CALCULATING TOXIC IMPACTS TO INDOOR POPULATIONS

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Baker Engineering and Risk Consultants, Inc. has performed quantitative risk analyses (QRAs) for many facilities including companies handling acutely toxic materials. This paper compares traditional methods of estimating toxic risk exposure to personnel located within buildings via current methods and explains the benefits of the updated methods.

1. TRADITIONAL TOXIC IMPACT CALCULATIONS

Historically, toxic impacts have been assessed simplistically by developing geographic contours for threshold values and applying corresponding vulnerability values for personnel within those areas (e.g., a dose function is applied by assuming an exposure time). Building occupants were treated in a similar manner as outdoor personnel, although mitigation factors were often applied to credit toxic gas detection, ventilation isolation, and protective equipment such as escape packs. Figure 1 shows a typical toxic dispersion prediction along with several buildings within the toxic plume.

A typical method of predicting consequences for this type of toxic exposure is to treat indoor concentration as if it were the same as outdoors and apply a probit equation to the assumed exposure duration for the category of concentration. In the example shown in Figure 1, Building 1 is in the "low" consequence (probability of death) plume while Buildings 2 and 3 are in the "medium" consequence plume. No buildings are in the "high" consequence plume in this example.

Consequences may be reported for occupants by assuming they evacuate the building, even if they would actually shelter-in-place. This is not a very good representation of what really occurs. People who shelter-in-place should be assumed to remain in the building and continue being exposed by the hazard for as long as the hazard is present (function of isolation time and blowdown duration). People who evacuate the building should be assessed by accounting for the predicted concentration profile as a function of location and determining concentration as a function of time based on the escape route and evacuation rate. This paper is limited to the impact of personnel sheltering in place.

Figure 2 reproduces the scenario depicted in Figure 1, but the labels have been changed to show the specific toxic concentrations calculated for each of the buildings as well as the consequence categories that may be assessed for those buildings.

Categorizing by toxic concentration can lead to dramatic discrepancies between predicted severity and actual severity of a given hazard. In Figure 2, Buildings 2 and 3 are both categorized as medium consequence (assigned 10% vulnerability), but the concentration at Building 3 is significantly higher than at Building 2. The vulnerability values also do not account for HVAC isolation reliability or building leak tightness.

2. ENHANCED TOXIC IMPACT CALCULATIONS

Using a detailed method of evaluating toxic risks to personnel in buildings means accounting for the specific concentration predicted at the building for each scenario rather than the concentration category. It also requires building specific information such as ventilation intake rate, ventilation isolation reliability, and building leak tightness to be factored into calculations. Scenario specific information such as wind speed, direction, and release duration are all required to properly characterize the indoor concentration and resulting vulnerability to building occupants. The resulting indoor concentration versus time profile along with material toxicity forms the basis for defensible and realistic occupant vulnerability (OV) calculations. As applicable, mitigation factors can be applied to account for protective equipment.

To provide an accurate risk result for a given toxic release scenario, a range of likely release durations and associated conditional probabilities should be assessed. For example, a release may be modeled as a 5 minute duration (rapid isolation and limited inventory blowdown) with a 75% conditional probability, 15 minute release (delayed isolation) with a 24% conditional probability, and 60 minute release (long duration) for the remaining 1%. See the example event tree in Figure 3.

A building's ventilation and infiltration characteristics should be explicitly modeled in an enhanced toxic risk calculation. For example, a building may have 6 air changes per hour (ACH) of forced ventilation with 10% of that flow coming from fresh air (ingression = 0.6 ACH), and tests may show that its air exchange rate due to infiltration is 0.3 ACH with 2.5 m/s winds outside. Toxics may be detected at HVAC inlets causing alarms that alert occupants to trip the HVAC system, which have been determined to occur with 98% reliability (Figure 4).

The predicted indoor concentrations as a function of time for the 60 minute release case with and without HVAC isolation are shown for Building 3 in Figure 5. These concentrations are based on standard perfect mixing calculations, as shown in the following equation.

$$C_{\text{indoor}} = C_{\text{outdoor}} \cdot (1 - \exp(-AXR \cdot t_{\text{release}}))$$

- C_{indoor} is the indoor concentration.
- C_{outdoor} is the plume concentration at the near wall of the building.

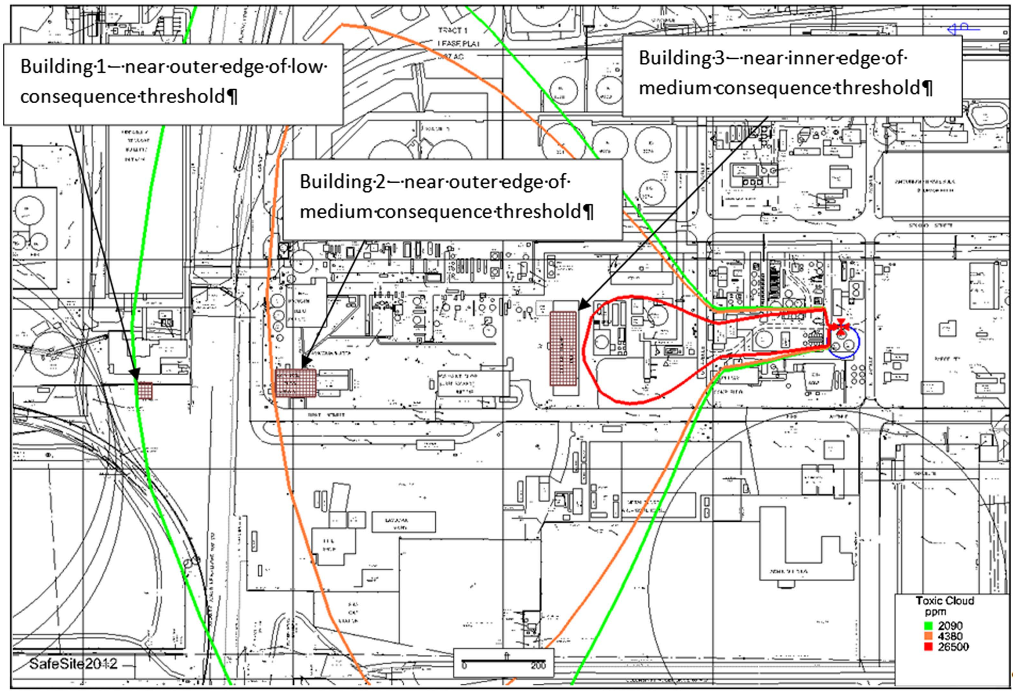

Figure 1. Typical toxic plume prediction

– *AXR* is the air change rate of the building based on the air changes from the HVAC system, infiltration, or both.
– $t_{release}$ is the duration of the toxic plume.

The probability of death for a given concentration and exposure time is solved using a probit equation of the form:

$$Pr = A + B \cdot Ln(t \cdot C^n)$$

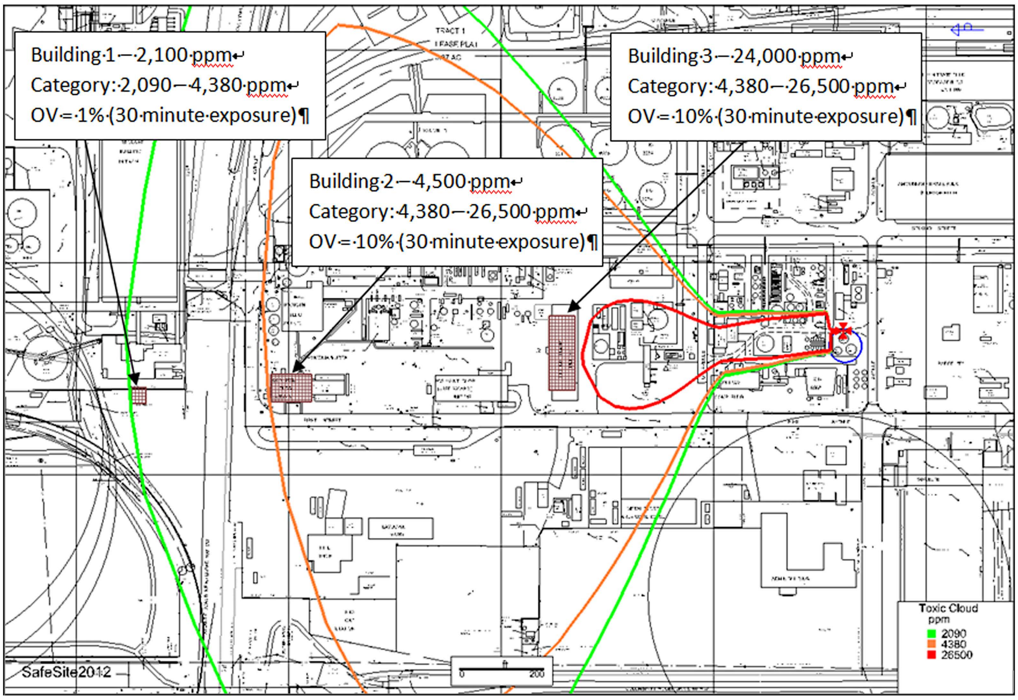

Figure 2. Toxic concentrations, concentration categories, and occupant vulnerabilities

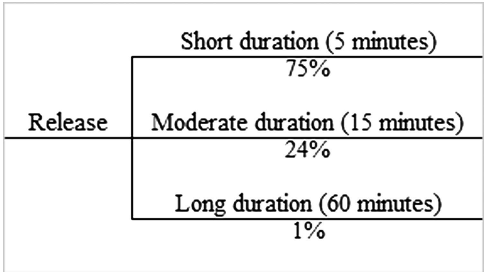

Figure 3. Simple event tree of example conditional probabilities for release duration

– *Pr* is the probit value for the toxic dose.
– *A*, *B*, and *n* are constants developed by research groups for a given toxin.
– *t* is the duration of exposure.
– *C* is the concentration of the toxin.

The probit value is converted to a probability of death using the probit dose response equation:

$$OV = 0.5 \cdot \left(1 + \frac{\Pr(C_{\text{indoor}}) - 5}{|\Pr(C_{\text{indoor}}) - 5|} \operatorname{erf}\left(\frac{|\Pr(C_{\text{indoor}}) - 5|}{\sqrt{2}}\right)\right)$$

Because indoor concentration changes with time, the vulnerability for each infinitely small time step is assessed

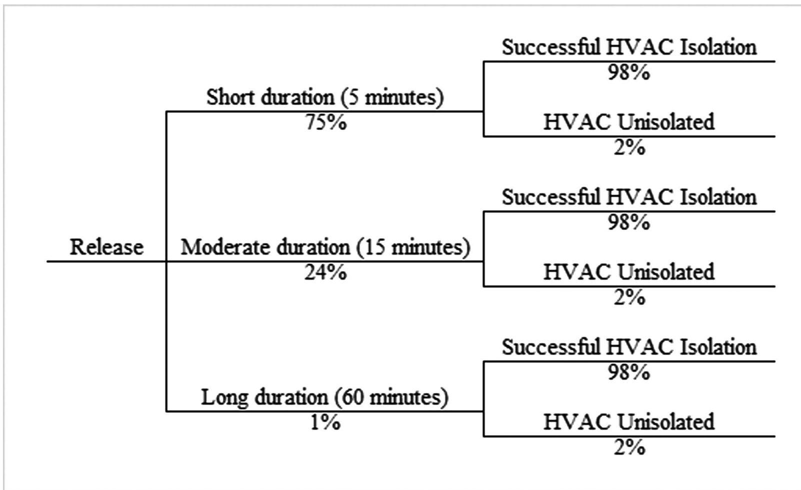

Figure 4. Event tree of example conditional probabilities

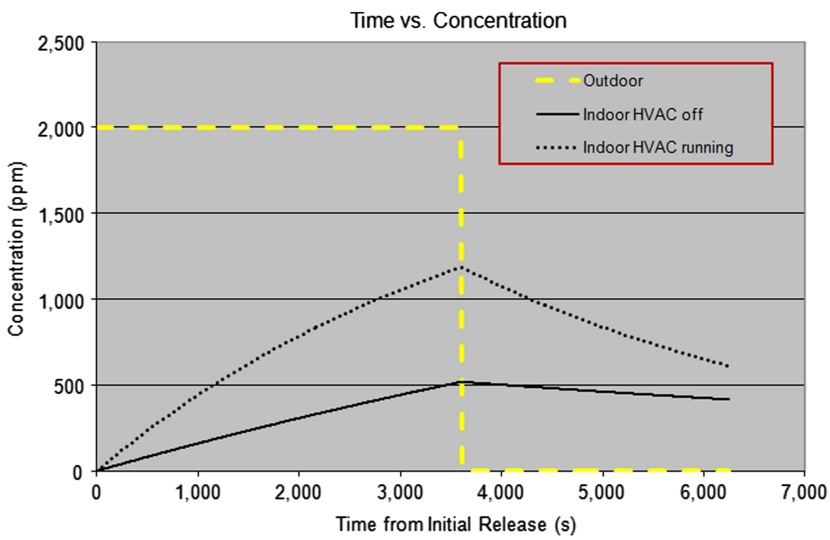

Figure 5. Building 3 indoor concentration vs. time

and they are summed, as defined by the following integrated dose equation:

$$\Pr = A + B \cdot Ln\left(\int_0^t C(t)^n \mathrm{d}t\right)$$

In this equation, the variables are all the same as defined earlier. This integral equation is coupled with the predicted indoor concentration (perfect mixing) equation to calculate vulnerability for the scenario.

The OV is assessed with the HVAC isolated and again with it running, and the weighted average OV is applied based on the reliability of isolating the HVAC system.

$$\begin{aligned} C_{\text{SIP-tox}} = {} & [(OV_{\text{SIP-HVAC-iso}} \times P_{\text{SIP-HVAC-iso}}) \\ & + (OV_{\text{SIP-HVAC-uniso}} \times P_{\text{SIP-HVAC-uniso}})] \\ & \times Pop_{\text{SIP}} \times MF_{\text{SIP-tox}} \end{aligned}$$

$C_{\text{SIP-tox}}$ is the weighted average consequence (number of fatalities).
$OV_{\text{SIP-HVAC-iso}}$ is the occupant vulnerability calculated for the SIP with HVAC successfully isolated.
$P_{\text{SIP-HVAC-iso}}$ is the probability that HVAC is successfully isolated.
$OV_{\text{SIP-HVAC-uniso}}$ is the occupant vulnerability calculated for the SIP with HVAC running.
$P_{\text{SIP-HVAC-uniso}}$ is the probability that HVAC isolation fails (continues running).
Pop_{SIP} is the number of people present in the SIP.
$MF_{\text{SIP-to}}$ is the mitigation factor for the SIP (applicable if PPE and indoor toxic monitoring is provided, and guidance is provided to evacuate at some threshold concentration).

Consequences of being exposed to these concentration profiles as well as other plume durations (same shapes but end earlier on the graph) are calculated by integrating the corresponding probit equation for the chemical. The scenario is split into multiple possible cases for the enhanced calculation (multiple durations, HVAC on or off), and each case is assessed for likelihood and consequence. Results are added to give a better picture of toxic risk to building occupants.

3. COMPARISON OF RESULTS

Results of an enhanced toxic risk exposure calculation can be significantly higher or lower than results from a simplified analysis. However, results from the enhanced method are more defensible and should be more accurate. Table 1 provides a comparison of results of the example case described above, based on a standard simplified toxic risk calculation method and the enhanced method described above. Results are shown for two leak tightness values (0.3 and 0.1 air changes per hour) and a range of ventilation isolation reliability values (50%, 95%, and 99%). Results are presented in terms of the predicted vulnerability for three release durations (1, 10, and 60 minutes). Blank cells in the table indicate that vulnerability is negligible for that configuration.

Notice that the traditional (simple) method is generally conservative, although it can also be non-conservative. In the example above, the reliability of timely source isolation is set high (95% success at isolating within 10 minutes), so the average vulnerability values (the merged cells to the right of the individual time slot cells) are all less than the simple method. However, if timely source isolation were less reliable, higher vulnerability values would be calculated. Cases in which the building is at the high end of the concentration category and the release lasts long (last row of the table) vulnerability results are predicted to be relatively high (19%–81%).

Table 1. Comparison of results from simplified and enhanced methods

<table>
<tr><th rowspan="3">Bldg</th><th rowspan="3">Duration</th><th rowspan="3">OV - Traditional</th><th colspan="12">Enhanced Method</th></tr>
<tr><th colspan="6">infiltration = 0.3 ACH</th><th colspan="6">infiltration = 0.1 ACH</th></tr>
<tr><th colspan="2">50% HVAC iso</th><th colspan="2">95% HVAC iso</th><th colspan="2">99% HVAC iso</th><th colspan="2">50% HVAC iso</th><th colspan="2">95% HVAC iso</th><th colspan="2">99% HVAC iso</th></tr>
<tr><td rowspan="3">Far</td><td>5 min</td><td rowspan="3">1%</td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td></tr>
<tr><td>15 min</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>60 min</td><td>2%</td><td></td><td></td><td>1%</td><td></td><td></td></tr>
<tr><td rowspan="3">Middle</td><td>5 min</td><td rowspan="3">10%</td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td></tr>
<tr><td>15 min</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>60 min</td><td>15%</td><td>6%</td><td>5%</td><td>12%</td><td>1%</td><td></td></tr>
<tr><td rowspan="3">Close</td><td>5 min</td><td rowspan="3">10%</td><td></td><td rowspan="3">2%</td><td></td><td rowspan="3">1%</td><td></td><td rowspan="3">1%</td><td></td><td rowspan="3">1%</td><td></td><td rowspan="3"></td><td></td><td rowspan="3"></td></tr>
<tr><td>15 min</td><td>6%</td><td>1%</td><td></td><td>3%</td><td></td><td></td></tr>
<tr><td>60 min</td><td>81%</td><td>69%</td><td>68%</td><td>55%</td><td>22%</td><td>19%</td></tr>
</table>

Table 2. Shelter in place example building input data

Building	AXR		HVAC Isolation Reliability
	Ingression	Infiltration	
Example SIP	0.6 ACH	0.5 ACH@5mph	95%

By implementing the enhanced calculation method, indoor toxic risks are more accurately predicted. This means attention is better focused on areas of true concern. In addition, the method provides a robust way of quantifying the potential safety benefit of implementing risk mitigation strategies such as more reliable toxic gas detection and timely HVAC isolation capabilities, better leak tightness of the building, more rapid detection and isolation of the toxic source, etc. This results in better input to decisions regarding safety improvements and project priorities.

Following is a summary of significant advantages gained by performing enhanced indoor toxic risk calculations instead of following traditional calculation methods:

- Enhanced calculations account for release duration and wind speed, which are typically not explicitly addressed in traditional indoor toxic impact calculations. These key parameters have a significant impact on indoor concentration and are required to accurately predict consequences and risk.
- Enhanced calculations explicitly factor HVAC ingression rate, HVAC isolation reliability, and building leak tightness into risk calculations. Traditional calculations typically use unsubstantiated factors to account for these parameters or may not address them at all. By explicitly calculating the effect of these parameters on risk results, sensitivity studies can be performed.
- Enhanced calculations use the predicted concentration at the building rather than the concentration category as input to consequence calculations. This refinement produces more accurate results and generally reduces conservatism.

4. CASE STUDY – EXAMPLE OF PRACTICAL RESULTS

Results of a risk analysis that uses the enhanced toxic risk calculation methods described in this paper can be used to answer the question, "How safe is safe enough?" Specifically, the results can explain the correlation between building leak tightness and risk, so practical, technically defensible decisions can be made regarding the design of a building that will be used for sheltering in place during an accidental release of toxic material. The following example is provided to clarify this concept.

An onsite building that will be used for sheltering in place has a ventilation system that draws 0.6 air changes per hour (ACH) of outside air into it. The system is isolated manually by occupants based on annual training they receive and toxic gas alarms initiated by control room operators. A review of procedures and interviews with operators and building occupants leads to the conclusion that ventilation would be isolated in a timely manner approximately 95% of the time. Its infiltration rate is 0.5 ACH based on a test performed with 2.5 m/s winds outdoors. These inputs are summarized in Table 2.

Based on discussions with operators, conditional probabilities for isolation times are 75% for 5 minutes, 24% for 15 minutes, and the other releases (1%) are assumed to last 60 minutes. Source isolation reliability inputs are summarized in Table 3.

Based on these inputs, a QRA is performed and toxic risk is determined to be 2.8×10^{-3} fatalities/year. To determine the safety benefit afforded by improving building leak tightness, a sensitivity study is performed by assessing risk with a range of leak tightness values applied. Results are summarized in Table 4 and Figure 6.

These results lead to some obvious conclusions, and they can be used as input to decisions regarding risk mitigation decisions. Following are examples of conclusions that can be drawn from this sensitivity study:

- If the building is very leaky (such as 1 ACH), occupants are better off evacuating than attempting to shelter in place. This is because evacuating the building limits the time a person is exposed whereas sheltering in place allows the exposure to continue until the toxic cloud has cleared and the building atmosphere has been purged.
- Risk drops significantly as a function of leak tightness until approximately 0.1 or 0.05 ACH. There is little risk mitigation afforded by making the building tighter than this. Therefore the goal value should be in the range of 0.05 ACH.

Because there are many ways to mitigate risk, and each may affect these results, it is not always straightforward to select the optimum set of changes to most efficiently mitigate risk. For example, in the case evaluated above, the facility may add toxic gas monitoring within the buiding and provide training and escape packs. Directions may be given

Table 3. Source isolation reliability and timing data

Isolation Time (Minutes)	Probability(%)
5	75
15	24
60	1

Table 4. Building toxic risk as a function of leak tightness

			Reduction	
Configuration	ACH	Risk	Abs	%
Corporate EHS Building		4.0E-3		
Corporate EHS Building 1ACH	1	4.2E-3	−2.7E-4	−6.7
Corporate EHS Building 0.75ACH	0.75	3.6E-3	3.4E-4	8.7
Corporate EHS Building 0.5ACH	0.5	2.8E-3	1.2E-3	30.1
Corporate EHS Building 0.3ACH	0.3	1.8E-3	2.1E-3	53.6
Corporate EHS Building 0.2ACH	0.2	1.2E-3	2.7E-3	68.6
Corporate EHS Building 0.1ACH	0.1	5.2E-4	3.4E-3	86.8
Corporate EHS Building 0.05ACH	0.05	1.6E-4	3.8E-3	95.8
Corporate EHS Building 0.03ACH	0.03	6.5E-5	3.9E-3	98.4
Corporate EHS Building 0.02ACH	0.02	3.5E-5	3.9E-3	99.1
Corporate EHS Building 0.01ACH	0.01	2.0E-5	3.9E-3	99.5
Corporate EHS Building 0.005ACH	0.005	1.8E-5	3.9E-3	99.6
Corporate EHS Building 0.003ACH	0.003	1.7E-5	3.9E-3	99.6
Corporate EHS Building 0.001ACH	0.001	1.7E-5	3.9E-3	99.6

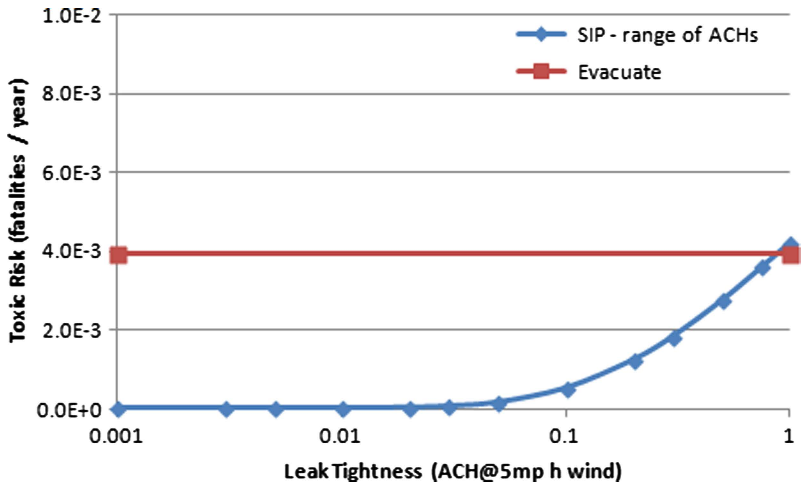

Figure 6. Risk as a function of building tightness

to don the escape packs and evacuate the building to a safe location if toxic gas concentration reaches a specific level inside of the building. Implementing such a mitigation plan would dramatically lower the baseline risk value in the building and therefore would also dramatically reduce the safety benefit available through improved leak tightness.

5. CONCLUSION

Indoor toxic impact calculations have traditionally been performed using simplified methods that fail to provide a means to quantify the safety benefit of implementing typical risk mitigation strategies. Results of traditional toxic risk calculations tend to give conservative results that can cause facilities to designate disproportionate resources to mitigating toxic hazards than hazards that are modelled more accurately. In some cases traditional calculation methods can also understate toxic risks.

Enhanced toxic risk calculations provide a means of accurately quantifying toxic risk to building occupants. They also enable sensitivity studies to be performed to quantify safety benefits available through implementation of potential mitigation strategies. By accurately assessing toxic risks to building occupants and evaluating safety benefits available through implementation of potential mitigation strategies, management can properly select and prioritize projects to optimize safety.