CHEMICAL ENGINEERING TRANSACTIONS

VOL. 36, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216

DOI: 10.3303/CET1436075

How Safe is “Safe Enough” for a Shelter-in-Place Design?

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Facilities with potentially significant toxic and/or flammable hazards often establish shelter-in-place locations (SIPs) in order to mitigate risks associated with an accidental release of hazardous materials. In addition to rapidly isolating the source of a release, typical SIP strategies include isolating building ventilation systems upon detection of dangerous concentrations of hazardous gases at the SIP ventilation intake and making the SIP as leak-tight as possible. However, the reliability of such detection systems and ventilation isolation mechanisms can vary dramatically, as can the leak tightness of SIPs. The adequacy of SIP tightness and the reliability of its ventilation isolation can therefore become sources of debate without any clear resolution. This paper provides guidance for establishing defensible values for these parameters based on standard risk analysis techniques.
An additional concern with SIP designs is that the building may be vulnerable to potential blast damage from vapor cloud explosions, so directing people to a shelter-in-place location may not be as effective as evacuating them to a safe outdoor muster point. This becomes especially pertinent with materials such as hydrogen sulfide which are both flammable and toxic. Issues associated with SIP blast vulnerability, loss of SIP pressurization, temporary loss of boundary integrity due to exterior door opening by “late comers,” and crediting escape packs, self-contained breathing apparatuses, air-supplied respirators and evacuation fallback plans are covered in this paper. SIP design challenges such as methods of creating a leak-tight volume, addressing oxygen depletion and carbon dioxide buildup, providing emergency communication, and development of practical fallback plans are also discussed in this paper.

1. Introduction

Toxic risk mitigation can be sought at the source of the toxic hazard through means of preventing accidental releases, reducing the severity of the hazardous source, and/or reliably detecting the release and isolating it in a timely manner. These are all risk mitigation strategies that should be considered as part of a facility’s risk management program. Toxic risk can be mitigated for outdoor personnel through reliable, timely detection and alarms, training for recognition of toxic hazards and proper response, and providing proper protective equipment such as escape packs staged in nearby locations or carried by personnel in some areas of the facility as required. These strategies should also be considered as part of the overall plan for managing toxic risks. This paper focuses on building occupants, and its main focus is on occupants of buildings that are designated as SIPs.

2. Shelter-in-Place Strategies

Buildings that are designated as SIPs can employ a range of strategies to ensure that toxic risk to occupants is as low as practical. These include pressurizing with clean air, isolating HVAC and minimizing infiltration, providing effective evacuation capabilities, or any combination of these approaches. Each is described in more detail below. Regardless of the toxic SIP design, it is important to evaluate the potential for blast impacts and to assess the risk of an explosion causing severe damage to the SIP, given that people are sheltering in it.

Please cite this article as: Sarrack A., 2014, How safe is “safe enough” for a shelter-in-place design?, Chemical Engineering Transactions, 36, 445-450 DOI: 10.3303/CET1436075

2.1 Pressurized Buildings / Rooms

One strategy for mitigating toxic and/or flammable risk is to pressurize the SIP with clean air. The method of accomplishing this varies as a function of the type of hazards applicable, the volume and leak tightness of the SIP, and the potential duration of the hazard impact.

Pressurizing an entire building usually requires the clean air supply to be provided by ventilation fans rather than pressurized air sources (cylinders or tanks), simply because of the volumetric flow required to achieve the desired differential pressure and/or purge effect. Exceptions to this include small volume buildings that are very leak tight.

Pressurized buildings that rely on stack height to provide clean air in case of a toxic or flammable impact typically have gas monitoring at the ventilation intake, and interlocks that trip the ventilation fans and/or shut dampers to isolate this air supply if concentration exceeds threshold values. The threshold values are usually set at safe thresholds such as 10% of the lower flammability limit (LFL) or ERPG-1 for a toxic gas. These thresholds are low enough that in most cases where the hazard is severe enough to potentially cause fatal conditions within the SIP (>>LFL or >> lethal concentration surrounding the building at ground level), the ventilation system will trip on high intake concentration, rendering the pressurization system non-functional. For this reason, the approach of pressurizing with a ventilation system that depends on elevation is generally not an effective means of mitigating hazardous gas impacts to a SIP. Exceptions are possible, but care should be exercised to ensure that the system does not provide a false sense of safety. That is, ensure that the risk of scenarios that would render the system non-functional is not overlooked.

If the hazardous plume does not exceed trip setpoints at the ventilation intake, this type of SIP is highly effective. Even if the system does not maintain the desired differential pressure, it would typically have enough purging to prevent a dangerous environment from occurring within the SIP. Its vulnerability to becoming non-functional because hazardous conditions reach the ventilation intake, however, can make it highly vulnerable to becoming ineffective for accident scenarios of concern. How effective a SIP of this type is when the ventilation system trips depends on how leak tight it is and how effective its fallback plan is. Additional details on leak tightness and fallback plans are provided later.

A modified version of this pressurization strategy is to include a scrubbing or filtration system on the ventilation intake. This prevents large hazardous plumes from tripping the system, as long as the scrubbing or filtration sufficiently reduces the hazardous concentration. Reliability of ventilation systems tends to be high and can be further improved by providing backup power. This is because ventilation systems normally run continuously and failure is easily detected and can typically be returned to service in short order due to redundancy built into the system design.

If the scrubbing or filtration system requires detection of the hazardous gases and startup of the system, reliability becomes a critical parameter. The detection and scrubbing system must be designed, tested, and maintained in a manner that ensures high reliability for such a system to provide a highly effective method of mitigating the flammable or toxic hazard.

The detection of hazardous gases downstream of the scrubbing or filtering system is typically monitored to ensure that dangerous gases aren’t drawn into the SIP. It is important that this system be reliable and not cause spurious trips. If it is not reliable, the likelihood of insufficient scrubbing or filtering, coupled with failure to detect the dangerous gases becomes a significant risk contributor. Likewise, if the system is vulnerable to spurious trips, the likelihood of the scrubber or filtration system failing when required can also be a significant risk contributor. How effective a SIP of this type is when the ventilation system trips depends on how leak tight it is and how effective its fallback plan is. Additional details on leak tightness and fallback plans are provided later.

It is practical to pressurize a SIP with cylinders or tanks of pressurized air or oxygen if the volume is small and the volume is leak tight. One major advantage of such a design over large systems that depend on ventilation systems for ventilation is that it has a leak tight design, which means that even if the system does not function, it remains a safe environment for short duration hazards and can even keep occupants safe for moderate or long duration events if the outdoor concentration is not extremely high, relative to lethal concentrations. The low infiltration rate also means that the pressurization system is generally not required to function to prevent indoor explosion / flash fire hazards.

A SIP that is pressurized by a small volume of compressed air or oxygen requires ventilation to be isolated, so detection of the hazardous gases must be highly reliable for the pressurization reliability to be high. Reliability of timely activation of the air or oxygen supply is less critical and would generally be sufficient with manual activation by trained occupants. If pressurization fails, the SIP becomes similar to a leak tight SIP, which is described later. The overall effectiveness of the SIP also depends on the effectiveness of its fallback plan, which is also covered later.

2.2 Leak Tight SIPs

Some SIPs rely on their leak tightness to prevent toxic or flammable gases from reaching dangerous levels within them. As with SIPs that use small compressed air or oxygen supplies to pressurize the volume, a leak tight volume may also implement a pressurized air supply to reduce the effective infiltration rate, provide a small amount of purge, and mitigate concerns with carbon dioxide accumulation or oxygen depletion. Calculations show that carbon dioxide accumulation and oxygen completion can be an issue for a small, leak tight volume with a large number of people in it for an extended period. However, most SIPs are not crowded enough or leak tight enough to pose a life threatening hazard from carbon dioxide accumulation or oxygen depletion for the maximum amount of time occupants would be expected to remain in the shelter.

Leak tight SIPs may be designed as an entire building, but it is generally much more effective to use a room or multiple rooms within the building as the SIP volume(s). Using a room within a building rather than an entire building can eliminate issues associated with outdoor winds causing differential pressures to develop as a result of their impacts on walls and the roof. The lack of differential pressure allows an interior room to essentially eliminate infiltration by simply providing a small amount of clean airflow (as described in the pressurized SIPs section above). Even without pressurization sufficient to prevent infiltration, supplying air can substantially reduce the infiltration rate into the SIP.

Another issue that is effectively resolved with a room within a building design is the rapid degradation of interior conditions due to a door being open after the hazardous plume is present. If the whole building is the SIP and a person outdoors enters the building after the hazardous plume is present, wind can cause a large amount of hazardous gases to enter the building in the brief time the door is open. The issue becomes more severe as more people attempt to enter the building after the hazardous cloud is present. If multiple doors can be opened at the same time, it is possible for the outdoor air to very rapidly enter the SIP and degrade its condition. The issue can be mitigated by a vestibule design (two doors in series), but even that approach has limited effectiveness if both doors may be opened at once. By buffering the entrance area into the building from the entrance area into the SIP, the effect of a briefly opened door is dramatically reduced.

2.3 Effective Evacuation

Some SIPs rely on short duration protection by the building, supplemented by highly effective evacuation to minimize risk to occupants. This strategy is really only applicable to toxic mitigation, but it can be implemented for any design of an SIP (pressurized or leak tight). An effective evacuation strategy can also be called a fallback plan for SIPs that do not expect to use it unless primary mitigation systems fail to afford adequate protection. Because this type of SIP provides protection for short duration events, and therefore occupants can remain safe as long as the hazard does not continue for a long time, it is referred to as a method of SIP rather than simply a means of mitigating risk in a standard building where occupants are expected to evacuate upon detection of the hazard.

One focus of safety in a SIP that relies on effective evacuation is detection of the indoor toxic gas concentration. Reliable toxic gas monitoring is essential, and training and procedures are necessary to ensure that personnel achieve the level of protection intended by the design of the SIP. A second parameter that is critical for a successful evacuation SIP is the ability to communicate with emergency response personnel. This aspect of mitigation is important because conditions within the SIP may be slowly degrading, and the determination of whether occupants should hold out a little longer to allow the hazard to pass or should make their escape before interior conditions further degrade requires input on the hazard, outdoor conditions, and the likelihood of its isolation. These are all things emergency response personnel are best suited to provide accurate answers.

The third important feature of an effective evacuation strategy is to have plenty of the proper protective equipment (PPE) for the number of people who may be present. A standard form of PPE for toxic gases such as ammonia, hydrogen sulfide, or chlorine is a 5 or 10-minute escape pack. Such equipment is designed for universal fit, is easy to use, and provides highly effective mitigation until the air supply is depleted. Because the duration of air supply may be the limiting item (most likely failure mode), it is important to train people to don them just prior to exiting the building. The number of PPE should be sufficient for peak occupancy (to the extent practical), understanding that when more people are present than PPE, the SIP's toxic mitigation effectiveness is degraded.

3. Cost vs. Benefit

To implement the fundamental principle of minimizing risk to the extent practical, one must equate risk to financial costs. The issue of “putting a price tag on life” is not easily resolved in a defensible manner. An extensive study performed in 2003 regarding values used around the world (Viscusi and Aldy, 2003) concluded that an average value per fatality for the U.S. was about $7MM. Depending on inflation rates used, this is approximately $8MM per fatality. This is the value that will be used in example calculations for this paper.

Building societal risk is defined as the total amount of risk incurred by occupants of a building, accounting for all hazards that may impact the building, and the average number of people present. It is reported in units of fatalities per year. By assuming the number of years a building will be used, the total amount of risk over that time can be calculated as the product of that number of years and the building societal risk. For example, if a building societal risk is 10^{-3} fatalities per year, and it will be used for 50 y, the total risk for the building is 10^{-3} fatalities per year x 50 y = 5 x 10^{-2} fatalities. This can be converted to financial terms by simply multiplying that total risk (fatalities) by the assumed cost of a fatality, which is assumed to be $8MM for the purpose of this paper. In this example, the risk for the building is 5 x 10^{-2} fatalities x $8MM/fatality = $400,000.

The safety benefit of a proposed mitigation strategy is evaluated by calculating the change in risk between the baseline configuration and the proposed configuration, as shown in the following equation:

$$B = (BSR_{base} – BSR_{proposed}) \times T_{bldg} \times \$8MM/fatality$$

Where B is the safety benefit (dollars)

- BSR_{base} is the baseline building societal risk (fatalities/y)
- $BSR_{proposed}$ is the proposed building societal risk (fatalities/y)
- T_{bldg} is the assumed duration the building will be used (y)

For example, if the building described above were to be upgraded lowering the building societal risk from 10^{-3} fatalities per year to 2 x 10^{-4} fatalities per year, the safety benefit of that modification would be calculated as follows:

$$B = (10^{-3} \text{ fatalities/y} – 2 \times 10^{-4} \text{ fatalities/y}) \times 50 \text{ y} \times \$8MM/fatality$$
$$= 4 \times 10^{-2} \text{ fatalities} \times \$8MM/fatality$$
$$= \$320k$$

4. Optimizing a SIP Design

A basic toxic risk calculation for a SIP accounts for HVAC ingression rate, HVAC isolation reliability, infiltration rate, and plume duration. The impact of each toxic impact should account for the indoor concentration with respect to time and the resulting dose and corresponding vulnerability for the accident (Sarrack, 2012). To minimize the risk as low as practical, it is necessary to identify a range of possible designs and evaluate the corresponding risk of each design.

An example case is presented to explain how HVAC isolation reliability and leak tightness of the SIP can be optimized, assuming all other parameters are fixed. In this example, assume that the baseline toxic risk for a building is 10^{-3} fatalities per year, including credit for a fallback plan that is 90% effective. Assume that HVAC isolation is 90% reliable, and the building has a leak tightness of 0.3 air changes per hour (ACH) with a 5 mph wind speed. Sensitivity analyses are performed to evaluate leak tightness values as low as 0.001 ACH and HVAC isolation reliability as high as 99.9%. Results are summarized in Figure 1.

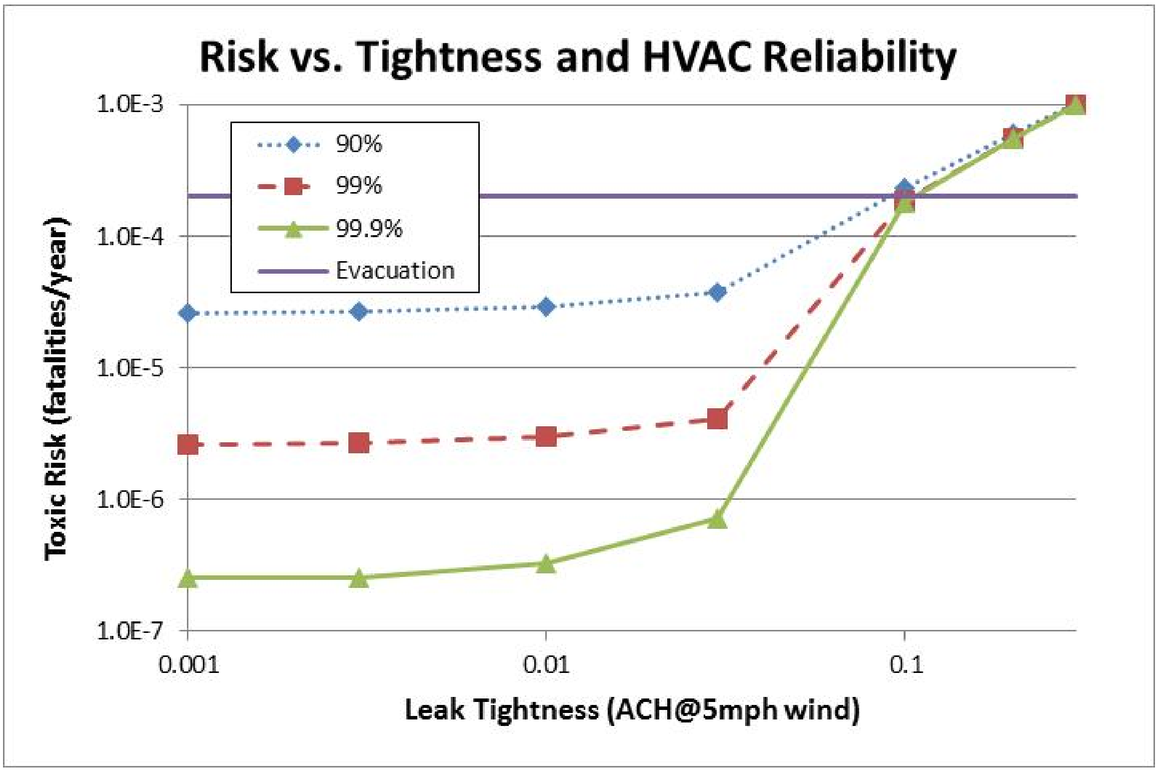

Figure 1: Toxic Risk as a Function of Leak Tightness and HVAC Isolation Reliability

From these results, it is clear that if the refuge cannot be improved to better than 0.1 ACH, then occupants are better off evacuating than sheltering in place. Another conclusion is that the reliability of HVAC isolation becomes increasingly important as the building leak tightness improves. One last conclusion is that there is very little safety benefit afforded by improving leak tightness beyond 0.01 ACH for this building. The safety benefit of incorporating a progressively tighter building and/or increasingly reliable HVAC isolation can be readily quantified as shown in the example calculation above. The cost associated with each improvement can be estimated by facility personnel and compared to the incremental costs. The risk has been minimized to the extent practical when additional improvements cost more than the safety benefits they afford.

A more extensive example is provided to better clarify how this concept can be carried out for a more diverse range of design decisions. The above example remains the baseline configuration. However, improvements to parameters affecting the fallback plan and pressurization are also assessed in this example. In the previous example, only two parameters were varied, so a wide range of each could be assessed without creating an unmanageable number of configurations to assess. As the number of parameters being varied increases, the number of potential configurations grows exponentially, and it can quickly become impractical to evaluate every possible outcome. For this reason, it is important to use good engineering judgment in selecting potentially optimal design options for evaluation.

Results of the more extensive sensitivity analysis are summarized in Table 1. It shows that each parameter on its own affords little to moderate safety benefit. However, certain combinations of enhancements have synergistic effects, which can dramatically reduce toxic risk for the SIP. If the cost of each enhancement is estimated and compared to the safety benefit, the optimum SIP design can be determined (Genserik et al., 2013).

Configuration	Risk Mitigation Strategies: More PPE		HVAC Isolation		Leak Tightness							Pressurize		Risk Mitigation Effectiveness	
	Add 20 escape packs	Add 30 escape packs	Simple interlock	Very reliable interlock	Reduce to 0.1 ACH	Reduce to 0.03 ACH	Reduce to 0.01 ACH	Reduce to 0.003 ACH	Reduce to 0.001 ACH	Indoor monitoring	ER communication	90% reliable	99% reliable	Building Societal Risk (fatalities/yr)	% Risk Reduction
Baseline														1.0E-3	NA
More PPE														9.2E-4	8%
Lots of PPE														8.5E-4	15%
Better HVAC isolation														9.2E-4	8%
Excellent HVAC isolation														9.1E-4	9%
Improved leak tightness														6.4E-4	36%
Highly improved tightness														7.2E-5	93%
Room within a bldg														5.2E-5	95%
Improved room within a bldg														4.4E-5	96%
Excellent room within a bldg														3.8E-5	96%
Indoor toxic monitoring														5.2E-4	48%
Pressurize														3.5E-6	99.7%
Reliable pressurization														4.2E-7	99.96%
Improved fallback plan														2.4E-4	76%
Much improved fallback plan														4.0E-5	96%
Improve mitigation and fallback														2.1E-8	99.998%

Table 1: Summary of Risk Values for Each SIP Configuration

Results of the sensitivities show that risk is most dramatically reduced by pressurizing the SIP, so this example focuses on that configuration. It reduces risk approximately 10^{-3} fatalities/year. Assuming that the building will be used for 50 y, the safety benefit of providing reliable pressurization is estimated to be $420k. The costs of those upgrades, including maintenance for 50 y is estimated to be $399k, so the upgrade is considered practical and is recommended, consistent with minimizing risk to the extent practical.

To determine if it is practical to make the pressurization highly reliable, the additional cost associated with that improvement is compared to the safety benefit gained by that further enhancement. The safety benefit is calculated to be 3.1×10^{-6} fatalities/y, which is converted to a value of $1,200. Therefore, if the improvement can be done for approximately $1,200 or less, it would be practical to implement that improvement.

5. Conclusion

This paper provides an overview of basic concepts for mitigating toxic and flammable risks, particularly to occupants of SIPs, and some of the primary parameters that impact the effectiveness of the SIP are identified. The concept of cost-benefit analysis is presented as a means of accomplishing the fundamental principle that risk should be minimized to the extent practical. The method of quantifying the safety benefit of a given SIP enhancement is described, and examples are shown to clarify the idea. The examples show that a practical, defensible design can be defined for a given SIP using this technique.

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