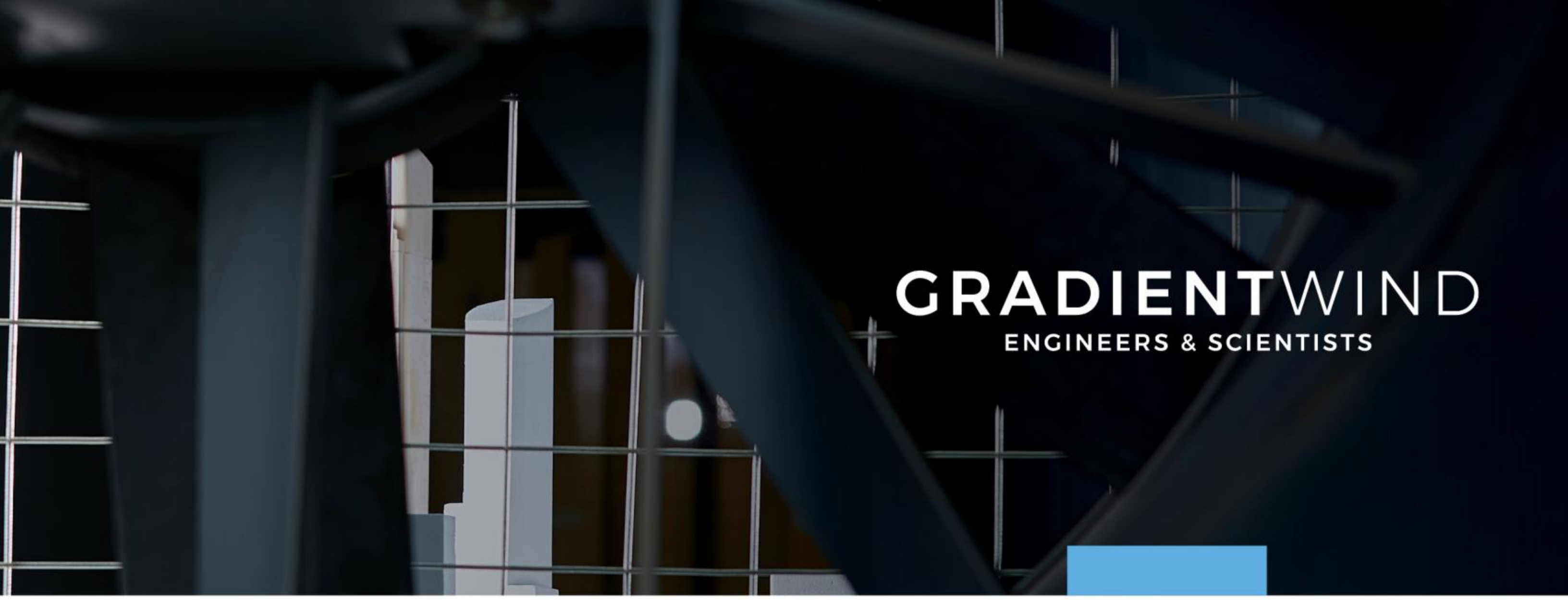

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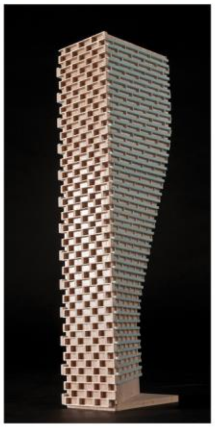
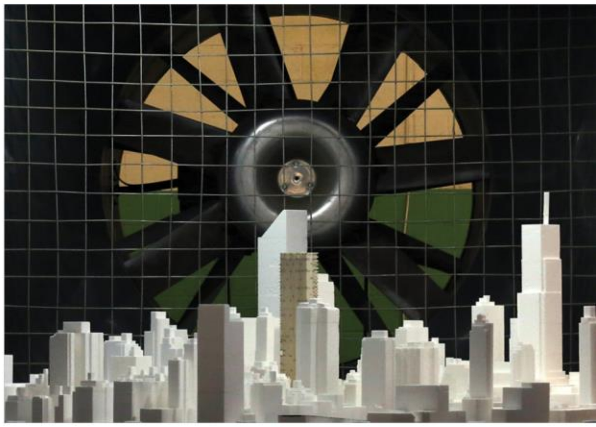
AIR QUALITY STUDY

930 Carling Avenue & 520 Preston Street
The Ottawa Hospital New Campus Development

REPORT: GW20-049-Air Quality





September 30, 2022

PREPARED FOR
The Ottawa Hospital
1053 Carling Avenue
Ottawa, ON K1Y 4E9

PREPARED BY
Michael Lafortune, C.E.T., Environmental Scientist
Joshua Foster, P.Eng., Lead Engineer

EXECUTIVE SUMMARY

This report describes a preliminary air quality study undertaken to assess the impact of exhausting pollutants from proposed equipment associated with the proposed New Campus Development serving The Ottawa Hospital (TOH) located at a portion of 930 Carling Avenue and 520 Preston Street in Ottawa, Ontario, including generators, boilers, laboratory, hot lab and kitchen exhausts. This report is based on architectural drawings prepared by HDR Architects, mechanical information provided by Chorley + Bisset Consulting Engineers, Eequinox and Smith & Andresen, surrounding context data obtained from the City of Ottawa, and recent site imagery.

The results of the air quality study indicate generally favourable air quality conditions within The Ottawa Hospital property boundary and beyond, inclusive of all fresh air intakes, building access points, and outdoor amenity spaces. The predictions show that pollutant concentrations will be within acceptable levels, as outlined by the MECP AAQC and industry standards. While the results are generally favorable the outcome of the study provides the following recommendations:

- The diesel generators shall be equipped with the appropriate exhaust scrubbers for peak shaving activities, in order to meet the MECP emission limits for non-emergency use.
- A 3 m stack height above the CUP building roof for the boiler and generator exhausts is considered suitable minimum height.
- The emission rates of chemical species out of the laboratory exhaust and hot lab exhaust should be verified, as the design develops.
- The kitchen exhausts shall be equipped with standard ecologizer units.
- The hospital will be designed with fixed / non-operable windows
- An updated air quality study should be performed during the design / build stage of the project to ensure all source of emission are compliant with MECP standards.

TABLE OF CONTENTS

1. INTRODUCTION

Gradient Wind Engineering Inc. (Gradient Wind) was retained by The Ottawa Hospital, through a sub-consultant agreement with Parsons Inc., to undertake an air quality assessment to satisfy Site Plan Control application and Federal Land Use and Design Approval requirements for the proposed New Campus Development for The Ottawa Hospital (TOH), located between 930 Carling Avenue and 520 Preston Street in Ottawa, Ontario (hereinafter referred to as "subject site" or "proposed development"). This report summarizes expected air quality conditions on site and at surrounding properties due to proposed equipment associated with the subject site, including generators, boilers, laboratory, hot lab and kitchen exhausts. Environmental noise and vibration impacts are discussed in Gradient Wind's Environmental Noise & Vibration Assessment report (*ref. GW20-049-Noise & Vibration Final, dated May 7, 2021*), and Stationary Noise Assessment report (*ref. GW20-049-Stationary Noise, dated September 30, 2022*).

2. TERMS OF REFERENCE

The New Campus Development for TOH is located between 930 Carling Avenue and 520 Preston Street in Ottawa; situated on a parcel of land bounded by Carling Avenue to the north, Preston Street to the east, Prince of Wales Drive to the southeast, Birch Drive to the southwest, and Maple Drive to the west. The New Campus Development includes a main Hospital building and a Central Utility Plant (CUP), referred to as Phases 4 and 3 respectively and both form the focus of the present study. A future research building will be located to the north of the previously approved Phase 2 parking garage to the southeast, and three future towers to be located at the northeast corner.

**ARCHITECTURAL RENDERING, NORTH PERSPECTIVE
(COURTESY OF HDR ARCHITECTURE ASSOCIATES INC.)**

The main Hospital building comprises two nearly rectangular building components connected by a common podium. The building to the west is an eight-storey building, hereinafter referred to as the "Tower A", and the building to the east is a 12-storey building, hereinafter referred to as the "Tower B".

The Tower A includes terraces along the east and west elevations at Levels 5 and 6 and the Tower B includes a helicopter pad on the roof. Entrances to the main hospital building are provided below-grade on the east elevation (public access to the emergency room) and west elevation (ambulance access), and grade-level access on the south (loading area) and north. Additionally, a pedestrian bridge at the northeast corner provides access between Level 1 of the main hospital building and the parking garage to the northeast. The covered emergency level includes short-term parking, and the main entrance level includes short-term parking and barrier-free parking surrounded by landscaping towards the northeast of the main entrance plaza. A wellness garden is located north on the main entrance plaza.

The CUP is a one-storey rectangular building located at the southwest corner of the subject site aligned with Maple Drive to the southwest. There is a fuelling and loading area located at the northeast corner, and a main entrance located at the northwest corner. The CUP is located below the level of Maple Drive and includes open areas and covered areas that will include surface parking. The CUP will include exhaust stacks that extend above the surface of the CUP roof and parking area.

The near-field surroundings (defined as an area within 200 metres (m) of the subject site) include a mix of low to high-rise massing to the north of Carling Avenue, a mix of open space and the low-rise massing within the Central Experimental Farm to the west and southwest of the subject site, and open space known as Dominion Arboretum on the east side of Prince of Wales Drive. The far-field surroundings (defined as an area beyond the near-field but within a 2-kilometre (km) radius of the subject site) include a mix of mostly low and high-rise buildings from the south-southwest clockwise to the northeast, a mix of low-rise massing and the open exposure of Dow’s Lake and the Rideau Canal from the northeast clockwise to the east-southeast, a mix of the open exposure of the Dominion Arboretum and the mostly mid- and high-rise buildings of Carleton University from the east-southeast clockwise to the south-southeast, the open exposures of the Central Experimental Farm from the south-southeast clockwise to the south-southwest, and a mix of suburban massing and the open exposures of the Central Experimental Farm for the remaining compass directions. Figure 1 illustrates the site plan and surrounding context.

3. OBJECTIVES

The principal objectives of this study are to (i) assess the impact of exhausting pollutants from various polluted exhaust over sensitive locations on the hospital, within and beyond its property boundary; and (ii) provide recommendations for mitigation, should dilution of the exhausting streams be deemed inadequate or if concentration levels are found to exceed the established criteria.

4. METHODOLOGY

The approach followed to quantify potential re-entrainment problems over the various fresh air intakes, as well as to quantify air quality at sensitive areas at grade level throughout the site, is based on computational air dispersion modelling using "AERMOD", a software algorithm developed by the United States Environmental Protection Agency for the assessment of air quality impacts on residential and commercial sites. AERMOD is based on atmospheric boundary layer theory, and allows for considerations of wind downwash, advanced depositional parameters, and local wind climate data.

Generally speaking, the study methodology includes: (i) creating a three-dimensional computer model of the site and relevant surroundings; (ii) modelling the exhaust characteristics of pertinent pollutant sources; (iii) running pollutant dispersion simulations for five years of local meteorological data[1]; and (iv) comparing pollutant concentrations at each receptor with the provincial criteria.

4.1 Study Area Modelling

The AERMOD computer model encompasses an area within a 1000-meter (m) radius of the study site, including all existing, approved and proposed surrounding buildings within the influence zone. A building is considered to be in the influence zone if: (i) it is sufficiently close to a pollutant source to cause wake effects; and (ii) when the distance between the stack and the nearest part of the building is less than or equal to five (5) times the lesser of the building height, or the projected width of the building[2]. AERMOD only considers building downwash effects, while ignoring other influences such as screening and turbulence created by flow around buildings. Since these effects would increase dilution, pollution

[1] http://www.ene.gov.on.ca/envision/air/regulations/metdata/Central.htm
[2] MOECC, Air Dispersion Modelling Guidelines for Ontario Version 2.0, PIBs# 5165e02, March 2009

estimates provided by AERMOD and ASHRAE are considered to be conservative compared with more accurate tools, such as wind tunnel testing.

The details of the development are based on site plan drawings prepared by HDR Architects, as well as surrounding street layouts and building massing information obtained from the City of Ottawa, and recent aerial imagery. The most recent surface weather data and wind profiles, as a function of height appropriate for the exposures of the study site, were obtained for the Ottawa region from five years of measured data between 2000 and 2004.

4.2 Critical Points of Impingement

The critical points of impingement for this study include fresh-air intakes, public sidewalks, walkways, building entrances, balconies, terraces devoted to common amenity space. Receptors were placed across the site and surrounding areas using a nested grid at grade level. In addition to the grid, discrete receptors were located throughout the study site at key locations such as outdoor amenity spaces, building entrances, and fresh air intakes. The fresh air intakes for the development site are along various façades at Level 4.

Different receiver location types can have varying exposure times and sensitivities to pollutants. For instance, fresh-air intakes continuously provide air to the building's mechanical systems and can affect a large number of the building's occupants, making them the most sensitive. Main entrances operate intermittently, predominantly during daytime hours; therefore, the sensitivity of these receivers is lower.

4.3 Criteria Air Contaminants

4.3.1 Dilution Ratio Determination (Laboratory & Kitchen Exhausts)

The assessment of pollution levels at Points of Impingement (POI) for laboratory and kitchen exhausts requires calculation of chemical concentrations over a period of time, usually taken as one hour and based on measured Dilution Ratios (DRs), and comparison to available criteria established for the same time interval. The DR is calculated by dividing the concentration of a tracer gas at the source by the measured concentrations of the same tracer gas at the POI. The value of the DR is a dimensionless whole number greater than one, which can be applied to any chemical specie, assuming that the chemical does not change its composition (i.e., does not react with air) between the source and POI. A larger DR represents a lower pollution concentration in terms of mass density at the POI.

For example, if the concentration at a given POI is 500 times less than the concentration at the source of the emission, the dilution ratio is defined as 500/1 or simply 500. Hence, higher numbers equate to greater dilution and cleaner air. Following the determination of DRs, the concentration of any chemical specie, at a given POI, can be calculated by dividing the concentration of the chemical at the source by the DR. Specific exhaust parameters for the laboratory & kitchen exhausts are described in Section 4.4.

Gradient Wind has also conducted calculations using ASHRAE methodology for air intake and exhaust design to determine same-structure impacts from the proposed laboratory and kitchen exhausts at the proposed nearby intake louvers, for comparison purposes. It should be noted that the ASHRAE methodology is a simplified air dispersion calculation based on gaussian plume equations (see Appendix A).

4.3.2 Air Contaminants Benchmarks (Fuel Burning Equipment)

Pollutant concentrations for fuel burning equipment, including boiler and generator units, are measured in either parts per million (ppm) or micrograms per cubic metre ($\mu g/m^3$). Resulting concentrations are compared to clean air standards that have been set by the Ontario Ministry of the Environment, Conservation and Parks, (MECP) Standards Development Branch. The Air Contaminants Benchmarks (ACB) are the Ministry's targets for clean air from all sources of pollutants, including transit, transportation and industrial facilities when considered with other sources.

ACB standards are effect-based concentration levels for individual pollutants in air, with variable averaging periods for each pollutant. Averaging periods vary from one hour to 24-hours, according to the relevant impacts of each pollutant on people and the environment. For example, CO has acute health effects (poisoning) and has a corresponding short averaging period of one-half hour. Conversely, PM has an averaging period of 24-hours to account for the known long-term respiratory effects. The ACB standards for representative pollutants are listed in Table 1, with the averaging period for each pollutant indicated in parenthesis.

TABLE 1: AIR CONTAMINANTS BENCHMARKS

Pollutant	AAQC (µg/m³)	Limiting Effect
CO	36,200 (1 Hour)	Health
	15,700 (8 Hour)	
NO_x	400 (1 Hour)*	Health
	200 (24 Hour)*	
PM_{10} < 10µm	50 (24 Hour)	Health
$PM_{2.5}$ < 2.5µm	30 (24 Hour)	Health

Note: *Limit for NOx is a mixture of both NO and NO_2. In ambient air, NO converts to NO_2, which has more severe health effects than NO. Therefore, AAQC is based on health effects of NO_2. PM_{10} is studied as the primary contaminant over $PM_{2.5}$.

4.4 Emissions Sources

Study site contains a laboratory exhaust, radio isotope (hot laboratory) exhaust, and kitchen exhaust at the Level 5 roof between the towers; a kitchen exhaust servicing the cafeteria at the Level 2 lower podium roof; and diesel generators, natural gas generators, and hot water/steam boilers exhausting through the roof of the CUP building. All source locations are illustrated in Figure 2. Insignificant sources are discussed in Section 4.5.

The identified sources of emissions are presented in Table 2 along with the stack parameters that are known at this time. For fuel burning equipment, the main contaminant of concern is Nitrogen Dioxide (NO_2) which applies for both natural gas and diesel fueled equipment. For diesel consumption, in addition to NO_2, carbon monoxide (CO) and particulate matter (PM) are produced. Fuel burning equipment has a specified concentration of Oxides of Nitrogen (NO_x), which refers to the combination of NO_2 and Nitrogen Oxides (NO). During the combustion process NO is mainly produced at the source and then converts over to NO_2 in ambient air. The NO_2 is more harmful than NO. Based on the US Environmental Protection Agency's (EPA) Ambient Ratio Method (ARM), NO_x concentrations can be converted into NO_2 concentrations directly within the AERMOD program. With methane (natural gas) and propane fuels, NO_2 is the only significant contaminant of concern. For diesel fuel, carbon monoxide (CO) and particulate matter are also emitted, however NO_2 emissions dominate.

Diesel Generators

Eight planned 3500 kW generators were considered as part of the study for backup power and peak shaving operations. Under peak shaving operations, these generators can run continuously and concurrently depending on energy needs. The generator stacks are located on the roof of the CUP building. The design model was based on a Cummins Model QSK95 generator set. Based on manufacturers data, the exhaust flow rate of each stack is 10.3 m^3/s. The individual stack diameters of the combustion exhaust are assumed to be 600 mm. While CO and PM were considered, the critical contaminant is NO_X and NO_2. For generators, the 1-hour concentration limit is 400 µg/m^3. The generator stacks are assumed to extend 3 m above the roof. Gradient Wind notes that with the intent of using the diesel generators for peak shaving activities, the diesel generators must be fitted with exhaust scrubbers to achieve a maximum NO_X emission rate of 0.4 g/s as dictated by the MECP, if the generators will be used for producing prime power / peak shaving.

Natural Gas Generators

Four planned 2000 kW generators were considered as part of the study for backup power and peak shaving operations. Under peak shaving operations, these generators can run continuously and concurrently depending on energy needs. The generator stacks are located on the roof of the CUP building. The design model was based on a Cummins Model HSK78G generator set. Based on manufacturers data, the exhaust flow rate of each stack is 6 m^3/s. The individual stack diameters of the combustion exhaust are assumed to be 600 mm. Only the critical contaminant NO_X and NO_2 are considered. For generators, the 1-hour concentration limit is 400 µg/m^3. The generator stacks are assumed to extend 3 m above the roof.

Boilers

A number of hot water and steam boilers service the development. There are three boiler stacks located on the roof of the CUP building. According to the manufacturer's literature, the source concentration of NO_x for the boilers and each stack exhaust is 30 ppm (approximately 60,800 µg/m^3). The flue gas exit velocity is assumed to be and average of 5 m/s. As these boilers are expected to use natural gas fuel, only the critical contaminant NO_X and NO_2 are considered. The 1-hour concentration limit is 400 µg/m^3. The boiler stacks will be 3 m above the roof, each having an exhaust diameter of 1,000 mm.

Laboratory Exhaust

The laboratory exhaust is located on the southern edge of the Level 5 podium roof between the towers and is adjacent to the hot lab exhaust. The fan is a Cook Model QMXDVP with a flow rate of 11.3 m^3/s (24,000 CFM) and a stack diameter of approximately 1,000 mm. The fans discharge 4 m above the Level 5 roof. Regarding the laboratory fume hood exhaust, at the time of the study a comprehensive chemical inventory was not available and would not likely be available until detailed design. A conservative target dilution ratio of 5000:1 is suggested as a guideline by ASHRAE Handbook[3]. A more practical screening dilution ration of 3000 to 1 has been used on other projects with success. As an industry practice, it is common to use manifold exhaust systems to dilute the exhaust from the fume hoods before it reaches the laboratory exhaust fans. The exhaust system is evaluated to determine the total rate, which includes pre-dilution of the manifold. Due to the pre-dilution of the manifold, the assumption of 12 fume hoods, and the exit nozzle from the exhaust fan providing a 142% dilution, a target dilution ratio of 176 is used based on the concentration at exhaust stacks to the point of impingement.

Hot Lab Exhaust

The hot lab (radio isotope) exhaust is located on southern edge of the Level 5 podium roof between the towers and is adjacent to the laboratory exhaust. The hot lab exhaust will release air from magnetic imaging departments, such as X-ray, MRI, and CAT scans. Due to radiation used in these processes, the air emitted from these rooms may have small amounts of isotopes. The fan is a Cook Model QMXDVP with a flow rate of 1.2 m^3/s (2,500 CFM) and a stack diameter of approximately 1,000 mm. The fans discharge 4 m above the Level 5 roof. Based on previous experience with a Cyclotron involved assessing F-18 isotope radiation limits set by Canadian Nuclear Safety Commission, an acceptable dilution ratio 80 was used for the hot lab exhaust.

Kitchen Exhausts

There are two kitchen exhausts within the development, one at the Level 5 podium roof between the towers with a combined flow rate of 8 m^3/s, and one servicing the cafeteria at the Level 2 lower podium roof with a combined flow rate of 6.3 8 m^3/s. The primary contaminant from kitchen exhaust is odours. Currently, the MECP does not have a limit for mixed odour and prefers to use criteria based on specific chemical compounds. Common industry practice for mixed odour suggests odours would not have a

[3] 2011 ASHRAE Handbook- Heating, Ventilating, and Air-Conditioning Applications, Section 16. Laboratories

potential for detection if odour levels were below the detection level of 1 OU/m^3 averaged over a 10-minute period with a 99.5% frequency at receptors where human activity occurs, such as outdoor amenity spaces. A dilution ratio of 500 is considered suitable for most applications to ensure the detection level is not exceeded, which can be achieved with a standard ecologizer unit.

TABLE 2: SOURCE SUMMARY TABLE

Description	Source Data					Emission Rate (g/s)		
	Quantity of Stacks	Stack Gas Flow Rate (m^3/s) (deg C)	Stack Diameter (m) and orientation	Stack Height Above Grade (m)	Stack Height Above Roof (m)	NOx	CO	PM
Boilers (Below grade)	3	3.9 200ºC	1 Vertical	6	3	0.24	N/A	N/A
Diesel Generators (Below grade)	8	10.3 422ºC	0.6 Vertical	6	3	5.3 0.4*	0.21	0.044
Natural Gas Generators (Below grade)	4	6 390ºC	0.6 Vertical	6	3	0.22	N/A	N/A
Laboratory Exhaust	1	11.3 Ambient	1 Vertical	32	4	N/A	N/A	N/A
Hot Lab Exhaust	1	1.2 Ambient	1 Vertical	32	4	N/A	N/A	N/A
Kitchen Exhaust L2	1	6.3 Ambient	0.5 Vertical	7.5	1.5	N/A	N/A	N/A
Kitchen Exhaust L5	1	8 Ambient	0.5 Vertical	29.5	1.5	N/A	N/A	N/A

* - Maximum permissible emission rate for peak shaving activities.

4.5 Insignificant Sources

The following sources of noise were ruled to be insignificant and will not be included in the air quality assessment.

1. Cooling Towers

The current design uses evaporative cooling towers. There is sufficient dilution that recirculation is not anticipated for cooling towers. Ligonier's disease is mitigated by treating the water running inside the colling tower.

2. Parking Garage Exhaust

If the parking garage contains exhaust fans, these are typically connected to carbon monoxide sensors which are set to maintain concentration levels below a safe limit inside the parking garage of 15 ppm. Fans inside the parking garage will turn on and off automatically to ensure parkade is well ventilated. Due to low concentrations levels from these exhausts, entrainment is unlikely to occur at the fresh air intakes.

3. Anaesthetic Gas

Anesthetic gas is dispensed to operating rooms through surgical tubbing and a mask worn by the patients. In an unlikely event of a gas leak inside an operating room, the dispensed concentration of gas will be low enough not to adversely impact medical staff inside the room. Therefore, any release into the atmosphere would likewise be considered insignificant.

5. RESULTS

Based on the foregoing analysis, this section summarizes the most significant findings of the air quality and exhaust re-entrainment study for The Ottawa Hospital. Based on the results of AERMOD modelling, calculated dilution ratios, comparison to air quality standards, meteorological data analysis, and statistical calculations, the air quality predictions may be generally described as follows:

1. Contaminants from fuel burning equipment were found to fall below the AAQC at the nearest points of impingement, provided the diesel generators are equipped with the appropriate exhaust

scrubbers for prime power (peak shaving) activities, in order to meet the MECP emission limits for non-emergency use.

2. The Target Dilution Ratios (TDRs) for the laboratory exhaust and hot lab exhaust are achieved at the nearest points of impingement. However, once the list of chemicals that will be used or stored in the cabinets are known, their rates of emission should be verified that safe levels can be maintained.

3. The Target Dilution Ratios (TDRs) for the kitchen exhausts are not achieved at the nearest points of impingement, however with the use of a standard ecologizer unit, odours are expected to fall below the detection level of 1 OU/m^3.

The determined actual dilution ratios for laboratory exhausts are summarized in Table 3 below, with a direct comparison to the target dilution ratios. Table 4 contains the calculated concentration levels for the fuel burning equipment, and a comparison with the AAQC.

TABLE 3: SUMMARY OF CALCULATED DILUTION RATIOS

Exhaust Source	Contaminant	Target Dilution Ratio	AERMOD Dilution Ratio	ASHRAE Dilution Ratio
Laboratory Exhaust	Various	176	295	378
Hot Lab Exhaust	Isotopes	80	2,533	N/A
Kitchen Exhaust L2	Odours	500	**227**	360
Kitchen Exhaust L5	Odours	500	**378**	N/A

TABLE 4: SUMMARY OF FUEL BURNING EMISSION CONCENTRATIONS

Contaminant	Averaging Period	AAQC Limit (µg/m^3)	Calculated Concentration (µg/m^3)
NO_2	1-hour	400	241
	Annual	200	26.7
CO	1-hour	36,200	430
	8-hour	15,700	258
PM	24-hour	50	34

6. CONCLUSIONS

The results of the air quality study indicate generally favourable air quality conditions within the New Campus Development property boundary and beyond, inclusive of all fresh air intakes, building access points, and outdoor amenity spaces. The predictions show that pollutant concentrations will be within acceptable levels, as outlined by the MECP AAQC and industry standards. While the results are generally favorable the outcome of the study provides the following recommendations:

- The diesel generators shall be equipped with the appropriate exhaust scrubbers for peak shaving activities, in order to meet the MECP emission limits for non-emergency use.
- A 3 m stack height above the CUP building roof for the boiler and generator exhausts is considered suitable minimum height.
- The emission rates of chemical species out of the laboratory exhaust and hot lab exhaust should be verified, once a list of chemicals and usage is known, however target dilution ratios are achieved.
- The kitchen exhausts shall be equipped with standard ecologizer units.
- The hospital will be designed with fixed / non-operable windows
- An updated air quality study should be performed during the design / build stage of the project to ensure all source of emission are compliant with MECP standards.

This concludes our air quality and re-entrainment study and report. If you have any questions or wish to discuss our findings, please advise us. In the interim, we thank you for the opportunity to be of service.

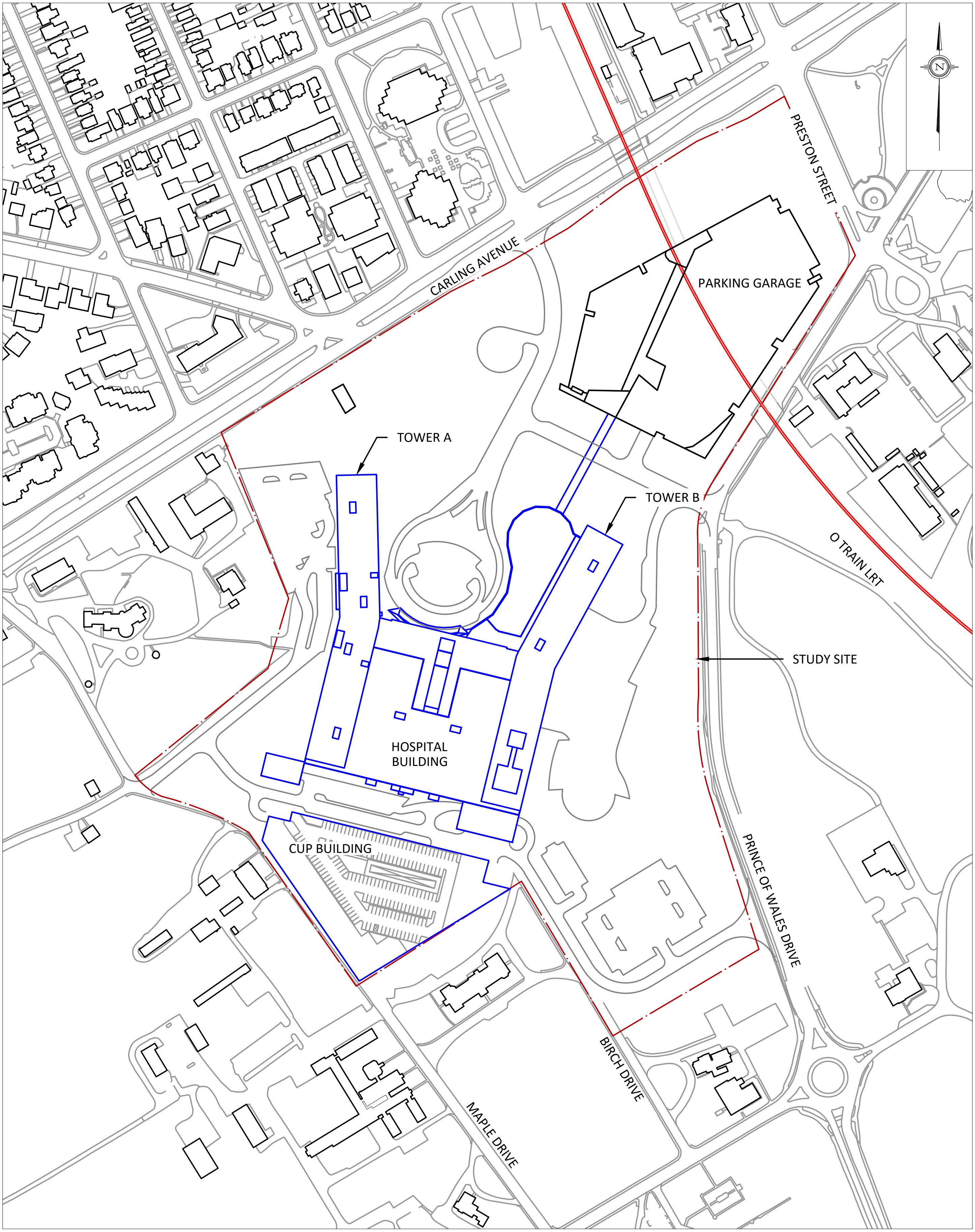
Sincerely,

Gradient Wind Engineering Inc.

Michael Lafortune, C.E.T.
Environmental Scientist

Joshua Foster, P.Eng.
Lead Engineer

Gradient Wind File #20-049-Air Quality



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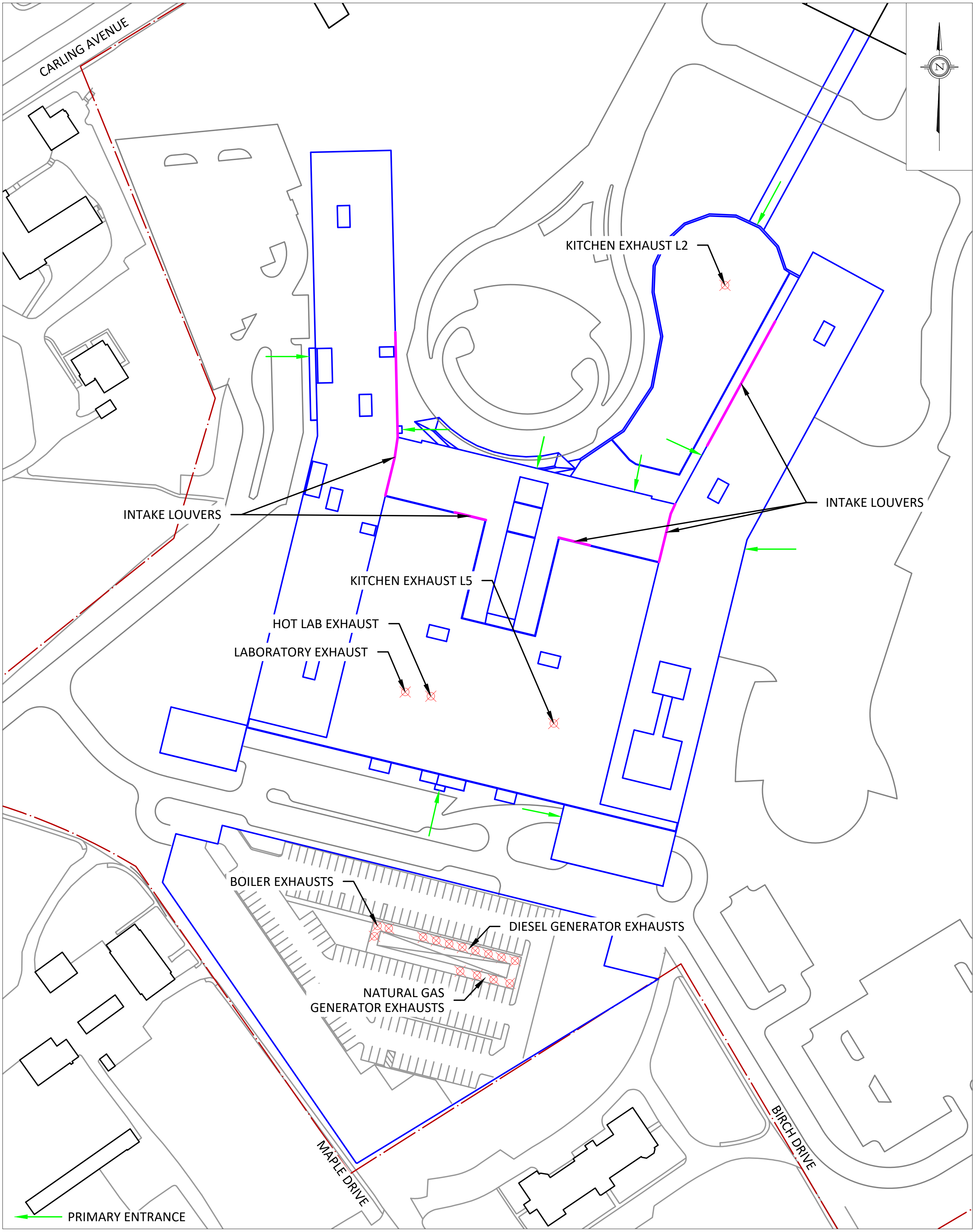
PROJECT: 930 CARLING AVENUE AND 520 PRESTON STREET, OTTAWA AIR QUALITY STUDY		DESCRIPTION: FIGURE 1: SITE PLAN AND SURROUNDING CONTEXT
SCALE: 1:4000 (APPROX.)	DRAWING NO.: GW20-049-1	
DATE: SEPTEMBER 30, 2022	DRAWN BY: M.L.	



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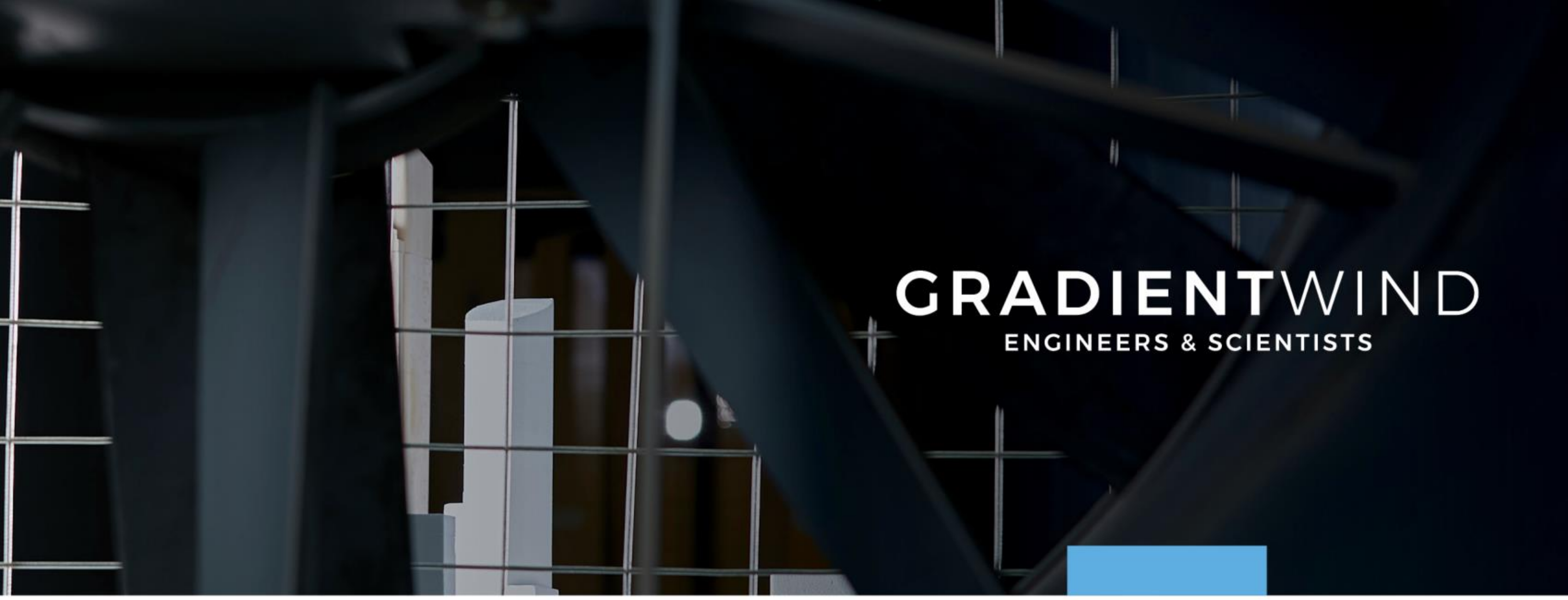
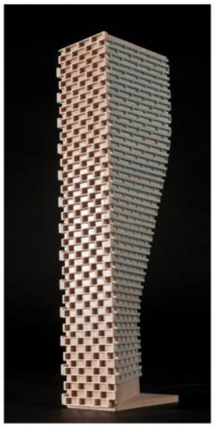
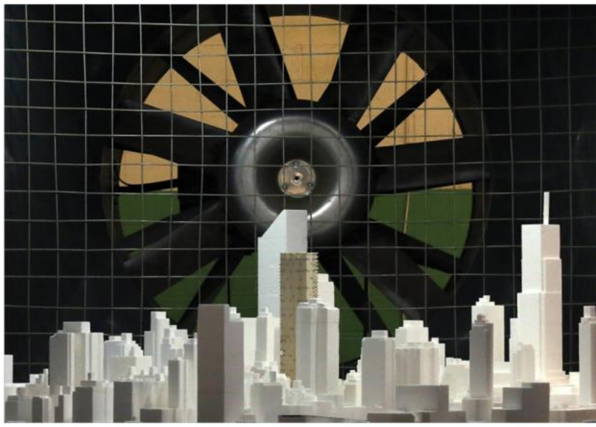
PROJECT: 930 CARLING AVENUE AND 520 PRESTON STREET, OTTAWA AIR QUALITY STUDY		DESCRIPTION: FIGURE 2: SOURCE LOCATIONS
SCALE: 1:2000 (APPROX.)	DRAWING NO.: GW20-049-2	
DATE: SEPTEMBER 30, 2022	DRAWN BY: M.L.	







APPENDIX A

ASHRAE METHODOLOGY AND CALCULATIONS

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ASHRAE EXHAUST-TO-INTAKE DILUTION ESTIMATION

The concentrations at fresh air intakes and building entrances were calculated by determine the dilution ratio between the exhaust and sensitive receptor, as demonstrated in Equation 1.

$$D = C_e/C \qquad (1)$$

where

D = Dilution ratio
C_e = contaminant mass constriction at exhaust, μg/m^3
C = contaminant mass concentration at receptor, μg/m^3

The dilution ratio for each source to intake was calculated using Equation 2, when the plume rise was demonstrated to be higher than the recirculation zone of the building and all rooftop obstacles.

$$D = \frac{4U_H\sigma_y\sigma_z}{V_e d_e^2}\exp\left(\frac{\zeta^2}{2\sigma_z^2}\right) \qquad (2)$$

where,

U_H = wind speed at height of the building
V_e = stack exhaust velocity
d_e = inside diameter of the stack
σ_y = crosswind plume spread calculated, using Equation 3
σ_z = vertical plume spread calculated, using Equation 4
ζ = is the height the plume rises above roof obstacles and recirculation zones.

The crosswind and vertical plume spreads are calculated as follows,

$$\sigma_y = \left(i_y^2 x^2 + \sigma_0\right)^{1/2} \qquad (3)$$

$$\sigma_z = \left(i_z^2 x^2 + \sigma_0\right)^{1/2} \qquad (4)$$

The parameter x is the distance downwind of the stack, σ_o is the intimal source size normally set equal to $0.35d_e$, i_y is the lateral turbulence intensity, and i_z is the vertical turbulence intensity and are calculated by Equation 5.

$$i_y = 0.75 i_x; \quad i_z = 0.5 i_x \qquad (5)$$

where

$$i_x = \frac{n \ln\left(\frac{30}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)}$$

$$n = 0.24 + 0.096 \log_{10} z_0 + 0.016(\log_{10} z_0)^2$$

The boundary layer roughness coefficient z_o was set to 2 m for a urban area, and z is a vertical dimension set to the height of the building.

When the plume rise is lower than the recirculation zones created by the building and rooftop obstacles ($\zeta = 0$) and the stack is considered to be a Flush exhaust and Equation 2 is modified to be

$$D = \frac{4 U_H \sigma_y \sigma_z}{V_e d_e^2} \qquad (6)$$

Plume rise and recirculation zone dimensions were calculated using the protocol described in Chapter 45 of the 2011 ASHRAE Handbook – HVAC Applications. The dilution ratios estimated by Equations 2 and 6 are suitable for one-hour averaging periods. To convert to 24 hour averaging period, a factor of 2.5 is applied. To convert to an annual averaging period, a factor of 12.5 is applied to the one-hour dilution ratios.