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PPE – Can you have too much of a good thing?

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Abstract

Specifying Personal Protective Equipment (PPE) after a hazard has been identified is a critical aspect of a facility's ability to protect their workers. In a chemical manufacturing facility, manual operations and maintenance activities have the potential to expose workers to hazardous chemicals and flammable atmospheres. Even though it is generally recognized to be one of the least effective safeguards in the hierarchy of controls, PPE is often the last line of defense, and sometimes the only feasible defense, that isolates workers from potential hazards. As a result, companies may lean toward putting workers in higher levels of PPE to provide additional protection. However, in many cases higher levels of PPE may introduce new hazards associated with limited worker mobility, fatigue, unreliable job performance, or limited egress. Therefore, PPE specification should focus not only on what is necessary to protect the worker, but also what is appropriate for a given job task. In this paper, a risk-based approach to PPE selection, specification, and use will be presented. Discussion will focus on potential hazards that can be inadvertently introduced because of PPE over-specification. Studies related to the impact of PPE on worker performance will be presented to help demonstrate the potential negative impacts of over specifying PPE. Lastly, a case study will be presented where a PPE specification was questioned, and the impact of increasing the PPE specification for a job task was evaluated.

Keywords: Operational Integrity, Personal Protective Equipment, PPE, Risk Assessment, Qualitative Risk Matrix

1 Introduction

All workplaces contain some inherent level of risk — defined as the potential for loss or injury — to which workers are exposed.[1] In the process industry, engineers and safety professionals manage risk to employees through the process of hazard control. Hazard control is the recognition,

[1] Speegle, M. *Safety, Health, and Environmental Concepts for the Process Industry, 2nd Ed.* Delmar, Clifton Park, NY, 2013, Chapter 11.

evaluation, and minimization of hazards. A hierarchy of hazard controls is typically followed, listed below in the order of most to least desirable:[2]

1. Elimination (removal of the hazard)
2. Substitution (replacing the hazard with a lower risk hazard)
3. Engineering Controls (equipment-related methods of control)
4. Administrative Controls (documented rules and procedures)
5. Personal Protective Equipment

Personal protective equipment (PPE) is the last line of defense protecting workers from known hazards.[3] However, properly specifying PPE is often complex because each protective device has limitations. Gloves, for example, can protect workers from a chemical, thermal, puncture, or abrasion hazard as well as provide other specialized protective functions. Selecting the correct PPE for a job is a process that involves a combination of experience, hazard identification and risk assessment (HIRA), and general safety knowledge regard the process hazards, job task, and PPE functionality. PPE is commonly used in combination with other elements of the hierarchy of hazard control, so the functionality and reliability of engineering or administrative controls may be critical to PPE selection. For example, a lockout-tagout (LOTO) program is an administrative control that can reduce the potential hazard exposure to a worker, thereby lowering the PPE requirement for a specific task.

In some cases, laws or regulations impose PPE requirements. The U.S. Occupational Safety and Health Administration (OSHA), for example, specifies four levels of PPE protection for Hazardous Waste Operations and Emergency Response (HAZWOPER) operations:[4,5]

- Level A: Supplied-air respirator and fully encapsulating chemical-resistant suit
- Level B: Supplied-air respirator and chemical-resistant clothing
- Level C: Air-purifying full-face respirator and chemical-resistant clothing
- Level D: Coveralls or fire-resistant clothing

While most work in normal plant operations can be safely performed with Level D protection, it may be tempting to specify the highest level or multiple types of PPE to ensure worker protection during non-routine maintenance or operation. However, PPE that is uncomfortable or cumbersome to the worker could pose additional risks. This paper explores the implications of PPE over-

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[2] ANSI-ASSE Z590-3 *Prevention Through Design: Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes*, American Society of Safety Engineers, 2011.

[3] Speegle, M. *Safety, Health, and Environmental Concepts for the Process Industry, 2nd Ed.* Delmar, Clifton Park, NY, 2013, Chapter 13.

[4] Appendix B to 29 CFR § 1910.120 - Hazardous waste operations and emergency response.

[5] The equipment specified for each level within this list only includes examples of distinct PPE features. Other PPE requirements not specified in the list may include but are not limited to boots, safety glasses, hardhat, gloves, and/or radio.

specification and provides a case study that reviews the impact of increasing the PPE specification for a job task.

2 General PPE Selection Guidance

In any given chemical manufacturing facility, there will a range of jobs and worker responsibilities. Some of these activities are routine and some may be unique occurrences. Similarly, a worker may encounter a range of hazards depending on the work activity in which they are engaged. To protect workers from these hazards, it is important that a job hazard analysis has been performed to identify, evaluate, and control the hazards.6 In any work assignment, various hazard controls can be implemented to protect the worker. PPE is a frequent choice as one of those safeguards.

2.1 Hazard Identification and Risk Analysis

PPE selection begins with the identification of the hazards to be encountered. These hazards can harm different parts of the human body, and thus various kinds of PPE may be required to control these hazards. In this paper, the focus is on the combined hazards of chemical and flammability exposure. Other hazards, such as mechanical, thermal, electrical, and biological, will be omitted only for the sake of brevity. A general discussion on PPE selection can be found in standard occupational safety and health references.7

As previously discussed, a range of engineering and administrative controls that may eliminate or mitigate the hazards involved should be considered prior to the specification of PPE. However, the hierarchy of controls is not a mandatory prescription which must be followed without the benefit of critical thinking. On the contrary, the hierarchy of controls is a powerful and useful guideline for evaluating the pros and cons of different types of safeguards. Although PPE is generally recognized as one of the least effective safeguards in the hierarchy of controls, PPE is often the last line of defense, and sometimes the only feasible defense, that isolates workers from potential hazards. If engineering and administrative controls cannot reduce the residual risk to an acceptable level, then the use of PPE is justified.

In the chemical process industries, it is not unusual to identify both chemical and flammability hazards in a work assignment. This combination of hazards can complicate PPE selection. The physical characteristics of PPE that best control chemical hazards may not offer any protection from flammability hazard such as a flash fire exposure. Similarly, the PPE that best protects a worker from a flash fire hazard may provide little or no protection from chemical hazards. While there are garments that provide protection from chemical exposure with an optional capability to provide escape protection from chemical flash fire hazards during hazardous materials incident response,8,9 the flame resistance and thermal protection requirements for these garments are not as robust as those that satisfy the NFPA standards for flame-resistant or arc-rated

[6] OSHA 3071 *Job Hazard Analysis*, Occupational Safety and Health Administration, 2002.

[7] Plog, Barbara A., Jill Niland, and Patricia Quinlan. *Fundamentals of Industrial Hygiene, Fourth Edition*. Chapter 18 Methods of Control. Ithaca, NY: National Safety Council, 1996.

[8] NFPA 1991 *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies and CBRN Terrorism Incidents*, 2016, Section 7.7.

[9] NFPA 1992 *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*, 2018, Section 7.6

garments.10,11,12 Hence, if at all possible, it would be preferable to eliminate either the flammability or the chemical hazard to permit a simpler selection of PPE garments.

If one must protect against both chemical and flammability hazards, one option to consider is a more complex, layered clothing ensemble. This complex PPE ensemble can present significant physiological and psychological burdens on the worker (this issue is explored further in the next section of this paper). It is also critical to understand the limitations of the various layers of the ensemble, to ensure that interior layers do not become compromised by the presence of an outer layer. For example, a flame-resistant fabric may stipulate that its protective functionality is only valid if it is the outer garment. Because PPE selection is so important to the protection of the worker, the selection process must be predicated on a sound basis.

Chemicals may present multiple hazards for the worker including toxicity, corrosivity, or carcinogenicity. Chemical clothing PPE is intended to limit or prevent exposure to these hazards. Typically, chemical protective clothing consists of one or more polymer layers. The primary purpose of chemical clothing PPE is to prevent dermal contact with hazardous chemicals. Two factors drive the evaluation of chemical clothing PPE: the fluid state of the chemical exposure (liquid or vapor) and the compatibility of the garment material with the chemical. The fluid state is important because that determines how the chemical is presented to the garment, either by liquid splashing or by vapor intrusion.

For liquid splashing the garment design must be impermeable to liquid entry at the surface of the garment. Furthermore, the garment design must prevent entry or accumulation of any liquid through the garment seams or the interface of the skin and garment. Generally, liquid-splash protective garments will provide a much lower level of protection from vapor intrusion (if any at all). The performance requirements for liquid-splash protective garments are presented in NFPA 1992 (cited previously).

The potential for vapor intrusion presents a more stringent design constraint. Generally, to prevent vapor intrusion, the garment must be fully encapsulating. These garments also provide protection from exposure to liquid splashing. The performance requirements for vapor-intrusion protective garments are presented in NFPA 1991 (cited previously).

2.2 Fabric Evaluation

The compatibility of a garment material with a chemical of concern depends on the ability of the garment to resist the permeation (diffusion) of the chemical through the polymeric material. Permeation through polymeric materials depends on the chemical composition of the polymer, the thickness of the polymeric material, the molecular properties of the chemical of concern, and other environmental factors (temperature, pressure, exposure time, etc.). The permeation of a chemical through the garment surface can be evaluated through chemical resistance tables provided by the manufacturer. These tables will usually indicate whether the garment material is suitable for the

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[10] NFPA 2112 *Standard on Flame-Resistant Clothing for Protection of Industrial Personnel against Short-Duration Thermal Exposures from Fire*, 2018.

[11] NFPA 2113 *Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel against Short-Duration Thermal Exposures from Fire*, 2020.

[12] NFPA 70E *Standard for Electrical Safety in the Workplace*, 2018.

chemical of concern, and if it is, a breakthrough time is reported. The breakthrough time is the time duration over which the garment will offer protection following an exposure to the chemical. Alternatively, one can determine the compatibility of a polymeric material with a chemical of concern by consideration of the Hildebrand solubility parameter for both the polymeric material of the garment and the chemicals of concern.[13]

2.3 Training

Simply selecting the correct PPE fabric for chemical protection is not sufficient to protect workers. Workers must also be trained in the proper donning, use, decontamination, and doffing of their PPE garments.[14] Prior to donning of PPE, the worker should inspect the garment for punctures, tears, or other defects that might permit entry of the chemicals of concern past the protective boundary of the garment. The worker should also read any labels, warnings, or instructions provided with the garment or on the garment tags. In donning the PPE, the worker must be careful to avoid damaging the garment and ensure that it is properly assembled. It is often helpful for a second worker to assist with the inspection after donning to ensure a full 360-degree inspection. During the use of the PPE, the worker must note the nature and duration of any direct exposures with chemicals of concern as this may limit the useful life of the garment (i.e., the garment should not be worn for a period exceeding the permeation time of a chemical of concern). Finally, the worker should be familiar with necessary decontamination and doffing procedures for the PPE. If an exposure occurs, the worker must carefully guard against exposure to the chemicals of concern which may have adhered to or penetrated the PPE garment prior to and during removal. Decontamination protocols and inherently safer doffing procedures (e.g., remove contaminated gloves by rolling them inside-out off of the hand, touch PPE garments only with gloves and not bare hands) can prevent or at least mitigate chemical exposures during the doffing of PPE.

2.4 Complex Specifications: Flammability and Chemical Hazards

Flammability hazards in the chemical process industries are manifested as flash fires, liquid pool fires, and jet fires. Flash fires are caused by the ignition of a diffuse fuel cloud followed by a flame sweeping through the cloud without causing significant overpressure damage.[15] Flash fires tend to be transient events with a duration measured in seconds. A liquid pool fire is caused by the ignition of a discrete accumulation of liquid fuel into a region of finite extent called a pool.[16] A pool fire rapidly achieves a steady burning rate and will continue burning until the fuel supply is consumed. A jet fire occurs when a flammable gas, vapor, or liquid is released under pressure from its containment.[17] The jet fire can persist until the discharge of fuel is stopped or the fuel supply is exhausted.

One important feature of flammability hazards is the duration of the exposure. Both pool fires and jet fires can present sustained fire hazards and therefore require PPE that is quite different from that required to protect against a flash fire. The workers most likely to be exposed to sustained

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13 Moseman, J. "Are these the right gloves?" *Professional Safety*, pp. 40-47, April 2016.

14 NIOSH. *Occupational Safety and Health Guidance Manual for Hazardous Waste Site Activities*. National Institute for Occupational Safety and Health, Chapter 8 Personal Protective Equipment (PPE), 1985.

15 NFPA 921 *Guide for Fire and Explosion Investigations*, 2017, Section 3.3.87 and 6.3.7.11.2.

16 NFPA 921 *Guide for Fire and Explosion Investigations*, 2017, Section 5.7.3.

17 NFPA 921 *Guide for Fire and Explosion Investigations*, 2017, Section 23.8.2.2.5 and 23.18.6.

fires are firefighting personnel. Turnout gear or aluminized fire suits are the PPE of choice for firefighting activities. In comparison to pool fires and jet fires, flash fires present a hazard of much shorter duration. Therefore, PPE for protection from flash fires tends to be much lighter and less bulky than the full firefighting turnout gear employed for combatting sustained fires. Flash fire PPE garments are typically labeled as flame-resistant clothing (FRC).

Flash fires cause burn injuries by heating the skin tissue to injurious temperatures. Flash fires can lead to essentially two types of thermal exposure: direct flame impingement (related to convection) and radiant heat. The potential for thermal injury is characterized by the incident heat flux, the duration of the exposure, and the total energy deposited into the skin. FRC must satisfy six different thermal performance criteria as determined through standardized testing to successfully demonstrate that the garment will offer protection from these thermal damage mechanisms.[18] One common FRC garment uses cotton fabric treated with flame retardants. FRC is often intended to be reused on a routine basis much like a work uniform. To preserve the protective features of FRC, the user must follow the manufacturer's instructions regarding the laundering, inspection, and reuse of these garments.

NFPA requires that a hazard analysis for flash fire hazards be performed for the determination of whether FRC PPE is required, and if so, what performance characteristics it must satisfy.[19] An example of a flash fire hazard analysis procedure has been developed by BASF.[20] It is based on a consideration of the hazardous properties of the materials involved, the process area or equipment location where the work is to be performed, and the job task to be performed. The determination and specification of FRC PPE requirements follows from this hazard analysis. The BASF hazard analysis identifies three material hazard thresholds:

- Is it a flammable gas?
- Is it a liquid being handled or processed above it flashpoint?
- Is it a combustible dust where the particle size less than 75 µm, the minimum explosive energy is less than 100 mJ, and the moisture content is less than 10%?

The considerations for the process area are the following:

- Evaluation of the area's flash fire history and near-misses
- Are flammable gases, vapors, or combustible dusts present in the atmosphere during normal operations?
- Are potential ignition sources present?
- Is there a potential for personnel to be present in the vicinity of a flash fire event?

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18 NFPA 2112 *Standard on Flame-Resistant Clothing for Protection of Industrial Personnel against Short-Duration Thermal Exposures from Fire,* Appendix B Properties for Evaluating Flame Resistant Garments, 2018.

19 NFPA 2113 *Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel against Short-Duration Thermal Exposures from Fire*, 2020.

20 BASF. Flash Fire FRC Assessment Tool, 2010. Accessed at http://www2.basf.us/DocSearchWeb/displaydoc?docbase=Wyandotte_MI_US&cabinet=EHS&folder=Publish/WSTD&docname=WYN032.007a&rend=pdf.

Finally, the considerations for the job task are the following:

- Credible release scenarios
- Exposure potential: does the task involve the potential for exposure to the material of concern or are there other activities nearby that could create a flash fire potential?
- Ignition potential: does the task introduce an ignition source for the material of concern or are there other ignition sources nearby?

Based on this hazard analysis, if it is concluded that there is a potential for both exposure to the material of concern and its ignition, then FRC may be required.

Generalizations about PPE selection must be tempered by the specific circumstances encountered at each worksite and each work assignment. Given that caution, some generalizations are reasonably indicated. First, if a worker must be protected from both flash fires and chemical hazards, then the in most cases the outerwear for their PPE clothing should be the flash fire protection (the FRC). In the event of a flash fire, the FRC will not only provide protection for the worker, but it will also provide some protection for the chemical hazard PPE. Thus, the worker will still be protected from chemical hazards.

On the other hand, if the worker is exposed to a chemical hazard, the FRC may be degraded or contaminated by the exposure event. If the chemical exposure is an unexpected, acute exposure, the condition of the FRC should be immediately evaluated. The condition assessment of the FRC in this circumstance may require an interruption of the work assignment. For example, if a flammable liquid splashes onto the worker, the chemical PPE clothing may protect the worker from a chemical exposure. But the saturation of the FRC fabric with a flammable liquid could compromise its effectiveness. In fact, the saturation of FRC fabric with a flammable liquid clearly increases the magnitude of the fire hazard presented to the worker. Whether the work should be discontinued will depend on several factors. One example of an important factor in this scenario is the quantity of liquid splashing onto the worker. A spill onto FRC fabric equivalent to one cubic centimeter of flammable liquid is likely an acceptable risk. The spill of a liter of flammable liquid onto the worker presents a higher, and likely unacceptable, fire risk. The manufacturer's instructions and warnings should also be consulted for potential guidance regarding contamination of PPE.

Following the work activity, the condition of both the FRC and the chemical PPE should be assessed for potential reuse. The ability to reuse the FRC will depend on the degree to which the FRC can be decontaminated or repaired. To prevent damage to the FRC, the laundering and maintenance instructions should be closely followed.[21,22,23,24] The ability to reuse the chemical PPE

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[21] Hoagland, H. "How to properly care for flame-resistant garments," *Welding Journal*, pp 38-40, November 2008.

[22] ASTM F1449-08 Standard Guide for Industrial Laundering of Flame, Thermal, and Arc Resistant Clothing, 2015.

[23] ASTM F2757-09 Standard Guide for Home Laundering Care and Maintenance of Flame, Thermal and Arc Resistant Clothing, 2016.

[24] NFPA 2113 Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire, 2020.

will depend on the manufacturer's recommendations. Many, if not most, of chemical protection garments are intended for one-time use only.

Finally, it must be emphasized that combining PPE for both flash fire and chemical hazards results in a complex PPE ensemble. This complex PPE ensemble can present significant physiological and psychological burdens on the worker and may introduce new hazards that must be managed.

3 Potential Negative Impacts of PPE

As previously discussed, PPE is the critical last line of defense to protect workers from chemical, physical, and biological hazards, but the trade-off for this protection primarily impacts the worker through a reduction in performance, efficiency, and stamina. The proper selection of PPE requires a consideration of these trade-offs to ensure the worker is adequately protected without unknowingly introducing new hazards, or otherwise unduly impacting their ability to perform the job. As OSHA cautioned in an appendix the HAZWOPER standard, 29 CFR 1910.120, "The use of PPE can itself create significant worker hazards, such as heat stress, physical and psychological stress, and impaired vision, mobility, and communication."[25] While adequate protection for an employee is critical, "over-protection, as well as under-protection, can be hazardous and should be avoided where possible."[26] The impact of chemical protective equipment on human performance has been the subject of extensive studies funded by the United States military due to the threat of chemical warfare, which can require the use of chemically protective clothing during combat.[27] Chemical warfare protective combat clothing bears many inherent similarities to the PPE employed in industrial settings, consisting of a non-encapsulating over-garment and a full-face respirator with a hood, gloves, and boots.[28] The military studies have identified the following primary causes of performance degradation experienced by soldiers wearing chemical warfare protective combat clothing:[29]

- *Heat stress due principally to the weight, insulation, and low moisture vapor permeability of the overgarment.*
- *Reduced manual dexterity due to the constraints imposed by the gloves, overgarment, and boots.*
- *Restricted vision due to the design and optical characteristics of the mask, e.g., reduced field-of-view and poor optical quality of the mask faceplate.*
- *Restricted communication (hearing and speaking) due to the mask and hood.*
- *Respiratory stress due to air resistance of mask filters and outlet valves.*

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25 Appendix C to 29 CFR § 1910.120 - Hazardous waste operations and emergency response.

26 *Ibid*.

27 Taylor, H.L. and Orlansky, J. The Effects of Wearing Protective Chemical Warfare Combat Clothing on Human Performance. Institute for Defense Analysis, IDA Paper P-2433. August 1991.

28 Grugle, N.L. An investigation into the effects of chemical protective equipment on team process performance during small unit rescue operations. Master's Thesis. pp. 37-41.

29 Taylor, H.L. and Orlansky, J. The Effects of Wearing Protective Chemical Warfare Combat Clothing on Human Performance. Institute for Defense Analysis, IDA Paper P-2433, April 1991. p. I-4.

These causes parallel the hazards identified by OSHA and underscore the fact that the process of PPE selection is truly one of risk management: balancing the hazards posed by PPE against the external hazards the PPE is intended to control.

3.1 Heat Stress

Heat stress is an obvious and widely discussed concern relative to PPE that cannot be overemphasized. Any level of additional clothing can increase the risk of the worker developing heat stress, and the amount and type of PPE worn directly influences the magnitude of this risk.[30,31] Garments designed to protect against physical and chemical agents are most often highly impermeable to water vapor, which imposes a considerable restriction on the body heat balance.[32] As a result, once PPE has been selected, it may be necessary to impose limitations on work duration and require mandatory rest periods to manage the risk of heat stress.

3.2 Mobility

Wearing a chemically protective ensemble may also impair dexterity and mobility. This fact has been recognized by the National Fire Protection Association (NFPA), which publishes standards on PPE for fire fighters and other emergency responders during incidents that involve hazardous material operations. Again, much of this PPE is comparable, if not identical, to the PPE used in the chemical process industry. As previously discussed, the NFPA 1991 and NFPA 1992 standards cover vapor-protective and liquid splash-protective ensembles, respectively. Both NFPA 1991 and NFPA 1992 directly address the loss of hand dexterity due to wearing gloves by requiring a standardized test and setting limits based on a comparison to a barehanded control test.[33,34] The standardized test compares the time required for a user to place a series of pegs into a specifically designed pegboard while wearing the protective equipment versus barehanded. The measure of dexterity is reported as "percent increase over barehanded control," where a value over 100 percent indicates that a greater time was required to accomplish the task while wearing gloves. For liquid splash-protective gloves, the average percent increase over barehanded control must be less than 200 percent, and for vapor-protective gloves, the average percent increase of barehanded control must be less than 600 percent. In other words, depending on the type of protection deemed necessary, it can increase the amount of time required to complete a manual task by a factor of between 2 and 6. Thus, workers may need to spend more time in high hazard locations to accomplish the same task.

3.3 Vision

Vision can also be significantly impaired by PPE, which can diminish visual acuity (sharpness or clarity of vision) and limit the field of view of the user. NFPA 1991 and NFPA 1992 require a minimum visual acuity of 20/35 for garments where hoods with visors are provided, and 20/100

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30 Hazardous Waste Operations. National Institute for Occupational Safety and Health (NIOSH). 1985.

31 Cheremisinoff, N.P., and Graffia, M.L. Environmental and Health and Safety Management: A Guide to Compliance. 1995. pp. 446-447.

32 Holmer, I. Protective Clothing in Hot Environments. *Industrial Health*, **44**, pp. 404-413, 2006.

33 NFPA 1991 *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies and CBRN Terrorism Incidents*, 2016, Section 7.4.6, 8.17, and A.7.4.6.

34 NFPA 1992 *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*, 2018, Section 7.2.6 and 8.13.

for ensembles with flash fire escape protection.[35,36] Consider a scenario where a worker who has 20/20 visual acuity is required to wear a vapor-protective ensemble with flash fire escape protection. Objects that were clearly visible to the worker at 100 feet without PPE may now need to be as close as 20 feet from the worker to be clearly visible while wearing the ensemble.[37] For reference, a visual acuity of 20/100 is comparable to the ability to read only the first two lines on the typical Snellen Eye Chart used by many American optometrists and ophthalmologists. Thus, the decision to provide PPE to protect against vapor and/or splash hazards may result in a measurable loss of visual acuity, and simultaneous protection from a flash fire hazard can cause a significant trade-off in visual acuity.

3.4 Psychological Effects and Decision Making

In addition to the physiological effects that PPE can impart on a worker, studies have also suggested that protective clothing can impact a person's decision making and psychological effects. The previously referenced military studies of soldiers wearing chemical warfare protective combat clothing also found that clothing could result in symptom intensification, and general deterioration of mood. [38] This included intensification of feelings of sleepiness, dizziness, and unhappiness, while aggressiveness, friendliness, and clear thinking decreased. When combined with other factors, such as heat stress, cognitive performance has been shown to markedly decrease, primarily due to errors of omission.[39]

3.5 Summary

Depending on the level of PPE necessary, each of these factors may also significantly impact the industrial worker in chemical protective clothing. Take for example the consideration of respiratory protection. The options can range between no PPE, carrying an escape respirator, wearing a half-face or full-face air-purifying respirator, wearing a self-contained breathing apparatus with supplied air via a hose or a tank, or wearing a fully-encapsulated suit with supplied air. Additionally, due to the impact of psychological and physiological stresses imposed using PPE, wearers may require medical clearance and surveillance before, during, and after its use.[40]

4 Case Study: Reevaluation of PPE for Line Breaks

After an injury or near-miss, personnel may find themselves questioning the resiliency of their safeguards. The following case study discusses a facility that reevaluated the PPE specified for line break activity following an exposure and chemical burn injury to a maintenance operator. The incident occurred during installation of temporary drain piping on an ethylene oxide header. The background of the incident, the root cause of the exposure, and the role of PPE and safe work

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35 NFPA 1991-2005, Sections 7.1.2(3) and 7.8.2.

36 NFPA 1992-2005, Sections 7.1.2.2 and 7.6.2.

37 "Low Vision and Legal Blindness Terms and Descriptions." American Foundation for the Blind. url: https://www.afb.org/blindness-and-low-vision/eye-conditions/low-vision-and-legal-blindness-terms-and-descriptions

38 Taylor, H.L. and Orlansky, J. The Effects of Wearing Protective Chemical Warfare Combat Clothing on Human Performance. Institute for Defense Analysis, IDA Paper P-2433, April 1991. p. I-4.

39 Fine, B.H. and Kobrick, J.L. Effect of Heat and Chemical Protective Clothing on Cognitive Performance. US Army Research Institute of Environmental Medicine, Report M4/86, November 1985.

40 Personal Protective Equipment (PPE). Chemical Hazards Emergency Medical Management, National Institute of Health. U.S. Department of Health and Human Services. url: https://chemm.nlm.nih.gov/ppe.htm.

practices will be reviewed. The facility's reevaluation of the PPE for line breaks will then be discussed.

4.1 Ethylene Oxide — Hazard Overview

Ethylene oxide (EtO) presents multiple types of hazards to workers, equipment, and the environment. EtO has a wide flammability range, forming flammable mixtures in air from 2.6%–100%.[41] Aqueous solutions of >4 wt.% EtO are flammable with flashpoints reported between -2°C to -57°C. In addition to its flammability, EtO is also extremely reactive and can react with other materials exothermically or decompose explosively in air or inert atmospheres. It also poses carcinogenic, reproductive, mutagenic, and neurotoxic hazards through inhalation, eye, or skin contact. Extended skin exposure from continuing to wear contaminated clothing can cause blistering, frostbite, and chemical burns. It is also toxic to microorganisms and marine life in the environment. It is typically stored as a liquid under pressure, with a boiling point of 10.8°C at atmospheric pressure. As a result, leaks and releases may include both liquid and vapor depending on the ambient conditions.

4.2 Line Break Overview: Temporary Piping Installation

At the facility, EtO was supplied to process equipment via a pressurized (200 psig), insulated, 24-inch diameter header. The header ran along a pipe rack that was elevated approximately 20 feet off the ground in an area outside of the manufacturing building as shown in Figure 1. As part of a scheduled shutdown, the EtO header was scheduled to be drained and purged so a temporary blind could be installed to isolate the EtO source from the process unit during maintenance. The EtO header was de-inventoried and depressurized to 50 psig. The next step of the job involved installation of temporary drain piping on a 2-inch diameter drain line on the header as shown in Figure 2. The temporary drain piping would be routed to a closed head drum on the ground so the remaining heel of EtO vapor and liquid in the header could be back flushed with inert gas.

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[41] S. Rebsdat and D. Mayer, Ethylene Oxide, Ullmann's Encyclopedia of Industrial Chemistry, 2012.

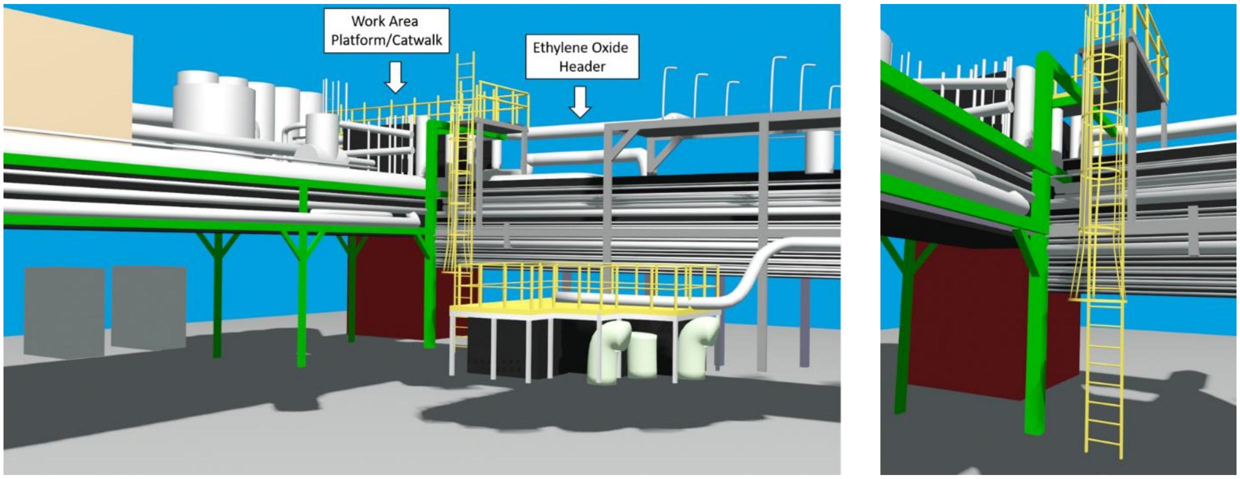

Figure 1. Ground view of the elevated work area (left) where the platform and catwalk were located to access the drain line on the Ethylene Oxide Header. Close-up view of the ladder and cage (right) to access the elevated platform.

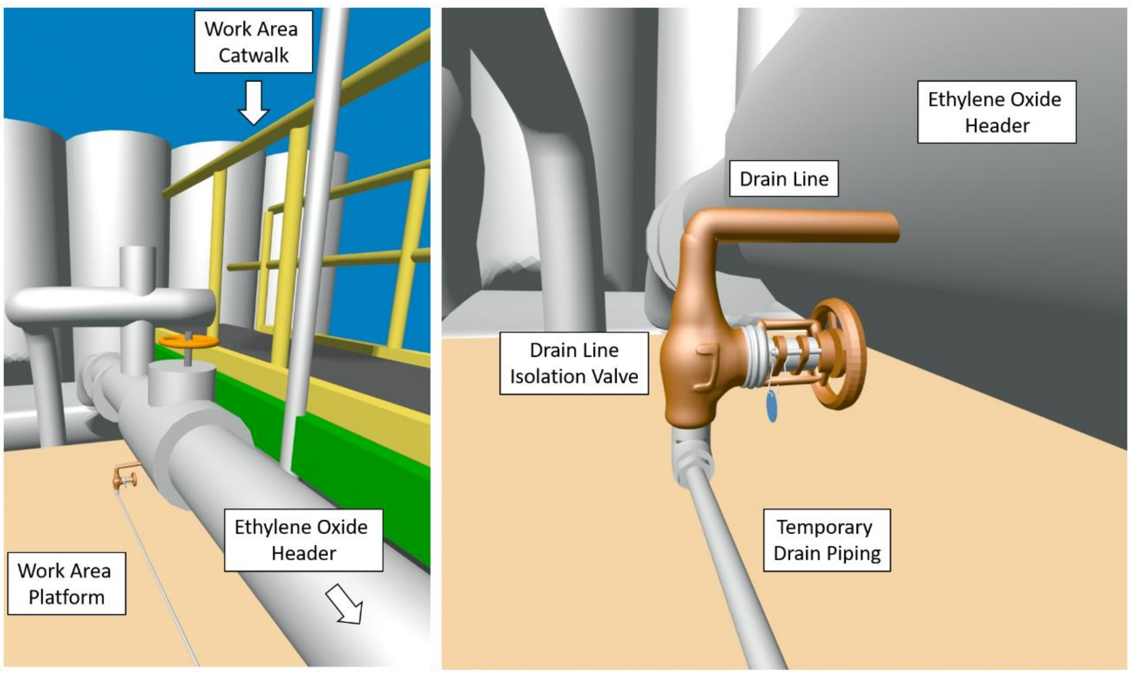

Figure 2. View of the work area from the elevated catwalk (left) with a close-up view of the isolation valve and temporary piping that was to be installed (right). Prior to installation of the temporary drain line piping, the isolation valve had a removable plug screwed into the discharge end.

Installation of the temporary drain piping required that a plug be removed from the discharge of an isolation valve on the header's 2-inch drain line, immediately followed by installation of the temporary piping. The facility considered the removal of the plug on the discharge of the valve a line break because there could be a small amount of pressurized EtO liquid or vapor between the drain isolation valve body and the plug. Pre-job planning paperwork with maintenance, engineering and operations staff was completed including a safe work permit, a LOTO form, a job hazard analysis, and a pre-job walk through.

The facility line break procedure specified several layers of PPE to protect workers from both vapor and liquid EtO. The Line Break Procedure at the facility specified PPE including a full body chemical suit with booties/socks, air supplied respirator, boots, butyl gloves, and a personal grounding strap. The specified full body chemical suit and gloves were made of materials that listed permeation breakthrough times of 480 minutes for vapor EtO, and 15 minutes for liquid EtO. The model of chemical suit provided to workers also included a tight-fitting respirator hood. The facility viewed this level of PPE appropriate for line breaks and had determined that fully-encapsulating suits (such as those worn by emergency responders in Level A PPE) were unnecessary based on a job hazard analysis performed prior to the incident.

4.3 Incident Overview

Two technicians from a maintenance contractor were assigned to the work order for the temporary piping installation. Since the facility did not perform line breaks often, the maintenance contractor viewed the installation of the temporary piping as an opportunity to train and qualify a newly hired maintenance technician on the procedure for performing a line break in EtO service. The newly hired technician was to learn the procedure by shadowing the job with his supervisor. As previously discussed, the pre-job planning paperwork was completed, and the job was staged. Non-sparking tools, two supplied air hoses and full-face respirators, and a 1.5-inch water hose were placed on the elevated platform near the ladder and catwalk approximately 10 feet from the work area. The two maintenance technicians donned their chemical suits, gloves, and grounding straps in the nearby locker room. Both technicians placed their chemical suit's attached booties/socks over their steel toed work boots, and then walked through the gravel parking lot to the ladder to ascend to the elevated catwalk and platform.

The plan was for each technician to don their respirator on the catwalk and then cross check that their coworker had properly donned their PPE. One technician would then provide a fire-watch with the water hose, while the other technician verified the drain isolation valve was closed and affixed his personal lock to the valve. This would complete the LOTO procedure (with the verification and personal lock of the person performing the line break completing the LOTO process). After completing LOTO, the technician would then remove the plug (break the line) and install the temporary drain piping. As shown in Figure 1, staff at ground level had an obstructed view of the work area. The technicians could be seen on the catwalk, but the work platform, drain line, isolation valve, or the technicians as they performed the line break were not visible.

The inexperienced technician climbed the ladder first and donned his respirator. His supervisor followed next and was in the process of donning his respirator on the catwalk when he heard a pressurized release. He turned and saw the inexperienced technician laying on his back near the drain line and a small blue flame under the platform. The supervisor used the water hose to extinguish the fire while the inexperienced technician stopped the release. Both technicians then removed their respirators, partially doffed their PPE (i.e. removed their butyl gloves and unzipped their chemical suits) and climbed down the ladder.

At ground level, operations and engineering staff could not see what happened, but saw the small blue flame. The inexperienced technician stated that he had mistakenly opened the isolation valve before removing the plug. Once he realized his mistake, he closed the isolation valve stopping the release. Both technicians confirmed there was not an active release, and that the fire had been extinguished. When asked by staff on the ground if EtO had contacted their PPE, both maintenance technicians from the platform said no. Staff on the ground reiterated that EtO, particularly in liquid form, can permeate chemical suits, and both technicians confirmed that EtO had not contacted their PPE. Staff then asked if the maintenance technicians could perform a field survey for EtO to confirm the leak was isolated while estimations were made regarding the amount of EtO that had been released. The field survey was conducted by the inexperienced technician, who rezipped the chemical suit he was wearing, and then put on his standard work gloves. The survey confirmed there was no EtO in the area. Staff on the ground estimated that the amount of EtO released was less than a gallon (a few pounds).

The inexperienced technician walked back toward the breakroom where he took off his work gloves, then removed his chemical suit and boots, before disposing of his chemical suit in a bin for used PPE. Over the course of the next 4 hours, he began to complain of a burning sensation on his hands, legs, and feet. He eventually admitted to emergency staff that EtO liquid and vapor had contacted his respirator face shield, gloves and suit during the line break. He was taken to the hospital and treated for chemical burns.

4.4 Root Cause Analysis

Following the injury, the facility conducted a root cause analysis of the exposure. During the investigation it was noted that several safe work practices had been violated during the line break:

- LOTO – The isolation valve on the EtO drain line was not closed and locked out prior to removing the plug. This exposed the technician to a larger potential volume of EtO than anticipated during the line break.
- Line of Fire – The technician was positioned underneath the valve, directly in the line of fire, as he removed the plug. When EtO was released, liquid and vapor contacted the technician's respirator face shield and chemical suit. The technician then wiped his face shield and suit with his gloves.
- Incident Reporting – The technician who was exposed to EtO failed to report his exposure to his supervisor or other staff at ground level. As a result, he was not properly decontaminated after his exposure.
- PPE Donning and Doffing – Both technicians did not properly don or doff their PPE while performing the work. The instructions, warnings, and labels on the chemical suit clearly indicated that the attached boots were not intended as boot covers and could tear if worn improperly over work boots. Both technicians also removed their gloves prior to removing other pieces of PPE, potentially resulting in cross contamination through their hands. The inexperienced technician also continued to use/reuse his PPE after it had been

contaminated with EtO, extending the potential exposure time and breakthrough risk. He also used his work gloves instead of a new set of butyl gloves while performing the field survey after the release.

Based on the information above, it was determined that the root cause of the injury was the failure to perform necessary safe work practices during the line break. This resulted in a worker being exposed to a larger amount of EtO than the amount anticipated when the PPE was specified. It was concluded that the injury occurred due to either improper PPE donning/doffing, or extended contact from lack of decontamination and removal of contaminated PPE.

4.5 Reevaluation of PPE for Line Breaks

The facility recognized additional layers of PPE (such as a fully encapsulating suit) could have provided a higher level of protection during the line break. However, there was concern associated with heat stress and more specifically the ability of the workers to access the platform, or egress in the event of an emergency if wearing a fully encapsulating suit. The site also questioned whether it was inappropriate to wear the chemical fabric over the FRC clothing. However, the site ultimately concluded that there was not a significant flammability hazard because safe work practices (LOTO) limited the amount of flammable material that could be released, the location was well ventilated because it was elevated and outdoors. Therefore, the site viewed the additional protection potentially provided by fully encapsulating suits as being marginal compared to the hazards presented by decreased accessibility and mobility of the workers at the job site.

The facility realized that safe work practices were a critical component of hazard mitigation during the line break. LOTO would have limited the amount of EtO release to a few drops (if any) because it would have isolated the worker from the source of hazardous energy. If a small amount of EtO was released when the plug was removed, employees had a very small risk of exposure if they remained out of the line of fire, since EtO liquid would rapidly vaporize and dissipate in the work area. It was also determined that the amount of liquid that could be trapped between the valve body and plug would not be sufficient to form a flammable mixture that would envelop the worker. If EtO contacted the gloves or suit of the worker, the fabrics were rated for 480-minute and 15-minute breakthrough times for vapor and liquid EtO, respectively. This provided ample time for employees to receive decontamination and remove the contaminated PPE. The facility also recognized that higher levels of PPE would still be ineffective if workers did not properly wear, use, or remove the equipment during work.

The facility also consulted industry regulations, literature, and references related to proper PPE and specific requirements for EtO service. These references stressed that PPE should not be relied upon to provide complete protection from hazards and instead should be used in conjunction with other safeguards such as engineering controls and administrative controls (e.g. safe work practices). As a result, the facility determined the PPE had been appropriately specified for the job and would not be changed. Instead, the facility focused on training workers on the importance of safe work practices and PPE donning/doffing/decontamination procedures for EtO service.

5 Conclusions

PPE, though often viewed as the least effective safeguard, can also be the last line of protection between workers and the hazards they encounter in chemical processing facilities. In this paper, several aspects of PPE specification, and the trade-offs of various forms of PPE were presented. The key conclusions were:

- PPE specification begins with hazard identification and risk assessment. The assessment should include a review of the materials/chemicals, the job tasks that will be performed in the PPE, and details of the performance of the PPE fabrics and materials. This helps a facility document the assumptions and decisions that were made in specifying the PPE for their employees.
- Training is a critical component of a robust PPE program. Workers need to recognize the hazards they encounter and the benefits/limitations of the PPE they wear. They must also understand how to properly don, doff, and decontaminate their PPE if it becomes contaminated.
- PPE specification can be very complex and complicated. Sometime, PPE intended for one hazard will be ineffective to another hazard encountered at a work facility. Multi-layer ensembles must be carefully evaluated to ensure that each layer is being used properly.
- Over-specification of PPE can negatively impact workers in various ways. Heat stress, decreased mobility and vision, and the psychological impacts of PPE were discussed in detail. Ultimately, it is important that the PPE specified is both adequate for protection, and practical for implementation.
- It is important to read and understand the documentation provided by the manufacture of the PPE. Their instructions and warnings often contain important information regarding the proper use of PPE. If questions arise, many manufacturers include contact information and will provide input based on their expertise.
- PPE is often a safeguard that is used in combination with other engineering and administrative controls, such as safe work practices. If other safeguards, such as a LOTO procedure, are compromised, then workers may be at a higher risk of injury due to exposure to larger quantities of chemicals or flammables. Facilities may benefit from stressing the importance of safe work practices in the context of the PPE specified for a hazardous task.

All work places, including chemical processing facilities, contain some inherent level of injury risk. PPE is one aspect of a safety program that can protect workers from harm, but it is important to critically evaluate PPE specified for a job in the context of the task and hazards. Facilities should not blindly increase PPE requirements without evaluating the hazard that PPE can pose to the worker. Facilities should also seriously consider whether engineering and administrative controls (in combination with PPE) would be more reliable or effective at protecting the worker.