TASK SHEET 1D

MODELING FOR EXTERNAL EXAUST SYSTEMS

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Introduction

Exhaust air from a laboratory is emitted externally through exhaust stacks to the outdoors. Due to contaminants use and generated in a laboratory, the external exhaust can be toxic, hazardous, and odorous, thus posing a potential outdoor air quality problem. Ideally, the exhaust stacks are be designed so that the exhaust is sufficiently diluted before reaching nearby outside air intakes, pedestrians, operable windows, or other sensitive receptors.

Exhaust stack design can be made difficult by the nature of wind and air flow around buildings. The locations and sizes of nearby buildings plus the locations of outside air intakes can also add difficulty. This Task Sheet discusses the nature of laboratory exhaust, wind and air flow around buildings, general guidelines on exhaust stack and intake design, and methods for analyzing a design for air quality problems. The Task Sheet also discusses the roles of designers, air quality consultants, and the university.

Nature of Laboratory Emissions

The primary sources of external emissions from laboratories are chemical fume hoods and bio-safety cabinets. These hoods and cabinets are primary safety devices in a lab and are designed to capture toxic, hazardous, and odorous materials and exhaust them to the outdoors. Emissions can be in the form of small, routine emissions or in upset conditions such as gas leaks or liquid spills.

There are other sources associated with laboratories that often need consideration. Animal research using vivaria or animal holding rooms generate strong odors within their rooms and these odors when exhausted can generate complaints for neighboring facilities. Laboratory buildings will often have a dedicated emergency generator apart from the central plant, and diesel generators are another common source of odor complaints. If a laboratory building is not served by a central plant, then boilers and cooling towers may need to be considered as well.

Each exhaust will need some amount of dilution between the exhaust point and nearby receptors to avoid air quality problems. A general discussion of the amount of dilution (dispersion) necessary for several types of exhausts is given in **Appendix A**. Specific buildings may require refinement of these recommended dilutions depending on such factors as combustion emission factors for the central plant or chemicals used within fume hoods.

Outdoor Exhaust Dispersion and Wind Flow Around Buildings

External exhausts will disperse, i.e. become diluted, when encountering the outside wind. The dispersion of exhausts emitted outdoors is heavily influenced by wind flow patterns around buildings. Another feature of exhaust dispersion is the exhaust momentum (exit velocity x flow rate) which causes the exhaust to travel upwards for a distance above the buildings. The primary objective of the stack design is to provide sufficient dilution to meet the various dilution requirements. This can best be accomplished by maximizing the exhaust momentum and to place the exhausts in favorable locations. **Appendix B** presents a more detailed discussion of exhaust dispersion and some design recommendations.

Methods for Predicting Dilutions

Several methods exist for predicting exhaust dispersion (also referred to as dilution) that will be achieved at nearby receptors such as air intakes. These methods are discussed below. With all of these prediction methods, the results must still be compared to dilution criteria, discussed in Appendix A, to determine the acceptability of exhaust and intake designs.

- **Wind Tunnel Modeling**. Wind tunnel modeling is currently the most accurate method for predicting exhaust dilutions around buildings, where wind flow is dominated by wake zones illustrated in Figure 1 (2007 ASHRAE Applications Handbook "Building Air Intake and Exhaust Design", Chapter 44.). Wind tunnel modeling represents a similarity scaling where non-dimensional quantities are matched in the model scale and the full scale. In the case of wind tunnel modeling of buildings, the flow Reynolds number is not matched, but is acceptably large enough to represent turbulent flow (Snyder, 1981). A wind tunnel modeling report should discuss methodologies such as how representative atmospheric approach turbulence and wind speed profiles were established and how exhaust flow rates were scaled. It is not sufficient to just have the mean (average) wind speed profile simulated. A more detailed description of wind tunnel modeling is provided in **Appendix C**.

- **CFD (Computational Fluid Dynamics)**. CFD is discussed in more detail in the companion Task Sheet 1E, where CFD can be used to model air flow inside a laboratory room. CFD can also be applied, in principle, to outdoor wind flow and exhaust dispersion. As discussed in Task Sheet 1E, there are two major types of CFD models used in atmospheric modeling, the simpler RANS models and the much more computer intensive LES method.

  In previous evaluations against field and wind tunnel data, the RANS models have not performed well in predicting air flow around buildings, as indicated for example by the inaccuracy of fluctuating wind pressures on building surfaces (ASHRAE Handbook of Fundamentals, 2005, Chapter 16 "Airflow Around Buildings"). In particular, simulations using RANS models with poor grid spacing has been observed to completely miss the presence of recirculation wind zones on the roof (Figures 1 and 2 in Appendix B).

  More detailed models like LES or hybrid RANS-LES models may be a future method. CFD for exhaust dispersion modeling is discussed further in **Appendix D**.

- **Simple Screening Models**. The ASHRAE 2007 Applications Handbook, "Building Air Intake and Exhaust Design", Chapter 44, presents two simplified methods for estimating required stack heights. The first, the "geometric method" does not employ dilutions and would likely yield unreasonably tall stack heights for laboratories. The geometric method is not recommended for this application. The "dilution" equations in the handbook can be a screening tool for laboratory exhausts, but are intended to be conservative. The screening tool should not be used in the presence of taller nearby buildings such as shown in Figure 3.

- **EPA Dispersion Models.** Another class of numerical models are those often used by regulatory agencies to model dispersion from industrial facilities or large scale air pollution sources. These types of models can have a rudimentary representation of air flow around buildings, but do not include the flow patterns seen in Figures 1 to 3 of Appendix B. They are not suited for detailed dispersion near buildings. EPA models such as SCREEN3, ISCST, and AERMOD should not be used for this application. A comparison of ISCST to wind tunnel modeling (Schajnoha, et al.) showed considerable insensitivity to stack height, meaning increasing stack heights on the order of 10 to 20 ft had no influence on dilution predictions for rooftop air intakes.

<u>Design And Analysis Recommendations</u>

Initial "Risk Assessment". It is recommended that the university or a consultant conduct a initial "risk assessment" of laboratory exhaust sources. The risk assessment would determine if laboratory exhaust sources could create air quality issues and if further study using one of the above modeling methods is necessary. The assessment should consider the following items:

- Fume hoods that use hazardous or odorous chemicals that also have a potential for emissions, such as high vapor pressures or being heated.

- Intakes or operable windows that are the same elevation or higher than exhaust sources of interest. The intakes, windows, and exhausts may be on either existing or proposed buildings.

- Intakes that are on the same roof as exhaust sources of interest, especially if both are within the same screen wall.

- The presence of nearby taller buildings than the emitting building. The taller buildings may create wind disruptions or have intakes/windows susceptible to impacts.

- Intakes and sources of interest are located together within large screen walls on the roof.

- Whether there are cooling towers, boilers (especially fuel oil versions), and emergency diesel generators on or adjacent to the laboratory.

- Whether fume hood stack exit velocities are below 3,000 fpm to save on energy costs. A wind tunnel study is recommended because low exit velocity may create stack-tip downwash, as discussed in Appendix B.

Decision Logic for Further Analysis. If the initial risk assessment indicates the potential for air quality issues with the laboratory, then further analysis and dispersion modeling is recommended. Most chemical and biological laboratories would be candidates for further analysis.

A decision logic is presented below based on the three main types of dispersion modeling available:

- SCREENING NUMERICAL MODEL (e.g., ASHRAE 2007). A simple dispersion model combined with dilution guidelines of Appendix A may be sufficient to rule out some exhaust sources from further consideration. This approach is especially useful under the following circumstances:
    - If the proposed building is relatively simple in shape (e.g., no curved roofs)
    - If there are no nearby taller buildings or taller wings on the proposed building compared to the stacks. Taller nearby buildings can present problems as described in Appendix B.
    - If there are no intakes/operable windows above the stacks.
    - If the intakes are on the side of the building rather than on the same level as rooftop exhausts. Intakes on the sides of the building experience better dilution for rooftop exhausts.
    - If there are operable windows and intakes on the sides of the building and there are no ground-level nearby sources of concern such as generators or loading docks.
    - If boilers and emergency generators are natural gas rather than fuel oil or diesel. Natural gas is cleaner.
    - If some tolerance of taller stacks is possible, due to the typical conservatism within the screening model.
    - If the test plan for more detailed modeling needs to be refined.
    - If large, manifolded exhaust stacks are used for fume hood exhausts. Such stacks often do well in the initial screening model.

- WIND TUNNEL MODELING. Wind tunnel modeling is the recommended method when accurate results are needed, under the following circumstances:
    - If refinement of exit velocity (below 3,000 fpm) is desired to reduce energy consumption but stack-tip downwash is to be avoided.
    - If there is a strict limitation on stack heights.
    - If there are nearby taller buildings or taller wings, compared to the exhaust stacks "Nearby" can be roughly defined as a smaller horizontal separation distance -- between the new building and the taller nearby building -- than the height of the taller nearby building. For very wide nearby buildings (width 3x or more than the height) more separation is needed.
    - If there are intakes above the elevation of the stacks.
    - If the building design is complicated, such as multiple levels of exhaust sources, curved roofs or high screen walls.
    - If there are diesel emergency generators and operation during off-hours is not feasible (such as 24hour facilities for animal research or health care, or residences).
    - If there are operable windows and intakes on the sides of the building and there are ground-level nearby sources of concern such as generators or loading docks.
    - If there are individual fume hood or specialty exhausts (e.g., Perchloric).
- CFD MODELING.
    - Simpler RANS models are generally not recommended unless demonstration of adequate grid spacing and good representation of recirculation zones above the roof (as shown in Appendix B). If there are no recirculation zones for winds directly approaching the side of the buildings, this is an indication of inadequate grids and computing power.
    - LES models can be used, but should have some upwind pre-generated turbulence. Computational power may be difficult to obtain in the near future. Grid spacing is also critical.

Expectations of Design Team

Air Quality Consultant – The consultant should use appropriate dispersion tools and dilution targets and to have previous experience with other laboratories. If wind tunnel modeling or CFD is used, the consultant should be able to demonstrate appropriate approach turbulence and wind profiles. These models should account for shapes of nearby surrounding buildings. For CFD modeling, there should be use of appropriate grid spacings and CFD methodologies, and capture of major flow features such as rooftop recirculation zones for winds directly approaching a side of the building. The consultant should produce findings and recommendations that are understandable, not just dilution predictions. Ideally several design options should be pursued and evaluated if the initial design is not satisfactory, including evaluating emissions. The consultant should provide initial feedback in early Schematic Design stages to avoid difficult revisions later in the design, such as intake relocation.

Mechanical Engineer – The mechanical engineer should be able to provide exhaust and intake information such as locations, desired stack heights, flow rates, desired exit velocities, and specifications for devices such as boilers, cooling towers, and generators. The mechanical engineer should review consultant recommendations for feasibility.

University Oversight. University personnel should review or perform the initial risk assessment described above. The university should also review and approve modeling approaches prior to modeling. Reviewing findings and discussing optional mitigation strategies is helpful for the consultant to understand requirements and design goals, such as height limitations. University personnel can help locate exhaust and intake information on existing buildings. The university should require consultant input at early design stages, such as 50% Schematic Design. Detailed modeling should commence at around 25-50% Design Development.

References

ANSI/AIHA 2003. *Standard Z9.5 Laboratory Ventilation.* American National Standards Institute/American Industrial Hygiene Association, 2003.

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Halitsky, James, 1988. "Dispersion of Laboratory Exhaust Gas by Large Jets" 81st Annual Meeting of the Air Pollution Control Association, Dallas, June 1988.

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Snyder, W.H. 1981. *Guideline for Fluid Modeling of Atmospheric Diffusion*, Environmental Protection Agency Report EPA-600/881-009.

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Appendix A: Required Dilutions for Various Exhaust Types

For quantitative assessments of exhaust dispersion, an accounting of the emission rates, toxicity, and odor strength is needed. With these quantities, required exhaust dilutions can be calculated. Required dilutions will vary greatly depending on the type of exhaust.

- **Laboratory Fume Hood Exhaust**. Laboratory chemical fume hood emissions vary with time and with the procedures conducted in the hood. In general, a detailed emissions inventory is difficult to obtain, and could be outdated by future changes. To overcome this, several groups have proposed an approach based on the maximum credible release for a series of chemicals. Maximum releases are usually based on liquid spills or gas releases because evaporation rates or release rates from compressed gas bottles are relatively easy to estimate.

  RWDI (2003) has performed calculations of required dilution for approximately 350 liquid chemicals based on evaporation rates, occupational health limits, and odor thresholds. Given a large spill size or potential release amount, some chemicals will need an extraordinary dilution that is not achievable with ordinary stack heights. For example, a spill of pure ethyl mercaptan would likely cause odors at numerous outdoor locations. RWDI (2003) has chosen a dilution of 3000:1 (referenced to 1000 cfm of exhaust) as a value that would meet the requirements of 90% of the chemicals evaluated. The 2007 ASHRAE Applications Handbook, Chapter 14 “Laboratories” recommends a value equivalent to 5000:1 for a 1000 cfm exhaust [originally expressed as 3 ppm of concentration at an air intake for a 15 cfm (425 lpm) release of pure gas], based on Halitsky (1988). The two methods are approximately equal. For flow rates larger than 1000 cfm, the flow rate amount above 1000 cfm can be considered to be relatively clean and to provide additional internal dilution, thus reducing the exterior dilution needed. This is consistent with a large non-routine release from a single hood. Smaller routine releases from numerous hoods could also be considered, but the end result in total emissions will likely be similar to the single large release.

  A special emission inventory for a specific laboratory could also be considered. However, it should be recognized that emissions can change with time, and a stack design should ideally be designed to perform with future emissions as well as currently expected emissions.

  Many ambient air toxic allowable concentrations are much lower than occupational health limits. However, for these air toxic situations, typically only longer term average emission rates are considered, which will be much lower than the large emissions assumed in the fume hood. The lower emission rate will offset the lower allowable concentration. The State of Washington does not currently require consideration of air toxics from research facilities (e.g., Chapter 173-490 WAC, “Emission Standards and Controls for Sources Emitting Volatile Organic Compounds (VOC)”).

- **Biological Exhaust**. For biological exhausts, there are no published exhaust dilution criteria analogous to that for chemicals, due to the even greater variability and uncertainty in biological emissions and health hazards. For biosafety cabinets, exhausts should be HEPA filtered unless the exhaust is acceptable for recirculation into room air. Ordinary chemicals such as solvents may also be used in biosafety cabinets and should be considered.

- **Vivarium Exhaust**. RWDI has conducted several air sampling programs for evaluating the odor strength of exhausts from vivaria and animal holding rooms. A dilution rate of 100:1 (referenced to the total exhaust flow rate from the animal areas) is recommended. There are some situations involving autoclaving of food or biological material that produces even stronger odors that may warrant more attention. More testing is needed to determine a dilution requirement.

- **Emergency Generator Exhaust.** RWDI has conducted several air sampling programs for evaluating the odor strength of exhausts from diesel generators and other diesel sources. Based on these tests, a dilution requirement of 4000:1 is recommended for odors. Diesel generators also emit nitrogen oxides that produce short-term health effects. A dilution criterion of about 500:1 is typically recommended for these short-term health effects. For large generators, achieving a dilution of 4000:1 usually requires an unacceptably tall stack. Other strategies, such as testing of generators during off hours or during certain wind conditions, may need to be used.

- **Cooling Towers**. In terms of dilution requirements, it is generally recommend to achieve at least 10:1. This value is low compared to the other sources but is actually not that easy to meet for large cooling towers. This dilution value will address typical nuisance odors but will not address Legionnaire's Disease in the case that legionnella bacteria counts get out of control. Once a cooling tower becomes out of control for legionnella, there is no reasonable dilution level that will avoid Legionnaires' Disease. We recommend that the latest ASHRAE guideline for cooling towers be followed (currently the 2000 version), which recommends chemical control of legionnella plus control of other factors such as scaling. Newer control systems that remove dissolved solids are becoming more common and may be found to be acceptable in the future.

Appendix B: Description of Airflow around Buildings and General Design Suggestions

When the exhausts are emitted from stacks, the outdoor wind will interact with the exhaust plume. The following are a few features of wind flow around buildings and dispersion from exhaust stacks important for evaluating air quality from an exhaust.

- **Exhaust Plume Behavior.** When the exhaust leaves a stack as an exhaust plume, the plume will rise for a distance according to the exhaust exit velocity, exhaust flow rate, and the ambient wind speed. The exhaust from the taller stack illustrated in Figure 1 shows how exhaust plumes normally behave without excessive the influence of buildings. Exhaust exit velocities typically range from 2,000 fpm to 4,000 fpm, and the ANSI Z9.5-2003 specifies a velocity of at least 3,000 fpm. Equally important in plume rise is the exhaust flow rate, which provides added momentum for a given exit velocity. Higher wind speeds will push the plume sideways and decrease plume rise.

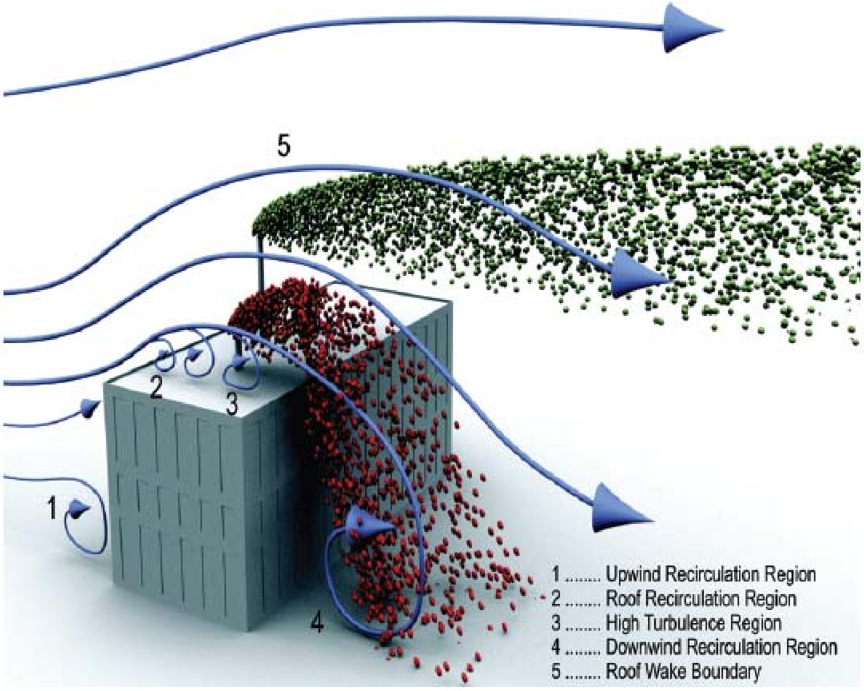


Figure 1 – Air Flow Around Buildings

Above a certain wind speed, equal to approximately 2/3 of the exit velocity, plume rise can sharply decrease due to the interaction of wind and the stack structure itself, called stack-tip downwash. In stack-tip downwash, the plume is pulled down into the wake zone downwind of the stack itself. To avoid stack-tip downwash, exit velocities should be maintained at least above 2,000 fpm for most wind climates. If exit velocities below 2000 fpm are desired, then a wind tunnel study should be conducted that will model the effects of stack-tip downwash in detail. Numerical approaches to study exhausts will likely not detect stack tip downwash because of the small scale of the stack diameter compared to the building air flow patterns.

Maximizing plume rise is beneficial in avoiding air quality impacts at rooftop locations. Rain caps must be avoided because they eliminate most of the plume rise. Higher exit velocity and flow rates may need to be balanced against the energy costs and noise of added fan horsepower.

As the exhaust plume rises, there is also dispersion, which spreads or widens the exhaust plume. Dispersion primarily arises from turbulence in the wind. Turbulence levels on roof tops can be greater than found in the open wind flow and should be accounted for in dispersion modeling. Turbulence can be good for dispersion but also can reduce plume rise and can bring portions of an elevated plume down to roof level.

- **Roof Recirculation Zones**. Figure 1 illustrates typical flow patterns over a building. As wind passes over a building, the wind cannot move at sharp angles when encountering the edge of the roof. As a result, the wind will separate from the building roof for a certain downwind distance before recovering. The separated zone (shown as Area 2 in Figure 1) has high turbulence, downdrafts, and counter-direction winds that can disrupt exhaust plume rise and carry portions of the exhaust down to roof level outside air intakes (Figure 2). A downwind wake zone (Area 4 in Figure 1) can also influence exhaust dispersion. It is important for an exhaust stack to avoid most of the separated zone. Having a stack located near the upwind edge of the roof, where the recirculation zone is lower, is one way to improve dispersion. It is also important to consider multiple wind directions and the roof recirculation zones produced by each direction.

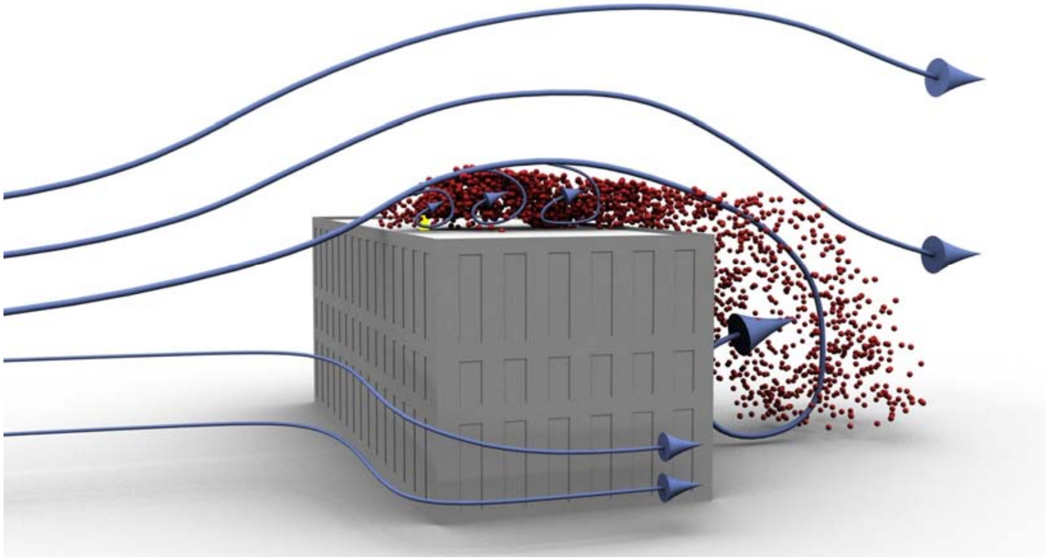
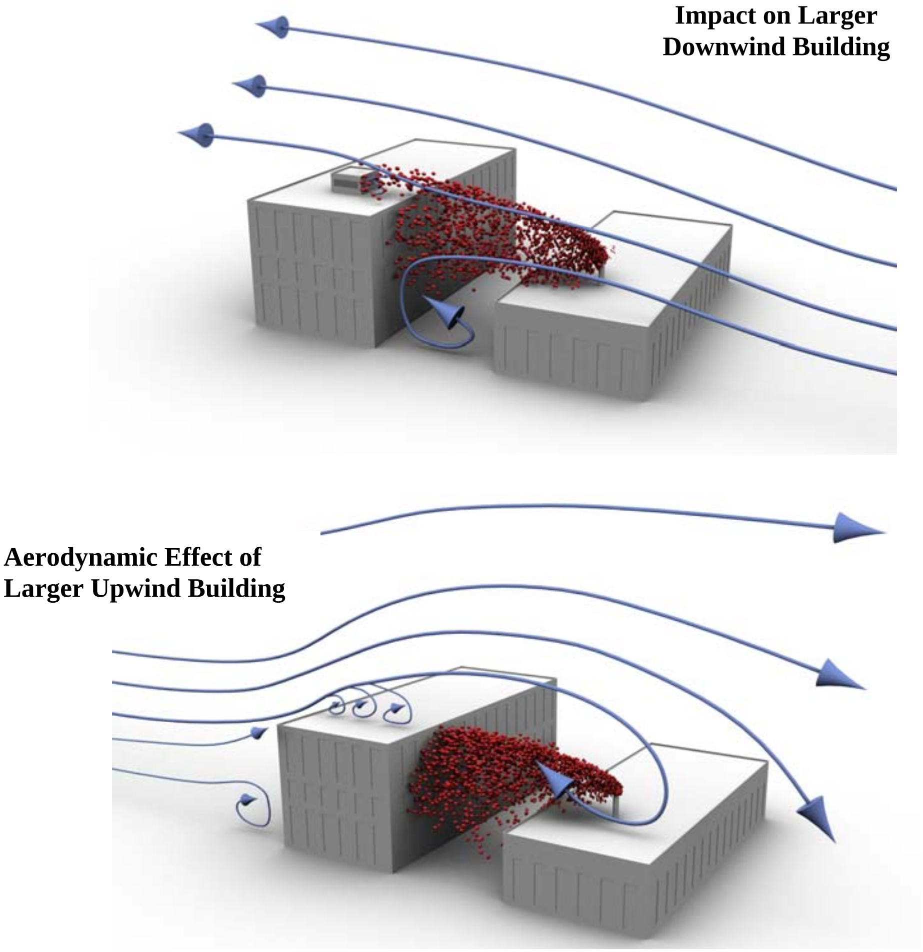


Figure 2 - Effects of Recirculation Zones on Local Plume Behavior

- **Avoid Intakes Above Stacks.** Due to the normal rise of the exhaust, it is undesirable to have an intake or other receptor located well above the stack top that could be impacted by the central portion of the exhaust plume. Such elevated intakes could include those on nearby buildings as well. Laboratory exhausts should be on the highest roof possible. This is illustrated in the top half of Figure 3.

- **Effect of Upwind Buildings**. A relatively tall upwind building can be problematic for dispersion. The upwind building may have a downwind wake zone (such as Area 4 in Figure 1) that directly impacts the stack area, creating a downdraft. The exhaust may travel backwards into the side of the upwind building, as shown in the bottom of Figure 3.



Impact on Larger Downwind Building

Aerodynamic Effect of Larger Upwind Building

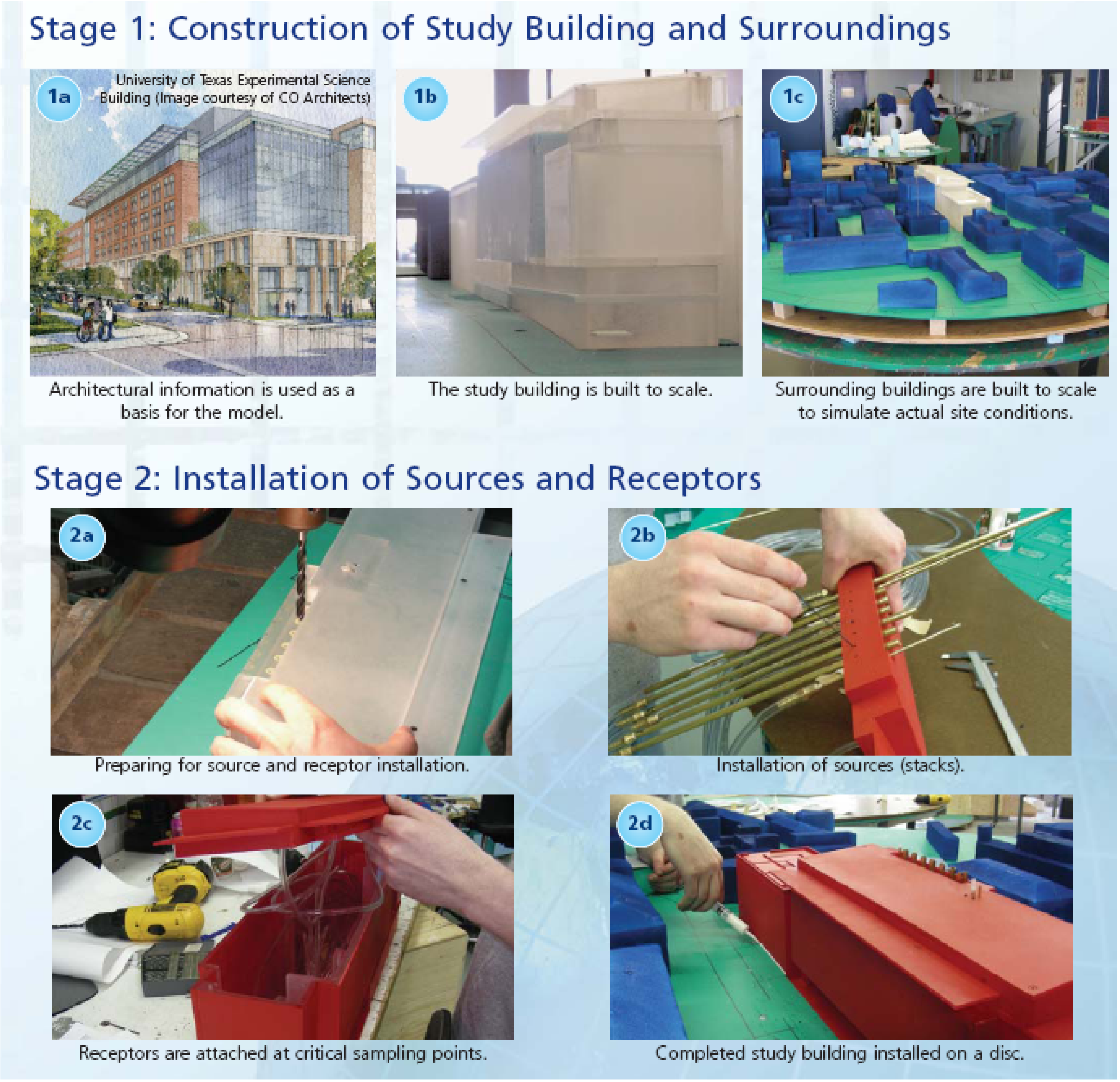
Figure 3 - Effects of Nearby Taller Buildings

- **Effect of Rooftop Structures and Screens.** Penthouses, architectural screens, and other structures can also cause disruption of exhaust plumes. They will create their own wake zones and enhanced turbulence if upwind of the stack. Ideally stack heights should extend above nearby penthouses and screen walls. Screen wall porosity (not counting the normal gap below the screen) is helpful in reducing aerodynamic effects, but may pose more noise issues.

- **Manifolded Laboratory Exhausts.** Manifolded laboratory fume hood exhausts are highly recommended to increase the exhaust plume rise due solely to the increased flow rate for a given exit velocity. Another advantage to manifolding is that a relatively large release from a single fume hood will be partly diluted prior to being emitted, on the basis that most fume hoods have minimal emissions most of the time.

Appendix C. Wind Tunnel Modeling Procedures.

The various steps for conducting a wind tunnel study are illustrated in Figures 4 and 5 below. The study is much like a field study but conducted in the controlled environment of the wind tunnel. Wind speed can be controlled by the fan speed. Wind direction is altered by moving a turntable underneath the model. Exhausts are installed through tubes that represent stacks. The model stacks will emit a tracer gas, while air intakes are equipped with sampling tubes that can measure the resulting diluted tracer gas at various locations.



Stage 1: Construction of Study Building and Surroundings

Architectural information is used as a basis for the model.

The study building is built to scale.

Surrounding buildings are built to scale to simulate actual site conditions.

Stage 2: Installation of Sources and Receptors

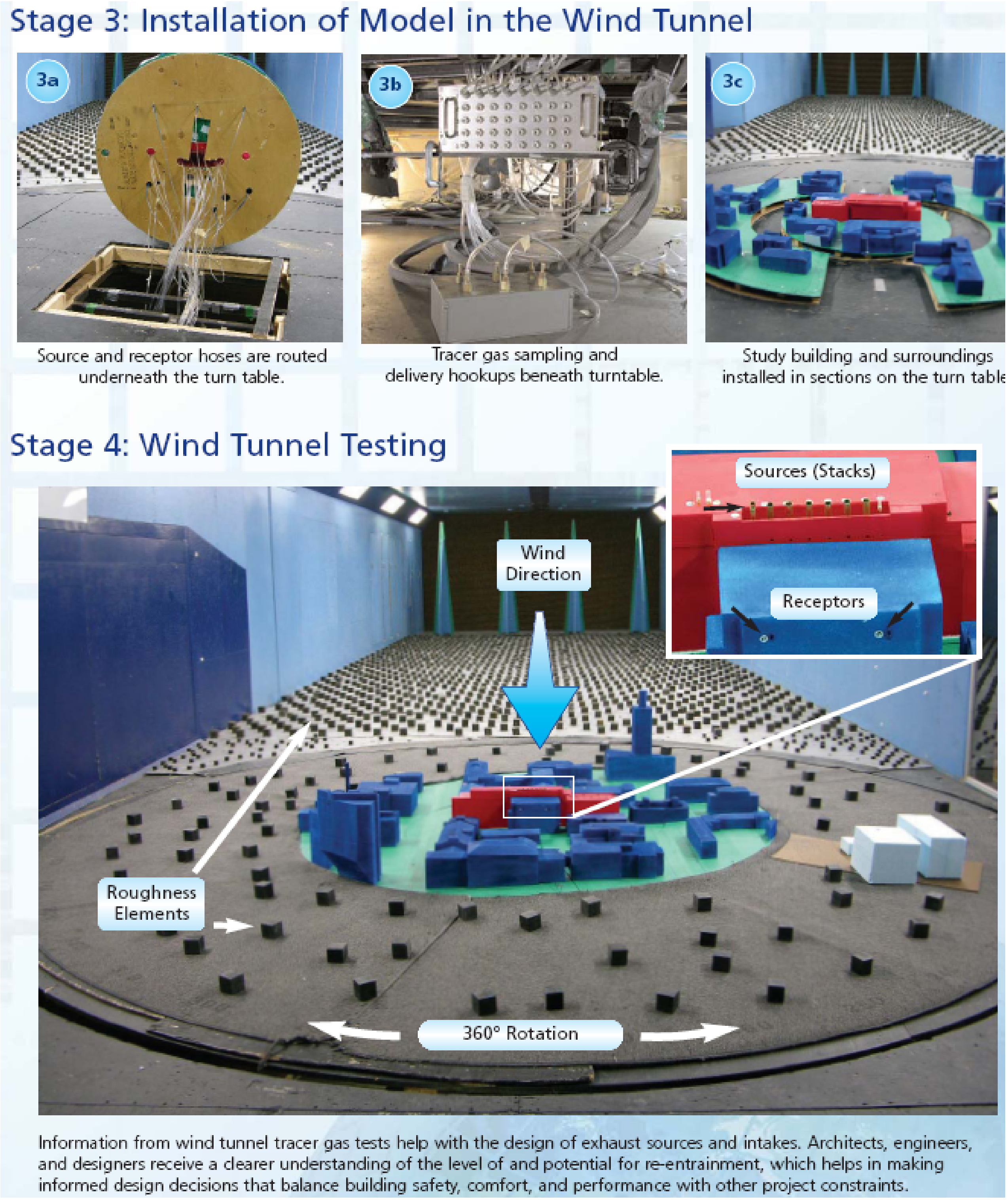
Preparing for source and receptor installation.

Installation of sources (stacks).

Receptors are attached at critical sampling points.

Completed study building installed on a disc.

Figure 4 - Steps in Performing Wind Tunnel Modeling (Part 1)



Stage 3: Installation of Model in the Wind Tunnel

Source and receptor hoses are routed underneath the turn table.

Tracer gas sampling and delivery hookups beneath turntable.

Study building and surroundings installed in sections on the turn tabl

Stage 4: Wind Tunnel Testing

Information from wind tunnel tracer gas tests help with the design of exhaust sources and intakes. Architects, engineers, and designers receive a clearer understanding of the level of and potential for re-entrainment, which helps in making informed design decisions that balance building safety, comfort, and performance with other project constraints.

Figure 5 - Steps in Performing Wind Tunnel Modeling (Part 2)

Appendix D. Additional Discussion of CFD Modeling of Wind and Dispersion Around Buildings.

An example of a detailed LES model result is shown in Figure 6 below for wind traveling past large buildings. As with wind tunnel modeling, methodologies should be reported, such as approach turbulence and wind speed profiles, grid spacing, and how to simulate small exhaust diameters. The problems with modeling exhaust plume rise from small diameter stacks is much like that for modeling flow from supply diffusers within a room. Some compromise or extra momentum may be needed to model the expected plume rise without the influence of buildings.

For LES simulations, an approach flow simulation, representing several kilometers upwind of the model, should be performed to generate the appropriate approach micrometeorological conditions. Such an approach simulation was performed for the LES example in Figure 6, but is excluded from the results presentation. Without an approach flow simulation, there will be insufficient turbulence in the wind approaching the buildings.

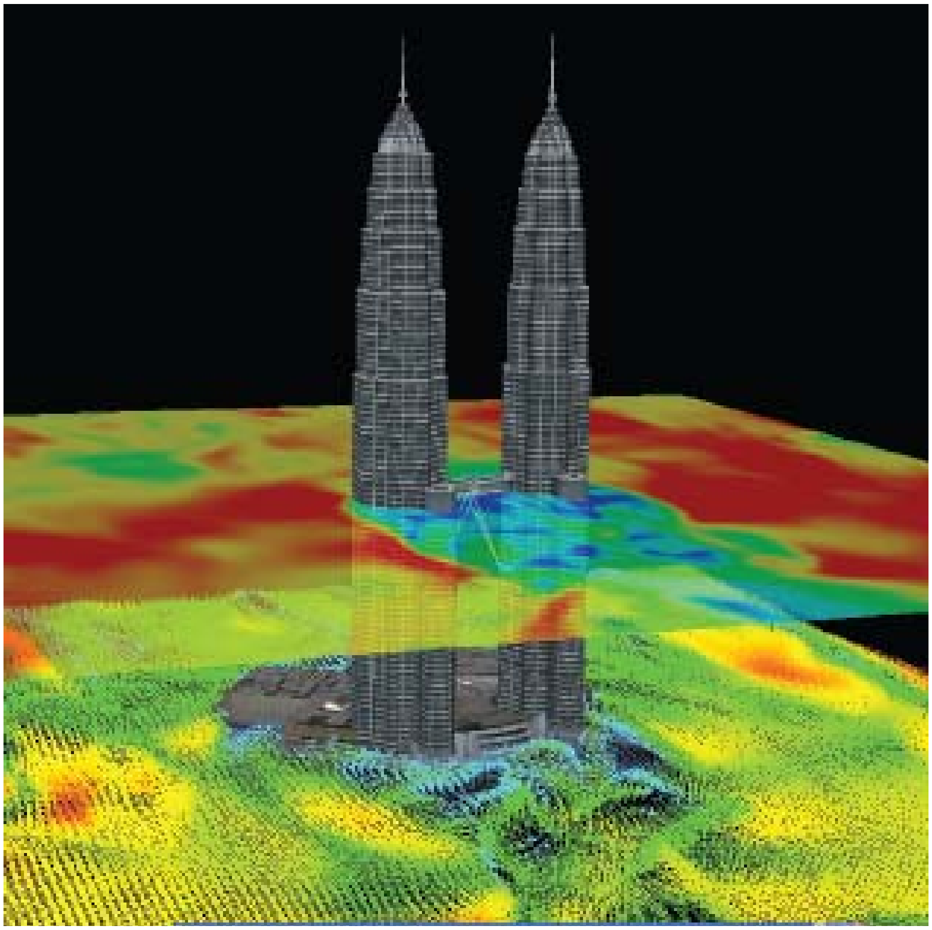


Figure 6 - Example of CFD (LES) modeling of Wind Around Buildings (VirtualWind, Inc.)