard (2013), 29 CFR 1910.119.

The HoC can be used as a benchmark to determine when a change analysis is warranted. For example, when there is an overreliance on PPE, it can indicate that there are likely to be significant direct and indirect costs (such as consumable materials and routine equipment failures) that will justify better control.

Layers of Control Vignette

Situation

The layered approach to risk management became popular in managing risks associated with the COVID-19 pandemic (AIHA, 2021; Lyon & Popov, 2020). Where the hazard cannot be completely removed, a combination of controls can do more to reduce risks than any one method used singly to reduce contaminant generation; limit exposure time; and train employees on how to use engineering controls, enclosures, PPE, and the like.

Hazard

When an unexpected pandemic or terrorist threat occurs, the true nature and severity of the hazard may be unknown. In this situation, exposure protection should protect the population at the highest available levels.

Application of HoC

Initial infection control methods involved administrative controls such as distancing, isolation, barriers to airflow patterns, aggressive cleaning, and the use of whatever masks or facial barriers that were available. As it became clear that inhalation of fine aerosols was an important route of exposure and that these aerosols would remain airborne for prolonged periods of time, a more nuanced approach was developed. Engineering controls such as increasing air exchange rates, improving filtration by using better filtration such as HEPA or higher rated MERV filters, and air treatment methods such as upper air UV irradiation were added. When respiratory protection became more readily available, it was added as well.

Key Takeaway

Where the hazard cannot be removed, a combination of controls to reduce contaminant generation, administrative controls to limit exposure time and/or to train employees how to use engineering controls, enclosures, PPE, and the like, as well as the use of PPE, can all combine to bring risks down further than if any one of these methods was used alone.

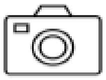
Confirm Through Reassessment

The process of managing hazards through anticipating, recognizing, evaluating, controlling, and confirming (ARECC) is cyclical, as demonstrated in **Figure 14.** After controls are selected and implemented, verification of control effectiveness and functionality is needed, both to ensure the desired level of risk reduction is achieved and maintained, and to ensure that opportunities are identified for continuous improvement (Stenzel et al., 2015).

The primary objective is to document the change or maintenance of exposure levels within acceptable parameters. This is achievable through direct monitoring of a hazard or indirectly through monitoring key process parameters to validate that controls are functional (airflow indication, pressure differential, temperature, humidity, carbon dioxide, heart rate).

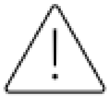
The frequency of monitoring may be defined in standards (such as the presence of an airflow indication for laboratory hoods) (ANSI/ASSP, 2022) or defined by an internal program with a frequency capable of detecting changing conditions that may lead to health outcomes.

Layers of Control Vignette



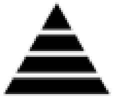
Situation

Pumps manufactured to survive in radioactive environments are significant capital investments. They are reused as liquid waste treatment processing progresses through multiple storage tanks at nuclear sites. Pump maintenance and repair requires pump removal from a highly radioactive waste storage tank, transfer and repair, and return to service



Hazard

Radioactive liquid waste contains hundreds of pCi of cesium-137. Exposure to Cs-137 can increase the risk for cancer via high-energy gamma radiation. Internal exposure to Cs-137, through ingestion or inhalation, distributes ß-particles and Y radiation in the soft tissues, especially muscle.



Application of HoC

Temporary shielding reduces the dose rate for maintenance staff. Liquid sludge slurry is drained to the extent possible, then flushed with water to further reduce the dose rate. Extended-handle tools reduce exposure to hands. Workers practice detailed mock-up scenarios to improve proficiency and identify problems with novel tools, focusing on time or distance improvements. Continuous exposure monitoring immediately detects exceedance when standby personnel must rotate in. Respiratory protection is worn to mitigate the effects of unintended releases. Outer glove layers are replaced frequently to reduce contamination during the job. Multiple layers of outer protective clothing are removed as workers exit progressively less contaminated areas. As the pumps move through the process, locations are decontaminated, and fixed contamination is encapsulated in place in preparation for pump operations and future activities.

Key Takeaway

While potentially subjective, ALARA policies imply that as many control layers as necessary are applied to reduce employee exposure.

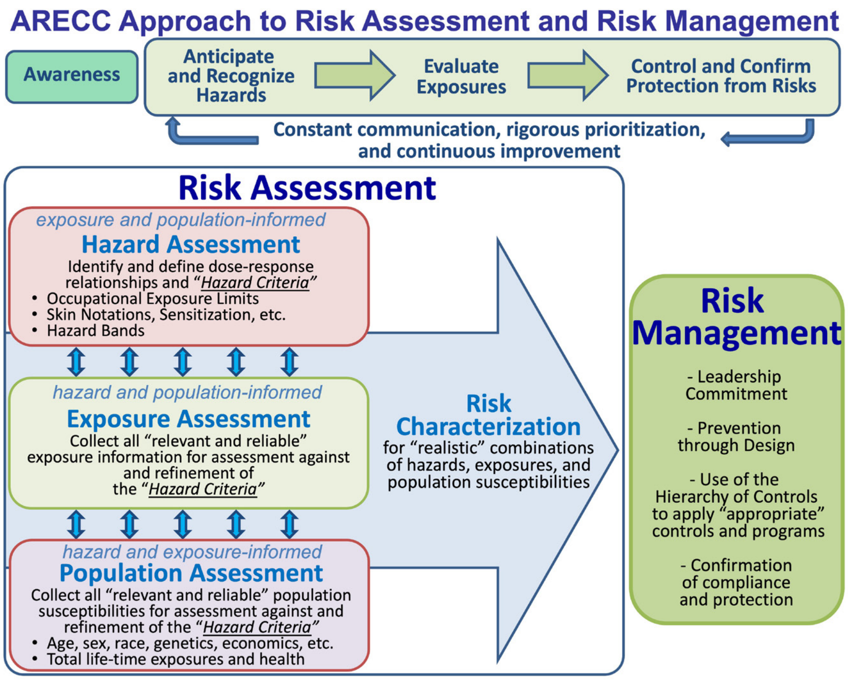


Figure 14. Model of the ARECC Process and the Relationship to Risk Assessment and Management

Note. From *Understanding and applying ARECC to occupational and environmental health and safety* (Competency framework), AIHA, 2022b.

Part of the verification process is to ensure control "quality"—that is, field practices must be compatible with the control strategy. All three of those conditions—human factors, functionality, and overall impact—should be part of the reassessment.

An example: use of a HEPA vacuum may seem preferable over a vacuum with lower filtration efficiency for controlling toxic dust. However, if the dust-loading is significant enough to reduce the capture efficiency of the device within the course of a single shift or task, a specialty vacuum for high dust-loading with back-pulse functionality may achieve a lower overall environmental dust concentration.

Another example: What if collecting dust from a shroud around a drill bit allows dust to escape as the capture device loads, and the exhaust system flow decreases, but capturing the dust from inside a hollow drill bit reduces the drilling as dust collection diminishes—both reducing dust levels and incentivizing proper use and maintenance of the capture device?

The incentive is there only if workers are not so frustrated with the diminishing performance—less-than-adequate change management—that they decide the control is terrible and do not use it. Enclosures and passive engineering controls require inspection and upkeep to detect failures. This does not mean that they are effectively "administrative controls," but rather that there is a layer of administrative support that must coexist to maintain the engineering controls established within a facility.

Reassessing the effectiveness and functionality of control measures provides valuable data for prioritizing and justifying resource allocations to management. Observations of use and weaknesses in the control strategy can assist with the prioritization of resources for improvements. Examples are opening gaps in a containment system, poor trends in system negative pressure, containment faults, workers scratching their nose or chewing gum in highly toxic areas, intermittent bolus "poofs," PPE degrading in its environment, and listening to workers complain.

The administrative burden of ensuring effectiveness of implemented control can also drive a natural desire to move control strategies up the HoC because of the increasing number of factors and assumptions that need to be continuously validated.

It takes a great deal of effort to ensure that the use of PPE is effective. Keep in mind that just because a set of controls does not come with *regulated* requirements to ensure effectiveness, the process for ensuring their effectiveness should be similarly rigorous, if done correctly. In other words, verification of control effectiveness should be extensive and thorough, even for controls that do not come with extensive regulatory guidance for ensuring effectiveness.

Conclusion

The HoC is a useful tool for prioritizing the use of different risk management tools in the workplace. It ranks the effectiveness of various risk management interventions in order, starting with elimination and replacement, engineering, then administrative and personal protection controls.

It is likely that combinations of the various controls within the hierarchy will be needed to achieve the desired level of risk management. Effective application of the HoC will guide the OEHS practitioner in selecting proper and innovative controls —or combinations of the various controls—to best manage risk for both workers and entity leadership.

Within the HoC and risk management strategies, it is crucial to recognize that, other than by use of elimination and passive engineering for risk management, all other strategies depend on people, who are fallible. People will forget what they learn in training, rush past posted warnings, and improperly don personal protective devices. Surveillance by supervisors and managers, supported by metrics monitored by corporate leadership or owners, is therefore obligatory.

The hierarchy's utility for driving continuous improvement, along with the TWH hierarchy as applied to programs and less traditional hazards, shows the applicability of the hierarchy as part of any management system.

Recommendations

The white paper committee intends the following recommendations as a guide to the use of the HoC in managing OEHS-related risks in the workplace. It should be recognized that the elimination of high-risk hazards and hazardous processes before their introduction (i.e., PtD) is the most effective way to mitigate and manage such risks.

It is also important to recognize that the implementation of a combination of HoC levels is commonly needed in the risk management process to effectively control potential hazards and hazardous exposures.

AIHA recommends that OEHS professionals consider the following actions to facilitate effective, efficient, and best use of the HoC:

- Develop a risk management strategy focused on risk mitigating controls that takes into account the specific hazards, risk of potential worker exposure(s), feasibility of applying the HoC system, required compliance, organizational needs, and the cost of risk mitigating treatment.
- Establish an operational model that implements the risk management strategy across all functions of the organization (such as PtD).
- Apply the HoC model as early as possible in the life cycle of project and product planning, to recognize and manage the risk of hazardous exposures and prevention of potential injury, illness, and/or harm.
- Develop effective working relationships and consult with all levels of the organization so that information such as input, evaluation, and decision-making may flow freely, in both directions, in a timely and efficient manner that reinforces HoC concepts.
- Apply the most effective risk management strategy for a given situation, which may involve a combination of some or all of the levels within the HoC and may require the approval and acceptance of individuals across the organization and human capital and financial resourcing.
- Perform ongoing review of projects and processes using the continuous improvement model, including gap identification, prioritization, planning, implementation, and verification. Account for control weakness and potential failure modes in the risk assessment, including potential weaknesses inherent to PPE and administrative controls and revisit (challenge) new information on occupational hazards and processes. Revisit and verify infeasibility assumptions for the most significant risks.
- Clearly communicate the nature and magnitude of OEHS-related risks in a timely and precise manner so that the HoC risk management model and application process is integrated across the organization with all stakeholders.

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