RWDI
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TRANSIT STATION FIRES

PART 2 – SEPARATION OF EXHAUSTS AND INTAKES: MODELING AND SOLUTION CONCEPTS

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Fire in a tunnel or transit station can cause rapid spreading of hot toxic smoke within minutes. Many transit systems have emergency ventilation systems to improve conditions in the event of a fire.

RWDI Technote 19 ***Transit Station Fires Part 1*** explained that, if these transit systems are not effectively designed, there can be a high risk of smoke re-entrainment into the station during a fire event. This can limit the ability of occupants to exit the station and emergency / rescue crews to enter.

This current Technote discusses identification of problems and quantifying potential solutions. Its approach includes first establishing design criteria and then carrying out dispersion modeling.


AP Photo

Howard Street Tunnel - Train Fire (Baltimore, MD)

TARGET DILUTION CRITERIA

Codes and design standards vary in their requirements for exhaust and intake separation. NFPA 130 (2003) is a commonly referenced standard for transit system design, from which Section 7.5 states that vent shafts "…shall be positioned or protected to prevent recirculation of smoke into the system through surface openings". It further states that "...adjacent structures and property uses also shall be considered".

These goals are well-defined and clearly important, but in practice may be difficult to achieve under all conditions. Therefore, RWDI suggests a process of design and analysis that seeks to reduce impacts to acceptable levels of probability, while accommodating safety goals and project cost constraints.

RWDI suggests that, at a minimum, smoke exhaust vents and make-up air intakes should be separated sufficiently to ensure that re-entrained smoke is adequately diluted and tenable conditions are maintained for people to exit safely.

Inside the station or tunnel environment, tenable conditions are defined, for example, by the criteria in NFPA 130 (2003). Appendix B states that doors and walls should be discernible at 33 feet and illuminated signs should be discernible at 100 feet. Temperature and toxicity criteria are also offered, but for many fire events these parameters are often acceptable if the smoke is diluted sufficiently to meet acceptable visibility levels.

Outside the station / tunnel, exhausted smoke should be diluted to similar tenable levels at intakes for make-up air drawn back into the station for the emergency ventilation system. This is particularly important at pedestrian entranceways which patrons would use as familiar exit pathways during an emergency.

RWDI has reviewed literature and conducted computer model simulations for a variety of fire events. To achieve the NFPA 130 visibility targets, smoke in the immediate vicinity of the fire should be diluted with fresh air by a factor of between 100 and 500, depending on a number of considerations, including the fuel type, fire location, ventilation of the fire, light levels in the station, etc.

Based on this assessment, RWDI recommends, in the absence of a comprehensive engineering analysis, a nominal criterion dilution ratio of 300:1.

This target dilution factor includes both internal and external dilution. The internal dilution is the reduction of smoke concentrations achieved by the mixing of relatively clean make-up air inside the station – a key design goal mentioned above. External dilution occurs when the smoke mixes with outside air due to the wind outside the station.

The level of internal dilution depends on several factors but is often estimated initially to be between 3:1 and 10:1. This requires the external dilution to be as high as 100:1 and as low as 30:1 to achieve the total target dilution of 300:1 (i.e., 3:1 combined with 100:1, yields 300:1 total). The exact external target must be estimated for each station / tunnel design.

Achieving this dilution criterion can be challenging because of the typically large exhaust flow rates and the effect of surrounding buildings on limiting plume dispersion.

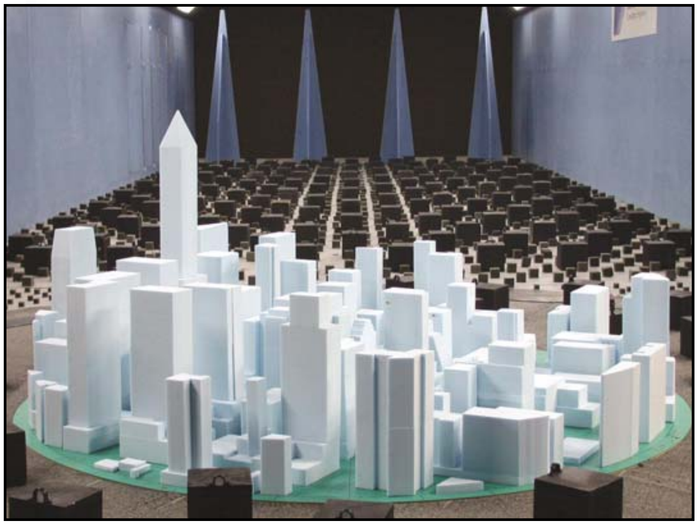
For these situations, quantitative risk assessment techniques provide a methodology to evaluate overall safety and prioritize the risks at different stations. A risk ranking matrix can be used to evaluate the likelihood, consequences and severity of an emergency event and also to evaluate the risks. This can lead to balanced risk-cost decisions which then assist in prioritizing capital spending for upgrades to existing transit stations or design of new facilities. Higher probability or higher consequence locations may be selected for screening level or more detailed analysis to assess the performance of the emergency ventilation system. (Visit http://go.rwdi.com/t20/ for further information.)

DISPERSION MODELING

Once discharged into the atmosphere, the dispersion of a smoke plume will be determined by the exhaust parameters, (e.g., volume flow rate, discharge velocity, location, temperature, etc.), and by the ambient conditions - most notably wind speed and wind direction, and the complexity of surroundings.

The level of external dilution achieved for various conditions and the probability of adverse impacts should be assessed by dispersion modeling. Dispersion models consider the interaction of the exhaust effluent with the wind flow behavior. These models can be used to determine the level of dispersion that occurs as the plume travels from the discharge point to the location of interest. For emergency ventilation exhausts, these locations are the make-up air intakes and pedestrian exits.

Dispersion modeling techniques include numerical calculations on a computer, or physical scale modeling in a boundary layer wind tunnel. Choosing the proper dispersion model and interpreting the results correctly can be challenging because the local wind flow behavior is difficult to predict and will be affected by the site characteristics.



Wind tunnel model of urban setting at 1:200 scale. Model is constructed on a circular disk, which rotates to simulate wind directions. Fan speed is adjusted to simulate different approaching wind speeds.

For example, in an open setting, predicting the wind behavior is relatively straightforward. However, in a more built-up urban environment, the wind and plume behaviors are more complex. In fact, in many cases the smoke plume trajectory and spread patterns can behave in a counter-intuitive manner (e.g., reverse flow patterns, urban street canyons, etc.). Examples of these complexities are discussed later in this article.

Numerical Models

There are many numerical plume dispersion models. Each employs different mathematical equations for plume dispersion in specific situations, such as tall elevated releases or low roof-top releases, for example. All model equations use empirical constants derived from wind tunnel tests or full-scale experiments. Many models require expert inputs.

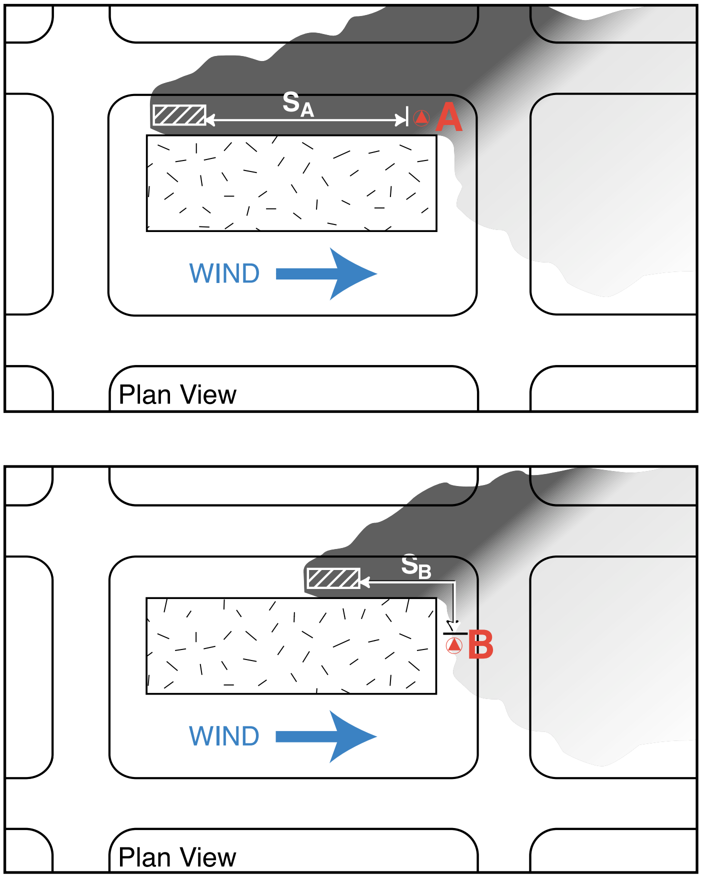
Computational Fluid Dynamics (CFD) is the most sophisticated numerical airflow model. It is the correct tool to assess the performance of the emergency ventilation system designs inside the station. In the future, it may also be developed sufficiently to be quite useful for modeling external plume dispersion in urban wind conditions. However, at this time, standard CFD methods have limited applicability to these situations, due in a large part to serious limitations in the ability to model turbulence.

Any assessment of the performance of an emergency ventilation system must account for the re-entrained smoke concentrations at the make-up air vents or pedestrian exits. This is a detail that is often overlooked, leading to an incorrect assessment of the tenability of exit pathways and the level of internal dilution.

RWDI finds that traditional numerical plume dispersion models can be useful and cost effective when correctly applied by an air quality engineer. These methods can be used as a screening tool to determine aspects of the design that require further study with more sophisticated tools.

Horizontal Separation Distance - Example

The following figures illustrate an example of the use of numerical modeling to predict plume dispersion from a street-level exhaust vent near a simple building geometry in an open setting (no surrounding buildings). Table 1 presents the separation distance (S) required to reduce the smoke concentration to a 100:1 external dilution target at two receptor points (A and B). This evaluation determines whether locations A or B would be suitable for pedestrian exits or used for make-up air for the station emergency ventilation system). The estimated distances are provided as a function of the volume of exhaust released from the point of discharge. Two typical exhaust volume flow rates are shown. These amounts could be discharged at one, or both ends of a station.



Comparison of Location A Versus Location B

Location A requires a large separation distance to meet the target dilution. This is because the exhaust is located at grade, which limits the dispersion, and the receptor point is on the same side of the building. To reduce the amount of separation distance required for a grade-level vent to grade-level receptor, the two points should not be located on the same side of the building.

Location B illustrates the benefit obtained by locating the receptor point around the corner of the building. A lower separation distance is acceptable for this configuration because location B is protected from the exhaust plume by the building itself.

Table 1 Minimum Horizontal Separation Distance (S)

Exhaust flow (cfm)	S_A (ft)	S_B (ft)
200,000	400	250
400,000	550	400

For Illustration only. Not to be used for design.

This design strategy of "protecting" an intake involves placing a building or other obstruction between the exhaust source and the intake. The purpose of creating this obstacle is to break up or mix the plume before it can reach the point of intake. This mechanical mixing of the plume will result in additional exhaust dilution benefit and an improved level of local air quality at the intake location.

Although the configuration with location B is preferred, this example of grade-level exhausts also illustrates the substantial separation distance required for either scenario. The benefit associated with separation distance shown in this numerical modeling example would be less significant in a complex urban setting. Surrounding buildings can create a "canyon" effect between buildings. In that case, air movement is limited between buildings and there is less surface area on the edge of the exhaust plume for entrainment of fresh air, both of which reduce dilution of the smoke plume.

Physical Scale (Wind Tunnel) Modeling

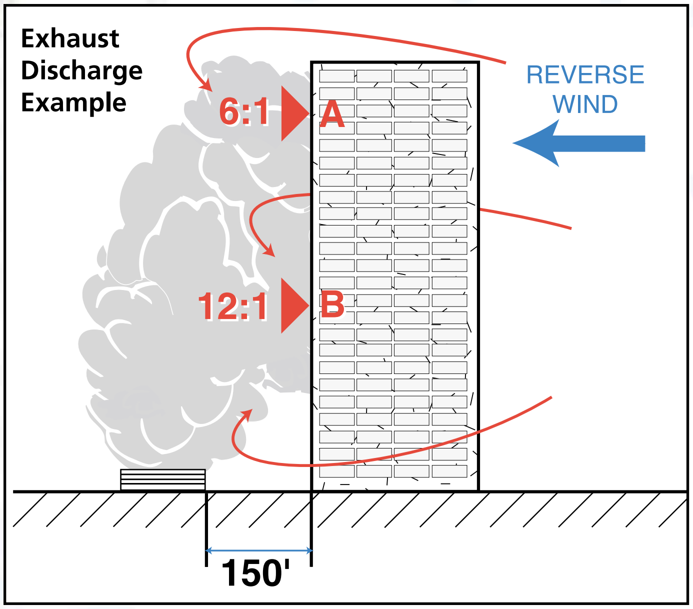
Experience with urban wind flows and numerical modeling can be used to identify exhaust re-entrainment potential. As discussed above, numerical models help guide initial decisions and rank options.

For more detailed assessments where quantitative answers are needed to support costly decisions, physical scale modeling in a boundary layer wind tunnel is the most accurate means of simulation. It can simulate the complex behavior of wind flow around buildings. Tracer gas plume dispersion measurements quantify the dilution ratios for immediate comparison against target criteria. Wind tunnel simulation is also more cost-effective than numerical modeling for testing many wind directions, wind speeds and a variety of design solution alternatives. (Visit http://go.rwdi.com/t20/ for further information.)

Wind Flow Behavior - Example

Accurate wind tunnel simulation of complex wind flow behavior around buildings often identifies counter-intuitive behavior in plume dispersion.

In the following image, an exhaust discharge is located at grade 150 feet from a tall building with intakes facing the exhaust. As shown in the figure, the worst-case (minimum) predicted exhaust dilution ratios were observed for the reverse wind direction. Instead of carrying the exhaust away from the tower (as one might expect), the wind flow patterns created by the interaction of the wind with the tower causes the exhaust to be pulled back toward the tower, within the wake.



This example illustrates the severity of the potential impacts, and how accurate modeling of these building effects can be critical in determining the level of hazard and risk for smoke re-entrainment.

SOLUTION CONCEPTS

There are several factors that affect the performance of an emergency ventilation system. As discussed, some of these factors include the local wind climate and complexity of surroundings. These are examples of factors that are not under the control of the designer. However, there are many solution concepts which focus on factors and details that can be controlled within the design. These include:

- Exhaust location and configuration
- Exhaust parameters (volume flow rate discharge velocity and temperature)
- Separation distance from exhaust to make up air location

The interaction between, and optimization of, these parameters determines the efficacy of design options.

For example, a strategy of increased discharge velocity will not provide significant dilution improvement from a grade-level discharge point, but could substantially improve the dispersion from a rooftop smoke exhaust. Similarly, the buoyancy-induced dispersion benefit from the heated smoke exhaust will not be as evident for a grade-level discharge due to the dominant effect of the mechanical mixing created from wind flow around buildings.

In general, locating the intake at grade and the discharge point at an elevation above grade and out of the influence of building effects is preferred. A slightly elevated horizontal louver on a building sidewall will not provide significant improvement over a street-level exhaust because the dispersion will still be limited by the building.

A well-placed vertical rooftop exhaust will provide more dilution with smaller separation distances and will show the benefit of more optimal exhaust parameters, such as increased stack exit velocity. Table 2 provides an example for the case of rooftop exhausts to grade-level intakes (assuming no nearby buildings are taller and that a 100:1 external dilution is achieved).

Table 2 Required Vertical Separation Distance (i.e., building height, ft)

Volume Flow Rate (cfm)	Exit velocity of 1,000 fpm	Exit velocity of 3,000 fpm
200,000	135	75
400,000	180	105

For Illustration only. Not to be used for design.

This example clearly illustrates the benefit that can be obtained with a well-placed rooftop stack when compared to the horizontal separation distances required for the grade level discharge scenario (Table 1). In our example, for the exhaust flow of 200,000 cfm, the separation required to achieve the visibility criterion was reduced from a maximum of 400 feet (see Table 1) to a minimum of 75 feet with a vertical rooftop stack. The actual distances required will depend on the exhaust parameters and site specific parameters. With taller surrounding buildings, the wind flow behavior will become more complex, and wind tunnel testing would be necessary to accurately evaluate potential design modifications.

OTHER APPLICATIONS

The methods discussed in this article can be applied to the assessment of other hazardous release scenarios, including biochemical terrorism threats.

Dispersion models and local wind climate data can be used in a risk assessment procedure to rank potential problems and solutions. Predicted concentrations of airborne toxics are best acquired with quantative measurements in wind tunnel simulations. The data can support decisions that balance performance and cost. As well, the concentrations can be included in ventilation assessments inside buildings and underground facilities that can lead to improved emergency response procedures.

For more information, please contact Ray Sinclair at rjs@rwdi.com. Please visit http://go.rwdi.com/t20/ for further information.

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