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William M. Robertson, Ph.D.

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Disclaimer

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Introduction

The construction of a new compressor station, designated as the 563 compressor station, to be located on State Road 431 (White's Creek Pike) between Greenbrier and Morgan Roads was proposed by Tennessee Gas Pipeline, a subsidiary of Kinder Morgan as part of their Broad Run Expansion project (FERC Docket CP15-77). The goal of the Broad Run project is to increase the carrying capacity of the existing pipelines.

The site for the proposed compressor station is located in an agricultural/residential part of Davidson County. Although there are many issues of concern with the location of a large industrial facility close to centers of population, this study examines the potential impact of a single air pollutant, NOx, and its potential impact on public health. The motivation for this study was the large size of the facility combined with its proposed location close to residences, businesses, farms, and a city park. At 60,000 HP the proposed compressor station would be among the top 3% in size in the country. Most compressor stations are smaller and even those smaller units are constructed in isolated rural settings far from populated areas. However, pipeline companies are increasingly proposing to add more compressor stations in between existing ones in order to increase the natural gas carrying capacity of existing pipelines. The location of these proposed additional compressor stations are, by geographical necessity, coming closer to populated areas.

The study here is limited to only a single pollutant (NOx) and makes use of a simple dispersion model. The goal was to determine if, within the accuracy of this simple model, the level of emissions of NOx from the proposed compressor station was likely to reach or exceed EPA limits as defined in the National Ambient Air Quality Standards (NAAQS).

The values of the various regulated pollutants from the proposed compressor station were specified in the Title V air permit application filed by Kinder Morgan with the Metropolitan Davidson County Department of

Health. Only NOx dispersion was chosen for study because it was the largest pollutant by weight at 170 tons per year and because it is also a precursor for ground level ozone when combined under the right conditions with volatile organic compounds (VOCs).

The conclusion of this study is that, within the scope of this simple approach, the footprint of the proposed 60,000 HP compressor station is too small to allow for sufficient dispersion of NOx. The results indicate that there is insufficient distance between this compressor station and nearby populated areas to allow for the levels of NOx to reduce to concentrations below the levels set by the NAAQS. This finding means that the facility, at the size and location proposed, would pose a direct risk to the health of surrounding residents. The proposed compressor station adjoins Paradise Ridge Park—the newest city park in Nashville. Simulations show that NOx levels well above NAAQS primary limits could be realized at the location of the park. This finding is of particular concern because NOx is a respiratory irritant which could have especially detrimental effects on a population—particularly including children—who use the park for exercise and recreation. The effects of exceeding NOx limits are well documented [1-9].

AERMOD Analysis versus Gaussian Plume Analysis

This study makes use of a simple Gaussian Plume analysis. The EPA recognizes and recommends the program AERMOD as the standard in modeling atmospheric dispersion. The program is freely available—but it is not particularly easy to use. It draws both weather data from the National Weather Service with a separate program, AERMET, and topological data from the National Geographic Survey. The central underlying principle of AERMOD is a Gaussian Plume model as is used in this study; however, it uses more sophisticated air mixing models and a different, more modern, approach in place of air stability classes. The results of a full AERMOD study would undoubtedly be more accurate than the results of the rudimentary model employed here. However, it is unlikely that the AERMOD results would predict NOx levels an order of magnitude lower than this study which would be necessary to obtain results that would make the proposed compressor station compliant with the NAAQS standards.

NAAQS standards for NOX levels

The Clean Air Act mandates that the EPA sets standards for pollutants harmful to the public health. These standards are known as the National Ambient Air Quality Standards. In the case of oxides of nitrogen the NAAQS standards are defined for NO_2 and NO. In the Title V application for the Air Permit the value for the yearly output of NOx projected to be emitted is defined (in tons per year) but not a value for NO_2 separately. NO_x is the combination of NO (nitric oxide) and NO_2 (nitrogen dioxide). Both compounds exhibit health hazards; however, it is NO_2 that is recognized as being of significantly more concern.

The emission from a gas fired turbine consists of a mixture of NO and NO_2. The level of NO_2 is typically specified as the ratio of NO_2/NO_x. This ratio depends on the type and operating conditions of the turbine. The ratio can range to as high as 0.743 [10]. However, regardless of the exact ratio, in the atmosphere, NO converts to NO_2 settling, in less than an hour, to the ambient atmospheric ratio of 80% NO_2 [11]. In the approach taken here we assumed first that all of the NOx was emitted as NO_2. This is a standard Tier 1 approximation [12]. In a second, more nuanced, Tier 2 simulation, the emitted NOx level was assumed to be 80% NO_2 reflecting the conversion of NO to the ambient atmospheric ratio. This latter approach, known as the Ambient Ratio Method [10], results in lower levels for the NO_2 concentration. However, as the results of this study show, this decrease of 20% has a minimal impact on the final conclusion that the proposed compressor station cannot meet NAAQS standards for NOx emissions.

The Nitrogen Dioxide (NO_2) Standards from the EPA [13] are as follows. The primary standard is 100 ppb (parts per billion) averaged over a 1-hour interval. The primary and secondary standard is 53 ppb averaged over 1 year.

The Gaussian Plume program uses the emission rate from the source in grams per second and calculates the concentration in g/m^3. Thus, it is necessary to covert the NAAQS levels from ppb to g/m^3. The formula for conversion used is:

Concentration in mg/m^3 = concentration in ppm * molecular mass in grams/molar gas volume in liters.

The molecular mass of NO_2 is 46.0 grams/mole, the volume of a mole of gas is 24.45 liters at 25^{o}C and atmospheric pressure. Using these values, we conclude that <u>53 ppb is equivalent to 99.7 μg/m^3</u> and <u>100 ppb is equivalent to 188 μg/m^3</u>. [14]

NOx Emission Levels derived from the Title V Filing

The Title V Application for an Air Permit submitted to the Metropolitan Davidson County Department of Health was used to obtain the NOx emission estimate for the proposed 563 compressor station. The listed emission of NOx is listed at 170.9 tons per year. Converting this value to grams per second—the unit necessary for input to the Gaussian plume program—gives a <u>NOx emission value of 5 g/s</u>. [15]

Wind Speed and Direction

The Gaussian plume model requires the wind speed as an input parameter. The faster the wind speed the longer the distance a pollutant is carried per unit time and hence the more dilute its concentration. The model here simulates the dispersion of NOx for a range of wind speeds from 1 m/s (2.24 mph) up to 7 m/s (15.66 mph). The question is what is the appropriate wind speed and direction at the location of the proposed compressor station. The first approximation was derived from the general classification of the average wind speed for this part of the country. That value is between 4.5 m/s and 5 m/s [16] which corresponds to speeds of 10.0 mph to 11.2 mph. However, that value is a broad average over a large geographical area and it is measured at 30 m above ground level. The average value for wind speed measured at the Nashville airport shows an average wind speed of 6 mph over the one year period from Feb. 2015 to Feb. 2016. Finally, a more local value was obtained from a weather station that is located immediately adjacent to the proposed compressor site [17]. That station has a yearly average wind speed of 1.3 mph. The value is measured just a few feet above ground level. Wind speed will increase with height according to

$$v_z = v_0 \left(\frac{z}{z_0}\right)^p$$

where v_z is the wind speed at height z, and v_0 is the wind speed at a height z_0. The value of p is taken to be 1.5 for rural settings.

The wind speed value of 1.3 mph is low but it is in good agreement with other similar local weather stations in the neighborhood all accessed through wunderground.com. Using the above formula it predicts a wind speed between 2 and 3 mph at 30 m.

Air Stability Classes

In the Gaussian plume simulation the air stability plays a central role. In simple terms highly unstable conditions, in which the wind is turbulent and changes directions frequently, result in a more rapid drop in the concentration of a pollutant with distance from the source. Changing wind conditions under unstable conditions spread the pollutants in a wide angular range about the prevailing wind direction. The plume created is broad in angular spread and pollutant concentration drops rapidly with distance. In contrast, with highly stable wind conditions the concentration of a simulated pollutant remains high for a much longer distance. However, in the highly stable case the angular width of the plume centered on the stable wind direction is much narrower.

To model the dispersion of pollutants the air stability is divided into classes, known as Pasquill atmospheric stability classes [18]. The classes are identified by a simple letter scale as shown in Table 1.

Identifier	Air stability
A	Highly unstable
B	Unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Stable

Table 1. Air stability class definitions

A simulation to demonstrate the effect of different air stability classes on the dispersion of pollutants is shown in Figure 1. The Gaussian plume program was used to generate three two-dimensional concentration profiles at ground level (plumes) using identical wind speed of 4 m/s (approximately 9 mph), and NOx emission rate of 5 g/s, but with different air stability conditions corresponding to Pasquill classes A (Highly Unstable), D (Neutral), and F (Stable). The plume profiles generated by the program were then overlaid on a Google Earth image of a 1.5 mile by 1.5 mile area around the site of the proposed compressor station. The plume overlays on the Google Earth image are shown in Figure 1. Residences are marked on the map as the small green house symbols. The two walking figures at the lower right (largely covered by the plume) indicate the location of Paradise Ridge Park.

In Figure 1 the plume outline was curtailed once the concentration dropped below 53 ppb, the lower level as defined under NAAQS standards. Thus, in the Highly Unstable case (lower left plume, as if the wind were coming from the NNE) the outline of the plume shown disappears in a short distance from the compressor station because the unstable wind conditions disperse the NOx to low enough levels in a short distance. The plumes are all shown as emanating from a circle 100 m from the compressor station location because the Gaussian Plume simulation is not accurate for distances less than 100 m.

In the neutral wind condition case (upper left plume, as if the wind were coming from the SE) the plume is narrower in angular spread and extends for a very long distance—well past the distance to the nearby residences.

Finally, for the case of stable air flow (lower right plume, as if the wind was coming from the NW) the plume is long and very narrow. In the case shown, the plume outline indicating levels above 53 ppb, extends for a distance well beyond the location of Paradise Ridge Park.

Although the extreme cases of Highly Unstable and Stable result in dramatically different conclusions about the dispersion of NOx, both cases are relatively less common in practice. For a balanced quantitative assessment of the likely NOx levels from the proposed compressor only the Neutral air stability, class D, was considered in the final simulation results.

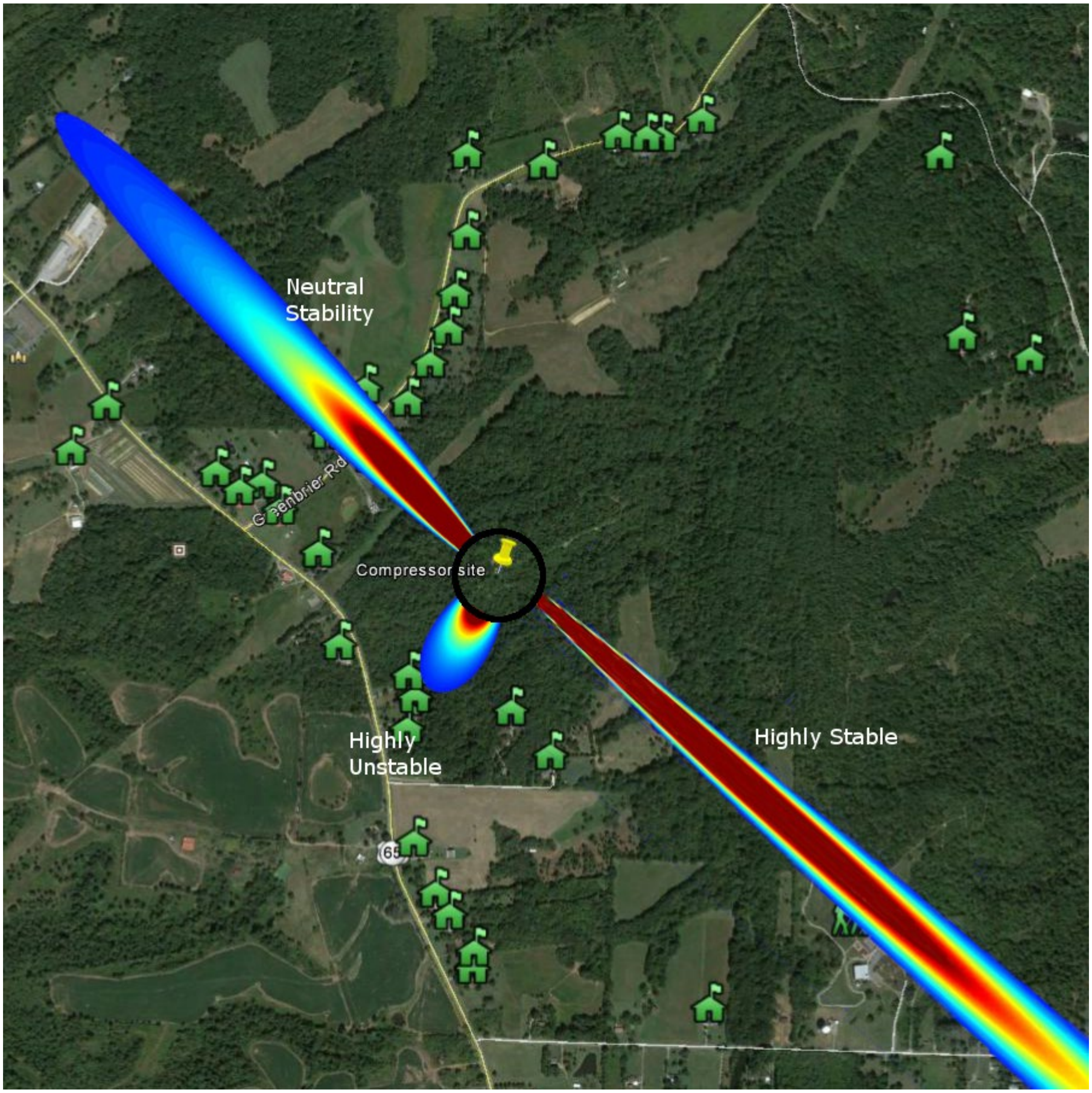

Figure 1. To illustrate the effect of air stability classes on the dispersion characteristics of a pollutant. Three plumes are plotted in this figure for classes A (Highly unstable), D (Neutral stability), and F (Highly stable) as indicated in the figure. The air speed was chosen to be 4 m/s (about 9 mph), the emission level of NOx was 5 g/s, the plume cut-off was taken at the NAAQS level of 53 ppb (i.e. where a plume is visible in the figure, the NOx level is above 53 ppb).

The Gaussian Plume Program

The Gaussian plume program used for the simulations in this study was written in the freely-available programming language Octave. A program listing is given in Appendix 1. The program can be configured for a one-dimensional simulation (change switch to '1D') which predicts the concentration as a function of distance directly along the line of the wind direction. Two-dimensional concentration plots which were used to create the plume profiles superimposed on the map of the area are created using the program switch '2D'. The concentration values are all calculated at ground level.

The core of the Gaussian plume program is fairly simple. It makes use of the

$$C = \frac{Q}{2\,\pi\sigma_y\sigma_z}\left[e^{-0.5\frac{y}{\sigma_y}}\right]\left[e^{-0.5\frac{H-z}{\sigma_z}} + e^{-0.5\frac{H+z}{\sigma_z}}\right]$$

where Q is the emission rate in grams per second, y and z are distance transverse and vertical respectively with respect to the wind direction x, and σ_y, σ_z are the spread functions (dependent on x). H is the stack height for emission.

The stack height for emission was taken to be ground level (H=0), although stack heights of 5 m and 10 m were also examined but not reported here. The results of stack height are complicated because they have a fairly large effect (up to 14% reduction) on the nearby concentrations, but a minimal effect (decreasing to less than 2% reduction) on concentrations further out. Higher stack heights reduce the concentration modestly at short distances but do little to reduce the overall length of the plume. From this analysis it is established that increased stack height would not have a sufficient impact to alter the conclusions of the study.

The program in 2D mode creates two different plume profiles. One, with array name PlumeP, sets the concentration to zero once the concentration drops below 100 ppb (188 $\mu g/m^3$) and the second, designated PlumeS, when the concentration drops below 53 ppb (99.7 $\mu g/m^3$). Thus, on a plot of the plume profile superimposed on the aerial map of the region surrounding the compressor site, the areas under the plume profile are either above the primary (PlumeP) or primary/secondary levels (PlumeS).

The program implements four different definitions of the Air Stability Class parameters. The classes are the Briggs, Martin, and two variations of the Pasquill-Gifford models. The purpose of the multiple Stability class models was to verify that they all gave essentially similar results for concentration profiles in both one and two-dimensions. Because they were all in close agreement with each other the final results reported in the Simulation Results section were all carried out with the Pasquill model (switch 'Pasqui' in the Octave program).

To ensure that the program was operating accurately the results were compared to calculations performed in different online Gaussian plume calculators [19]. Again the values obtained by the program here were in good agreement with similar calculators online, giving confidence that the program is operating correctly.

Simulation Results

The simulation results are presented first in a graphical format with plumes overlaid on the Google Earth image of the area surrounding the compressor location (Figure 2). The second analysis tabulates the quantitative data for 7 increasing wind speed indicating the distances from the compressor along the plume line before the level falls below the Primary (100 ppb) and Primary-Secondary (53 ppb) levels. The tabulated data also specifies, for each wind speed, the concentration in $\mu g/m^3$ at distances 0.25 mile, 0.5 mile, 0.75 mile, and 1.0 mile. The closest residences to the compressor station are less than 0.2 mile away and there are over 300 residences within a 1 mile radius of the site.

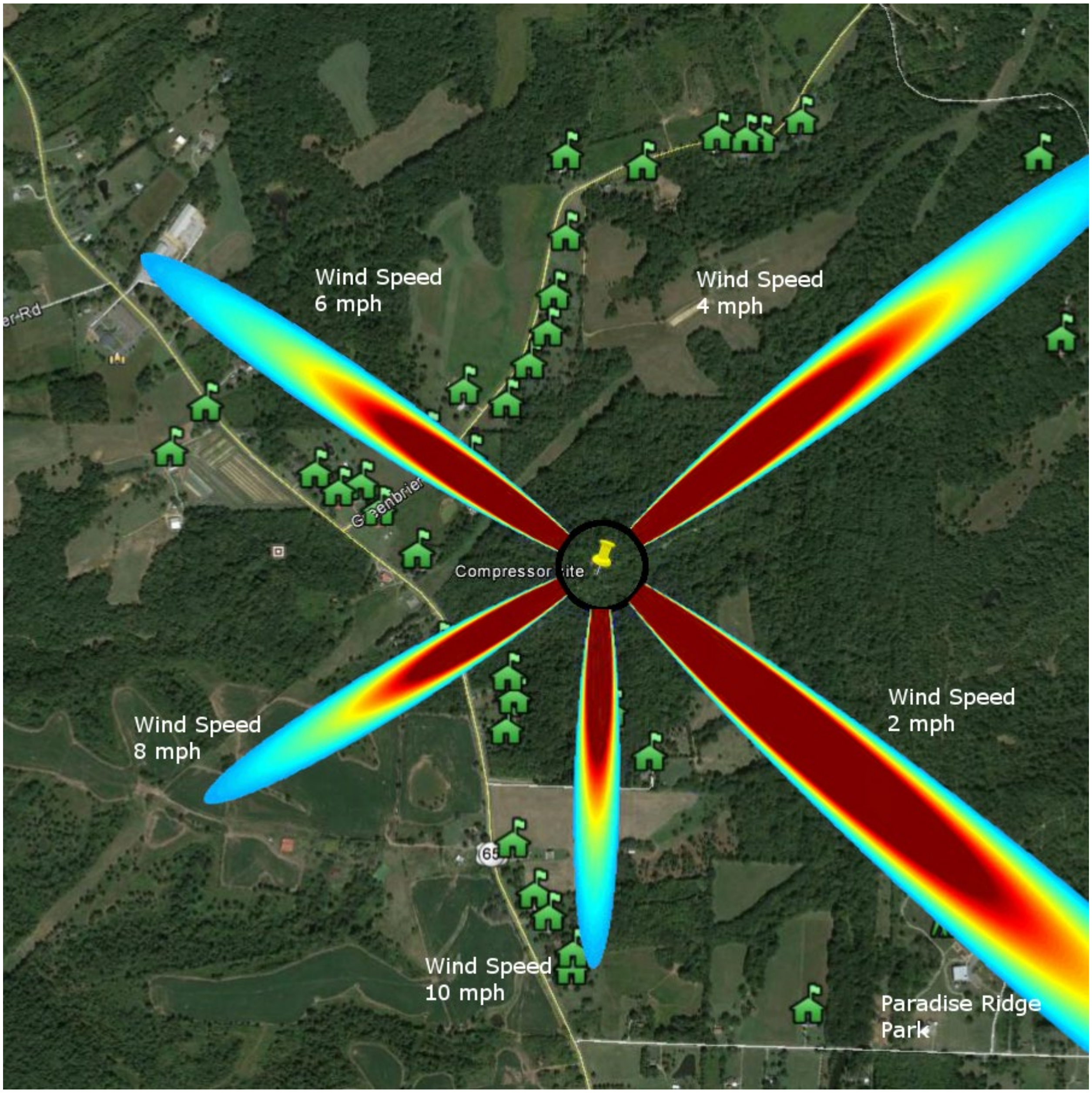

Figure 2. Plumes for 5 different wind speeds. The plume profiles cut off at the higher EPA NAAQS level of 100 ppb or 190 $\mu g/m^3$. The plumes depicted indicate that at any of the wind speeds shown NOx levels, at least some of the nearby residences, are above the EPA NAAQS limits. At wind speeds up to 5 mph the 100 ppb limit can be exceeded at the location of Paradise Ridge Park which is indicated at the lower right corner of the figure.

Figure 2 overlays 100 ppm plumes at 5 different wind speeds on the 1.5 mile by 1.5 mile Google Earth image of the area surrounding the compressor site. The plumes were generated by the Gaussian Plume program with the appropriate wind speed and with air stability class D (neutral stability). The proposed compressor station location is marked by the yellow push pin. Nearby residences are indicated by the green house symbols. The plot indicates that even at the highest wind speed of 10 mph the 100 ppb NOx limit will be exceeded if residences are in the general direction of the wind. At lower wind speeds the plumes encompass a longer range and with a breadth that would affect a large number of residences. Finally, the plot shows that at wind speeds up to 5 mph the NOx level above 100 ppb can extend to Paradise Ridge Park whose location is indicated at the lower right of the image.

The following two Tables give quantitative values for simulations using a Tier 1 approximation (100 NOx assumed to be NO_2) and a Tier 2 approximation (80% NOx assumed to be NO_2) respectively. The values are derived from a one-dimensional simulation along the center of the plume line again using the Pasquill model and conservative assumption of Air Stability class D (Neutral Stability).

Table 2

						Concentration in μg/m3 at			
Wind Speed (m/s)	Wind Speed (mph)	Primary distance (m)	Primary Secondary distance (m)	Primary distance (miles)	Primary-Secondary distance (miles)	0.25 mile	0.5 mile	0.75 mile	1.0 mile
1.00	2.24	2315	3532	1.44	2.19	**2300**	**853.9**	**467.7**	**304.9**
2.00	4.47	1487	2239	0.92	1.39	**1200**	**426.9**	**233.8**	**152.5**
3.00	6.71	1156	1726	0.72	1.07	**777**	**284.6**	**155.9**	**101.7**
4.00	8.95	970	1440	0.60	0.89	**582.7**	**213.5**	**116.9**	**76.2**
5.00	11.18	849	1253	0.53	0.78	**466.2**	**170.8**	**93.5**	**61**
6.00	13.42	761	1120	0.47	0.70	**388.5**	**142.3**	**77.9**	**50.8**
7.00	15.66	695	1020	0.43	0.63	**333**	**121.9**	**66.8**	**43.6**

Table 2 uses the results of the Gaussian Plume simulation at a set of 7 wind speeds from 1 m/s up to 7 m/s as listed in column 1. This study is a Tier 1 study in which 100% of the NOx emission is assumed to be NO_2 at an emission rate of 5 g/s. The second column lists the wind speed in miles per hour. The third column (Primary Distance) is the distance in meters directly downwind along the axis of the plume at which the NOx concentration drops below 100 ppb (188 μg/m^3). The fourth column (Primary-Secondary Distance) is the distance in meters directly downwind along the axis of the plume at which the NOx concentration drops below 53 ppb (99.7 μg/m^3). The fifth and sixth columns convert the Primary and Primary-Secondary distances from columns three and four to miles from meters. The final 4 columns give the NOx concentration in μg/m^3 at four distances between a quarter mile and one mile. The numbers in black on a green background indicate that the NOx concentration is below both Primary and Secondary levels (i.e. below 99.3 μg/m^3). The purple numbers on a yellow background indicate NOx level between the Primary and Secondary values (between 99.3 μg/m^3 and 190 μg/m^3). The values in green on tan background are above the Primary level of 100 ppb. Finally, the red values on blue background are above the maximum threshold limit value defined by the American Conference of Governmental Industrial Hygienists (0.38 mg/m^3). The highest value of 2300 μg/m^3 = 2.3 mg/m^3 is above the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) of 1.8 mg/m^3 (red and underlined). It should be emphasized that only the values in the seven cells (black ink, green background) in the table correspond to wind conditions and distance that satisfy the EPA NAAQS standard.

Table 3

						Concentration in μg/m3 at			
Wind Speed (m/s)	Wind Speed (mph)	Primary distance (m)	Primary Secondary distance (m)	Primary distance (miles)	Primary-Secondary distance (miles)	0.25 mile	0.5 mile	0.75 mile	1.0 mile
1.00	2.24	2004	3045	1.25	1.89	**1900**	**683**	**374**	**244**
2.00	4.47	1294	1939	0.80	1.20	**932**	**342**	**187**	**121**
3.00	6.71	1009	1500	0.63	0.93	**621**	**228**	**125**	**81.3**
4.00	8.95	849	1253	0.53	0.78	**466**	**171**	**93.5**	**60.9**
5.00	11.18	743	1093	0.46	0.68	**373**	**137**	**74.8**	**48.8**
6.00	13.42	668	978	0.42	0.61	**311**	**114**	**62.4**	**40.7**
7.00	15.66	610	891	0.38	0.55	**266**	**97.6**	**53.4**	**34.9**

Table 3 uses the results of the Gaussian Plume simulation at a set of 7 wind speeds from 1 m/s up to 7 m/s as listed in column 1. This study is a Tier 2 study in which 80% of the NOx emission is assumed to be NO_2, which means that the emission rate in the program is 4 g/s. The second column lists the wind speed in miles per hour. The third column (Primary Distance) is the distance in meters directly downwind along the axis of the plume at which the NOx concentration drops below 100 ppb (188 μg/m^3). The fourth column (Primary-Secondary Distance) is the distance in meters directly downwind along the axis of the plume at which the NOx concentration drops below 53 ppb (99.7 μg/m^3). The fifth and sixth columns convert the Primary and Primary-Secondary distances from columns three and four to miles. The final four columns give the NOx concentration in μg/m^3 at four distances between a quarter mile and one mile. The numbers in black on green background indicate that the NOx concentration is below both Primary and secondary levels (i.e. below 99.3 μg/m^3). The purple numbers on yellow background indicate NOx level between the Primary and Secondary values (between 99.3 μg/m^3 and 190 μg/m^3). The values in green on tan background are above the Primary level of 100 ppb. Finally, the red values on blue background are above the maximum threshold limit value defined by the American Conference of Governmental Industrial Hygienists (380 μg/m^3 = 0.38 mg/m^3). The highest value of 1900 μg/m^3 = 1.9 mg/m^3 is above the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) of 1.8 mg/m^3 (red and underlined). Again it is important to emphasize that only the ten values (in black ink, green background) at higher wind speeds and longer distances indicate circumstances in which the NAAQS standards are met.

Conclusions

The conclusions of this study indicate that the location of proposed compressor station as configured cannot meet the EPA NAAQS standards for NOx. The result is in some ways is not surprising. This compressor station would be one of the largest in the country and its location is in closer proximity to houses and a park than any other similar facility, as far as this researcher has been able to find. Up to a distance of 0.25 mile for all wind speeds up to 15.66 mph the NOx concentration level along the wind direction would exceed the 100 ppb, the upper level specified in the NAAQS. For this level to violate the EPA limit it must be sustained for at least an hour. To estimate how frequently this 1-hour condition would occur I used the wind speed average from the weather station immediately adjacent to the site but scaled up to the 30 m level. At 0.25 miles the level is exceeded for all wind speeds up to 15.66 mph. Thus, all that is required to exceed EPA NAAQS limits at 0.25 miles for a 1 hour interval is that the wind direction remain steady for an hour or more. By reviewing a week of hour-by-hour wind data, and examining direction only, the 1 hour 100 ppb limit will be exceeded at least once per day.

At low wind speeds at distances up to 0.25 mile, the predicted NOx levels exceed not only the EPA NAAQS levels but also the industrial levels set by NIOSH, ACGIH, and California OSHA (see Appendix 2). The Gaussian plume analysis conducted here is an earlier version of the more current AERMOD dispersion model. However, given the results presented here, it is highly unlikely that in an AERMOD study the results would be reduced by the factor of at least 10 that would be required to bring NOx concentrations down to a level at which they would be compliant with NAAQS standards. This facility is too large for the proposed location; it requires a much larger buffer zone free from residences in order to meet NAAQS standards.

The case of NOx levels at the Paradise Ridge Park are also of particular note. The playing fields of the park are 0.7 mile from the proposed compressor site. Tables 2 and 3 indicate that at wind speed below 6 to 9 mph the level of NOx at the park would exceed the 53 ppb limit and at speeds below 4 mph they would exceed the 100 ppb limit. The direction of the park relative to the compressor station is in a common prevailing wind direction. I examined the wind direction data for a single month (September 2015). On 7 of the 30 days of the month examined the wind would blowing in the direction of Paradise Ridge Park. On all of those days the ground level wind speeds recorded at the weather station adjacent to the proposed site were below 5 mph. This indicates a high likelihood that the 1-hour 100 ppb NAAQS limits would be exceeded at the park numerous times per year.

Parks are recognized as special facilities because they are a venue for community recreation, particularly for children and the elderly. The danger of high levels of a powerful respiratory irritant such as NOx is of special concern considering those sensitive park populations because long-term NO_2 exposure is implicated in decreased lung function and increased risk of respiratory distress [20].

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[13] EPA National Ambient Air Quality Standards (NAAQS): http://www3.epa.gov/ttn/naaqs/criteria.html)

[14] Concentration in mg/m^3 = concentration in ppm * molecular mass in grams/molar gas volume in liters. Using 0.1 ppm and 0.053 ppm for the two EPA NOx levels expressed in ppm instead of ppb. The molecular mass of NO2 is 46 grams, and the molar volume is 24 liters at ambient temperature.

[15] 171 ton/yr x 2000 lbs/ton x 454 g/lbs x (1/365)yr/day x (1/24) hr/day x (1/3600) s/day = 5 g/s.

[16] National Center for Environmental Information https://www.ncdc.noaa.gov/societal-impacts/wind/

[17] Smith Station. https://www.wunderground.com/personal-weather-station/dashboard?ID=KTNJOELT1#history

[18] Pasquill, F. (1961). *The estimation of the dispersion of windborne material*, The Meteorological Magazine, vol 90, No. 1063, pp 33-49.

[19] California State University Northridge: http://www.csun.edu/~vchsc006/469/gauss.htm (Note the final z-term is misinterpreted—there is a factor 2 missing).

[20] *Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide (PDF). World Health Organization. 13–15 January 2003. Retrieved 2016-2-19.*

Appendix 1

```
% Gaussian Plume Model
% W. Robertson 2015
%
clear C CS CP
CS=0;
CP=0;
Q=5;           % Emission rate of pollutant in g/s
u=4;           % Wind speed in m/s. Average wind speed in MT = 4.0 to 4.5 m/s
SC='D';        % Stability class A, B, C, D, E, or F
H=0;           % Effective stack height in meters
model='Pasqui'; % Stabilty model choices are Briggs, Martin, Pasqui,PasGif
SimType='1D';   % The '1D' plot give the concentration C in g/m^3 down the
                % centerline of the plume. '2D' gives a two-dimensional
                % array of values in the half-space in the plume direction.
                % The x direction C values start at 100 m from the source.

if(model == 'Briggs')  % Briggs Rural parameters
    if (SC == 'A')  %Briggs G. A. (1973) USAEC Report ATDL-106
        a=0.22;     % NOAA Dec 1974
        b=0.0001;
        c=0.2;
        d=0;
    elseif (SC == 'B')
        a=0.16;
        b=0.0001;
        c=0.12;
        d=0;
    elseif (SC == 'C')
        a=0.11;
        b=0.0001;
        c=0.08;
        d=0.0002;
    elseif (SC == 'D')
        a=0.08;
        b=0.0001;
        c=0.06;
        d=0.0015;
    elseif (SC == 'E')
        a=0.06;
        b=0.0001;
        c=0.03;
        d=0.0003;
    elseif (SC == 'F')
        a=0.04;
        b=0.0001;
        c=0.016;
        d=0.0003;
    end
elseif(model == 'Martin')
    if (SC == 'A')
        a=213;
        b=0.894;
        c=440.8;
        d=1.941;
        f=-9.27;
    elseif (SC == 'B')
        a=156;
        b=0.894;
        c=106.6;
        d=1.149;
        f=-3.3;
    elseif (SC == 'C')
        a=104;
        b=0.894;
        c=61;
        d=0.911;
        f=-0;
    elseif (SC == 'D')
```

```
        a=68;
        b=0.894;
        c=33.2;
        d=0.725;
        f=1.7;
    elseif (SC == 'E')
        a=50.5;
        b=0.894;
        c=22.8;
        d=0.678;
        f=1.3;
    elseif (SC == 'F')
        a=34;
        b=0.894;
        c=14.35;
        d=0.74;
        f=0.35;
    end
elseif(model == 'Pasqui')
    if (SC == 'A')
        k1=0.250;
        k2=927;
        k3=0.189;
        k4=0.1020;
        k5=-1.918;
    elseif (SC == 'B')
        k1=0.2020;
        k2=370;
        k3=0.162;
        k4=0.0962;
        k5=-0.101;
    elseif (SC == 'C')
        k1=0.134;
        k2=283;
        k3=0.134;
        k4=0.0722;
        k5=0.102;
    elseif (SC == 'D')
        k1=0.0787;
        k2=707;
        k3=0.135;
        k4=0.0475;
        k5=0.465;
    elseif (SC == 'E')
        k1=0.0566;
        k2=1070;
        k3=0.137;
        k4=0.0335;
        k5=0.624;
    elseif (SC == 'F')
        k1=0.0370;
        k2=1170;
        k3=0.134;
        k4=0.0220;
        k5=0.700;
    end
    elseif(model == 'PasGif') % The ISC3v2 version of the Pasquill-
    if (SC == 'A')           % Gidfford parameters. These agree
        c=24.167;      % closely with the values for Pasquill listed
        d=2.5334;      % in the option "Pasqui" above. In most cases
    elseif (SC == 'B') % the values for CP and CS are longer.
        c=18.3330;     % Ref ISC#v2 EPA-454/B-95-003b
        d=1.8096;
    elseif (SC == 'C')
        c=12.5;
        d=1.0857
    elseif (SC == 'D')
        c=8.333;
        d=0.72382;
    elseif (SC == 'E')
        c=6.25;
```

```
        d=0.54287;
    elseif (SC == 'F')
        c=4.1667;
        d=0.36191;
    end
end
y=0;
z=0;
if(SimType == '1D')
    for k=1:4500
            y=0;
            x=100+k;
            if(model == 'Briggs')
                sigy=a*x*(1+b*x)^0.5;
                sigz=c*x*(1+d*x)^0.5;
            elseif(model == 'Martin')
                sigy=a*(x/1000)^b;
                sigz=c*((x/1000)^d)-f;
            elseif(model == 'Pasqui')
                sigy=(k1*(x))/((1+((x)/k2))^k3);
                sigz=(k4*(x))/((1+((x)/k2))^k5);
            elseif(model == 'PasGif')
                TH=0.017453293*(c-d*log(x/1000));
                sigy=465.11626*(x/1000)*tan(TH);
                if(SC == 'A')
                    if(x < 100)
                        az=122.80;
                        bz=0.94470;
                    elseif((x >= 100) && (x < 150))
                        az=158.08;
                        bz=1.0542;
                    elseif((x >= 150) && (x < 200))
                        az=170.220;
                        bz=1.0932;
                    elseif((x >= 200) && (x < 250))
                        az=179.52;
                        bz=1.1262;
                    elseif((x >= 250) && (x < 300))
                        az=217.41;
                        bz=1.2644;
                    elseif((x >= 300) && (x < 400))
                        az=258.89;
                        bz=1.4094;
                    elseif((x >= 400) && (x < 500))
                        az=346.75;
                        bz=1.7283;
                    elseif((x >= 500) && (x < 3110))
                        az=453.85;
                        bz=2.1166;
                    elseif(x > 3110)
                        az=5000;
                        b=0;
                    end
                end
                if(SC == 'B')
                    if(x < 200)
                        az=90.673;
                        bz=0.93198;
                    elseif((x >= 200) && (x < 400))
                        az=98.483;
                        bz=0.98332;
                    elseif((x >= 400) && (x < 200))
                        az=109.300;
                        bz=1.09710;
                    end
                end
                if(SC == 'C')
                    az=61.141;
                    bz=0.91465;
                end
                if(SC == 'D')
```

```
    if(x < 300)
        az=34.459;
        bz=0.86974;
    elseif((x >= 300) && (x < 1000))
        az=32.093;
        bz=0.81066;
    elseif((x >= 1000) && (x < 3000))
        az=32.093;
        bz=0.64403;
    elseif((x >= 3000) && (x < 10000))
        az=33.504;
        bz=0.60486;
    elseif((x >= 10000) && (x < 30000))
        az=36.65;
        bz=0.56589;
    elseif((x >= 30000))
        az=44.053;
        bz=0.51179;
    end
end
if(SC == 'E')
    if(x < 100)
        az=24.26;
        bz=0.8366;
    elseif((x >= 100) && (x < 300))
        az=23.331;
        bz=0.81956;
    elseif((x >= 300) && (x < 1000))
        az=21.628;
        bz=0.7566;
    elseif((x >= 1000) && (x < 2000))
        az=21.628;
        bz=0.63077;
    elseif((x >= 2000) && (x < 4000))
        az=22.534;
        bz=0.57154;
    elseif((x >= 4000) && (x < 10000))
        az=24.703;
        bz=0.50527;
    elseif((x >= 10000) && (x < 20000))
        az=26.97;
        bz=0.46713;
    elseif((x >= 20000) && (x < 40000))
        az=35.42;
        bz=0.37615;
    elseif((x >= 40000))
        az=47.618;
        bz=0.29592;
    end
end
if(SC == 'F')
    if(x < 200)
        az=15.209;
        bz=0.81558;
    elseif((x >= 200) && (x < 700))
        az=14.457;
        bz=0.78407;
    elseif((x >= 700) && (x < 1000))
        az=13.953;
        bz=0.68465;
    elseif((x >= 1000) && (x < 2000))
        az=13.953;
        bz=0.63227;
    elseif((x >= 2000) && (x < 3000))
        az=14.823;
        bz=0.54503;
    elseif((x >= 3000) && (x < 7000))
        az=16.187;
        bz=0.4649;
    elseif((x >= 7000) && (x < 15000))
        az=17.836;
```

```
                    bz=0.41507;
                elseif((x >= 15000) && (x < 30000))
                    az=22.651;
                    bz=0.32681;
                elseif((x >= 30000) && (x < 60000))
                    az=27.074;
                    bz=0.27436;
                elseif(x > 60000)
                    az=34.219;
                    bz=0.21716;
                end
            end
            sigz=az*(x/1000)^bz;
        end
        Zterm=(exp(-0.5*(((H-z)/sigz)^2))+exp(-0.5*(((H+z)/sigz)^2)));
        C(k)=(Q/(2*pi*u*sigy*sigz))*(exp(-0.5*((y/sigy)^2)))*Zterm;
        if((C(k)< 100e-6) && (CS == 0))
            CS=x
        end
        if((C(k)< 190e-6)&& (CP == 0))
            CP=x
        end

    end
    C(402), C(804), C(1206), C(1608) %Concentration at quarter mile
                                       % intervals up to a mile.
elseif(SimType == '2D')
    for k=1:3500
        for j=1:500
            y=j-250;
            x=100+k;
            if(model == 'Briggs')
                sigy=a*x*(1+b*x)^0.5;
                sigz=c*x*(1+d*x)^0.5;
            elseif(model == 'Martin')
                sigy=a*(x/1000)^b;
                sigz=c*((x/1000)^d)-f;
            elseif(model == 'Pasqui')
                sigy=(k1*(x))/((1+((x)/k2))^k3);
                sigz=(k4*(x))/((1+((x)/k2))^k5);
            elseif(model == 'PasGif')
                TH=0.017453293*(c-d*log(x/1000));
                sigy=465.11626*(x/1000)*tan(TH);
                if(SC == 'A')
                    if(x < 100)
                        az=122.80;
                        bz=0.94470;
                    elseif((x >= 100) && (x < 150))
                        az=158.08;
                        bz=1.0542;
                    elseif((x >= 150) && (x < 200))
                        az=170.220;
                        bz=1.0932;
                    elseif((x >= 200) && (x < 250))
                        az=179.52;
                        bz=1.1262;
                    elseif((x >= 250) && (x < 300))
                        az=217.41;
                        bz=1.2644;
                    elseif((x >= 300) && (x < 400))
                        az=258.89;
                        bz=1.4094;
                    elseif((x >= 400) && (x < 500))
                        az=346.75;
                        bz=1.7283;
                    elseif((x >= 500) && (x < 3110))
                        az=453.85;
                        bz=2.1166;
                    elseif(x > 3110)
                        az=5000;
                        b=0;
```

```
    end
end
if(SC == 'B')
    if(x < 200)
        az=90.673;
        bz=0.93198;
    elseif((x >= 200) && (x < 400))
        az=98.483;
        bz=0.98332;
    elseif((x >= 400) && (x < 200))
        az=109.300;
        bz=1.09710;
    end
end
if(SC == 'C')
    az=61.141;
    bz=0.91465;
end
if(SC == 'D')
    if(x < 300)
        az=34.459;
        bz=0.86974;
    elseif((x >= 300) && (x < 1000))
        az=32.093;
        bz=0.81066;
    elseif((x >= 1000) && (x < 3000))
        az=32.093;
        bz=0.64403;
    elseif((x >= 3000) && (x < 10000))
        az=33.504;
        bz=0.60486;
    elseif((x >= 10000) && (x < 30000))
        az=36.65;
        bz=0.56589;
    elseif((x >= 30000))
        az=44.053;
        bz=0.51179;
    end
end
if(SC == 'E')
    if(x < 100)
        az=24.26;
        bz=0.8366;
    elseif((x >= 100) && (x < 300))
        az=23.331;
        bz=0.81956;
    elseif((x >= 300) && (x < 1000))
        az=21.628;
        bz=0.7566;
    elseif((x >= 1000) && (x < 2000))
        az=21.628;
        bz=0.63077;
    elseif((x >= 2000) && (x < 4000))
        az=22.534;
        bz=0.57154;
    elseif((x >= 4000) && (x < 10000))
        az=24.703;
        bz=0.50527;
    elseif((x >= 10000) && (x < 20000))
        az=26.97;
        bz=0.46713;
    elseif((x >= 20000) && (x < 40000))
        az=35.42;
        bz=0.37615;
    elseif((x >= 40000))
        az=47.618;
        bz=0.29592;
    end
end
if(SC == 'F')
    if(x < 200)
```

```
                        az=15.209;
                        bz=0.81558;
                    elseif((x >= 200) && (x < 700))
                        az=14.457;
                        bz=0.78407;
                    elseif((x >= 700) && (x < 1000))
                        az=13.953;
                        bz=0.68465;
                    elseif((x >= 1000) && (x < 2000))
                        az=13.953;
                        bz=0.63227;
                    elseif((x >= 2000) && (x < 3000))
                        az=14.823;
                        bz=0.54503;
                    elseif((x >= 3000) && (x < 7000))
                        az=16.187;
                        bz=0.4649;
                    elseif((x >= 7000) && (x < 15000))
                        az=17.836;
                        bz=0.41507;
                    elseif((x >= 15000) && (x < 30000))
                        az=22.651;
                        bz=0.32681;
                    elseif((x >= 30000) && (x < 60000))
                        az=27.074;
                        bz=0.27436;
                    elseif(x > 60000)
                        az=34.219;
                        bz=0.21716;
                    end
                end
                sigz=az*(x/1000)^bz;
            end
        Zterm=(exp(-0.5*(((H-z)/sigz)^2))+exp(-0.5*(((H+z)/sigz)^2)));
        C(j,k)=(Q/(2*pi*u*sigy*sigz))*(exp(-0.5*((y/sigy)^2)))*Zterm;
        end
    end
end
ws=u*2.23694    % Wind speed converted to mph from meters/sec.

if(SimType == '2D') % The following code creates 2-D arrays with plume
    PlumeP=C;       % profiles. PlumeP sets the level to zero after the
    PlumeS=C;       % concentration falls below the primary level of
    for k=1:3500    % 100 ppb NOx. PlumeS does the same for the secondary
        for j=1:500 % level of 53 ppb NOx.
            if(C(j,k)<99.3e-6)
                PlumeS(j,k)=0;
            end
            if(C(j,k)<190e-6)
                PlumeP(j,k)=0;
            end
        end
    end
end
```

Appendix 2

Exposure Limit	Limit Values	HE Codes	Health Factors and Target Organs
OSHA Permissible Exposure Limit (PEL) - General Industry See 29 CFR 1910.1000 Table Z-1	5 ppm (9 mg/m^3) Ceiling	HE10	Chronic bronchitis, emphysema
		HE15	Eye, nose, and upper respiratory irritation
OSHA PEL - Construction Industry See 29 CFR 1926.55 Appendix A	5 ppm (9 mg/m^3) Ceiling	HE10	Chronic bronchitis, emphysema
		HE15	Eye, nose, and upper respiratory irritation
OSHA PEL - Shipyard Employment See 29 CFR 1915.1000 Table Z-Shipyards	5 ppm (9 mg/m^3) Ceiling	HE10	Chronic bronchitis, emphysema
		HE15	Eye, nose, and upper respiratory irritation
National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL)	1 ppm (1.8 mg/m^3) STEL	HE7	Mild headache
		HE10	Bronchiolitis obliterans
		HE11	Acute pulmonary edema; lower respiratory irritation (cough, dyspnea)
		HE15	Eyes, nose, and throat irritation
American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) (2012)	0.2 ppm (0.38 mg/m^3) TWA A4	HE11	Lower respiratory irritation
CAL/OSHA PEL	1 ppm (1.8 mg/m^3) STEL		