Dependence of maximum concentration from chemical accidents on release duration

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Abstract

Chemical accidents often involve releases of a total mass, Q , of stored material in a tank over a time duration, t_d , of less than a few minutes. The value of t_d is usually uncertain because of lack of knowledge of key information, such as the size and location of the hole and the pressure and temperature of the chemical. In addition, it is rare that eyewitnesses or video cameras are present at the time of the accident. For inhalation hazards, serious health effects (such as damage to the respiratory system) are determined by short term averages (< 1 minute) of concentrations, C . It is intuitively obvious that, for a ground level source and with all conditions the same (e.g., the same mass Q released), the maximum C near the source will be larger for a shorter than a longer release duration, t_d . This paper investigates the variation with downwind distance, x , of the ratio of maximum C for two time durations of release. Some simplified formulas for dispersion from finite duration releases are presented based on dimensional analysis. A primary dimensionless number of importance is the ratio of the release duration, t_d , to the travel time $t_t = x/u$, at distance, x , where u is wind speed. Examples of applications to pressurized liquefied chlorine releases from tanks are given, focusing on scenarios from the Jack Rabbit I (JR I) field experiment. The analytical calculations and the predictions of the SLAB dense gas dispersion model agree that the ratio of maximum C for two different t_d 's is greatest (as much as a factor of ten) near the source. At large

distances (beyond a few km for the JR I scenarios), where t_i exceeds both t_d 's, the ratio of maximum C approaches unity.

Key Words: chemical accidents; chlorine; puff dispersion; plume dispersion; Jack Rabbit field experiment; effects of release duration

1. Background

Many hazardous gas releases from valve breaks or tank ruptures have a finite time duration, t_d , on the order of a few seconds to several minutes (CCPS/AIChE, 1996). The total mass of material, Q , in the tank or in the pipe is given. A number of dispersion models are available as software packages to assess the downwind concentrations resulting from these releases. For example, Hanna et al. (2008) compared the predictions of six of the more widely-used models using inputs from three major chlorine railcar accidents (Festus, Macdona, and Graniteville). For these large (10 to 50 ton) releases of chlorine, the important averaging times, T_a , for concentration, C , are a few minutes or less, since more serious health effects occur at such small T_a (Sommerville et al., 2007). One way to determine the variation in maximum concentration C with t_d for a given scenario is a brute force method involving running a model many times using a range of values of t_d and then choosing the maximum. This can be very time-consuming. A better way to determine the variations in maximum C with t_d is to carry out a set of controlled field experiments with side-by-side (but non-interfering) releases with everything the same except t_d . But field experiments with hazardous substances are expensive and it is difficult to

accumulate enough trials under the same conditions required to produce a statistically significant conclusion.

The current paper approaches the estimation of the variation of maximum C with release duration, t_d , by using fundamental similarity formulas for continuous plume dispersion, relative (puff) dispersion, and finite duration releases (e.g., Taylor 1921, Batchelor 1950, Pasquill 1974). These formulas can be written as one-line analytical expressions that can be easily manipulated to show how the maximum C varies as t_d and other inputs vary. Two Jack Rabbit I (JR I) chlorine field experiment trials (see Fox and Storwold 2011 and Hanna et al. 2012) are used as test cases.

It is assumed in the derivations in Section 3 that the fundamental release process (e.g., dense momentum jet, evaporation from liquid pool) is unchanged when comparing concentrations for two values of release duration, t_d . This assumption may not be valid for some release scenarios, such as an initial strong two-phase momentum jet, which may have significant rain-out (deposition of liquid to the surface) and a subsequent period of evaporative release from the liquid pool. In this case the entrainment rates and other processes are different for the two segments of the release.

In the case of flammables, where the concentrations of interest (e.g., LFLs) are a few percent, the results in this paper are valid in the near field as long as the t_d 's of interest are associated with the same general release scenario.

If the initial release scenario involves an instantaneous explosion, the concept of two different t_d 's is irrelevant, since t_d is always near zero and will be much smaller than the travel times to any distance of interest.

2. Overview of similarity theory of puffs and continuous plumes

In the days before computers, scientists put much thought into the derivation of analytical formulas to describe physical phenomena such as the transport and dispersion of materials released into the boundary layer of the atmosphere. Examples are the seminal papers by Taylor (1921) on dispersion of continuous plumes (one-particle dispersion) and Batchelor (1950) on puffs (two-particle or relative dispersion). Pasquill (1974) reviews this literature and unifies the theory so that it can be applied to time-variable releases, given knowledge of analytical formulas for the spectrum of boundary layer turbulence.

The atmospheric boundary layer is always turbulent and contains a wide spectrum of space or time scales. The material from any type of pollutant release encounters this full spectrum of motion. Depending on the duration of the release, t_d , and its initial size, σ_o , different ranges of this full spectrum have more influence on the turbulent dispersion of the material. Turbulent eddies with sizes much larger than the cloud (plume or puff) do not contribute much to the internal cloud dispersion, since all they do is move the cloud around bodily (e.g., a meandering plume). Pasquill (1974) points out that the range of turbulent eddy scales that affect the dispersion can be understood as a "window", in analogy with signal theory, described as high-pass and low-pass filters.

Gifford (1968) and Hanna et al. (1982) comment that the instantaneous cloud width of a continuous release seen in a downward pointing snapshot at a given downwind distance can be considered equivalent to the width of a single puff at that distance. If more snapshots were taken of the plume in rapid sequence over an averaging time period of T_a , and all snapshots laid on top of each other, the width of the averaged plume will gradually increase as T_a increases. When a large number of cases are considered, the dispersive spread (width) of a time-averaged plume at a given downwind distance is always larger than or equal to the dispersive spread (width) of an instantaneous puff at that distance. Gifford (1968) and Hanna et al. (1982, see Fig. 6.4) present observations of puff and plume widths that demonstrate this difference. The observations show that, depending on the initial cloud size, the wind speed, and the stability, the width of the puff could be as small as 10 % of the width of the continuous plume at positions not far from the source.

Batchelor (1950) used similarity theory to suggest a simple relation for the growth of the standard deviation, σ , of a spherical puff. The puff size, as denoted by σ (m), is assumed to increase with time due to turbulence in the inertial subrange, which can be characterized by the eddy dissipation rate ε (m^2/s^3). The variation of σ with travel time, t , is then given by:

$$\sigma^2 = c \varepsilon t^3 \quad (1)$$

where c is a non-dimensional constant that has been determined to be in the range from 0.5 to 2 based on comparisons with field observations.

The Taylor (1921) equation for the growth of continuous plumes is widely used as the basis for current Lagrangian particle dispersion models. It assumes a Lagrangian turbulent time scale of T_L , and gives σ proportional to t at $t \ll T_L$ and σ proportional to $t^{1/2}$ at $t \gg T_L$. Thus, based on the Batchelor (1950) and Taylor (1921) equations, at small to intermediate times of travel, the puff σ is growing at a greater rate (proportional to $t^{3/2}$) than the continuous plume σ (proportional to t). As mentioned above, the puff σ starts out smaller but asymptotically approaches the plume σ at large times of travel.

Gifford et al. (1985, 1988) show that the transition in the Taylor (1921) equation to a σ proportional to $t^{1/2}$ regime at large travel times or distances seldom occurs in the many sets of atmospheric observations that they analyzed of horizontal dispersion at scales from 20 to 2000 km (meso to regional scales). They conclude that there are significant magnitudes of horizontal turbulent variations at large time scales (from a few hours up to a day or more). This presence of ever-larger scales of motions causes the lateral standard deviation, σ_y , to continue to increase in proportion to t and not drop off to a $t^{1/2}$ relation.

The vertical dispersion, σ_z , is more strongly influenced than σ_y by stability and by the presence of capping inversions (at the top of the boundary layer or at the tropopause), which limit the vertical extent to which plume or puff material can be spread by turbulent mixing. The daytime boundary layer mixing depth is usually about 1 or 2 km and the tropopause is usually at a height of about 10 to 15 km. But during the daytime, at times less than about 30 min and distances less than a few km, before the cloud has dispersed throughout the mixed layer, the puff and plume σ_z 's follow similar relations as described above for σ_y .

3. Analytical dispersion formulas for puffs and continuous plumes

We are searching for simple analytical dispersion models that can be manipulated to study the ratio of the arc-maximum cloud centerline concentrations predicted for a given scenario for two different release durations, t_{d1} and t_{d2} , where $t_{d1} < t_{d2}$. We shall assume that the total mass of the release, Q , is constant. This would be consistent with a tank of chlorine where different hole sizes lead to different release durations.

To guide our analysis, we use the Buckingham pi theorem, which states that, given a scientific problem with N variables and with M units (e.g., time in s, distance in m), then $N-M$ independent dimensionless numbers can be created to describe the solution. Our current problem concerns the arc-maximum concentration, C , at downwind distance, x , for wind speed, u , for two different release duration times, t_{d1} and t_{d2} . The averaging time of the concentrations is assumed to be less than t_{d1} and t_{d2} . It is assumed that the initial cloud standard deviation is σ_o . Thus we have 7 variables (C_{td1} , C_{td2} , t_{d1} , t_{d2} , x , u , σ_o) and 3 units (m, s, and g), suggesting that there are $7 - 3 = 4$ independent combinations of dimensionless variables. Consequently, an option for the final equation could have the following dimensionless form:

$$C_{td2}/C_{td1} = f(t_{d1}/t_{d2}, x/ut_{d2}, \sigma_o/ut_{d2}) \quad (2)$$

Note that the ratio x/u defines the travel time, t_t , from the source to the distance x .

Gaussian distributions of concentrations are assumed. The release is assumed to be at ground level and so also is the receptor location. Since we are searching for maximum concentrations, C (g/m^3) at given downwind distances or times, the formula for concentrations applies to the plume or puff centerline (or arc-maximum). The well-known Gaussian formulas for ground-level centerline concentration for continuous plumes and for instantaneous puffs are:

$$\text{continuous plume} \quad C = (Q/t_d)/(\pi u \sigma_{yc} \sigma_{zc}) \quad (3)$$

$$\text{instantaneous puff} \quad C = 2Q/((2\pi)^{3/2} \sigma_{xi} \sigma_{yi} \sigma_{zi}) \quad (4)$$

For the current problem, wind speed, u (m/s), is assumed to apply at a height of 2 m. The lateral and vertical dispersion parameters, σ_y and σ_z , were discussed above, where it was shown that those for instantaneous puffs are always smaller or equal to those for continuous plumes. The along-wind dispersion parameter, σ_x , is important only if the cloud has a finite duration release. It is irrelevant for continuous plumes, whose back end is always at the source location, and whose front end extends indefinitely past the receptor location.

For clouds with significant excess density, the vertical spread (i.e., σ_z) is inhibited and the lateral horizontal spread (i.e., σ_y) is enhanced (see Briggs et al. 2001 and Hanna and Chang 2001). Hanna et al. (1993) and Hanna and Chang (2001) find that, when compared with neutral or passive gas dispersion, the reduction in σ_z due to density effects is approximately balanced by the enhancement in σ_y . Thus the product $\sigma_y \sigma_z$ is unchanged as density increases and hence, for continuous plumes, the predicted concentration is unchanged (see Eq. (3)). We will make use of

this finding in later paragraphs. For puffs, where along-wind dispersion, σ_x , is included, there will be an increase in σ_x in dense clouds near the source that could reduce the maximum concentration for dense gases compared with neutral gases.

Britter and McQuaid (1988) point out that, if $t_d \gg t_t$ (or x/u), the cloud is essentially a continuous plume, and if $t_d \ll t_t$, then the cloud can be thought of as a puff. When t_d and t_t are of the same order, the cloud is shaped like a “slug”, with an elongated central part associated with the release duration t_d and of length about ut_d , and with Gaussian-shaped back and front ends of length and shape determined by σ_x . This shape function with a central core and Gaussian edges was also suggested by Colenbrander (1980) for lateral distributions in dense gas clouds resulting from finite duration evaporation of liquid pools, and used as a basis for the widely-used SLAB model by Ermak (1990). For the slug scenario with finite t_d , we rewrite Eq. (4) as

$$\text{instantaneous slug} \quad C = Q/(\pi(ut_d + (2\pi)^{1/2}\sigma_{xi})\sigma_{yi}\sigma_{zi}) \quad (5)$$

This solution approaches the instantaneous puff solution (Eq. (4)) for $ut_d \ll \sigma_{xi}$. The solution approaches the continuous plume solution (Eq. (3)) for $ut_d \gg \sigma_{xi}$, assuming that $\sigma_i = \sigma_c$. To simplify the derivations, we drop the i and c subscripts and just use the symbols σ_x , σ_y , and σ_z .

The interpretation of the appropriate averaging times, T_a , for determination of the dispersion parameters becomes complicated for finite duration releases. Since the slug in the Eq. (5) formulation is assumed to be an entity with a central core, there is an implied averaging time of t_d .

Our main concern in this paper is the ratio of the arc-maximum centerline concentration, C , for two different scenarios with different release time durations, t_{d1} and t_{d2} , and everything else the same. Eq. (5) can be used to calculate this ratio:

$$C(t_{d2})/C(t_{d1}) = (ut_{d1} + (2\pi)^{1/2}\sigma_x)/(ut_{d2} + (2\pi)^{1/2}\sigma_x) \quad (6)$$

The along-wind dispersion coefficient σ_x is a function of the along-wind turbulence intensity σ_u/u , the distance x , and a measure of the integral turbulence scale. However, as mentioned earlier, Gifford et al. (1988) found that the horizontal cloud size continues to increase linearly out to travel distances much beyond 2000 km. Thus for the current purposes, we assume the general relation found by Hanna and Franzese (2000), who analyzed many field data sets involving puff releases during the daytime with moderate winds:

$$\sigma_x = 0.1x \quad (7)$$

In reality, nearly all accidental hazardous gas releases have an initial size, defined by σ_o . Thus

$$\sigma_x = \sigma_o + 0.1x \quad (8)$$

As mentioned earlier, the initial rate of horizontal spread of a dense gas cloud is larger than that of a neutral cloud. As travel time increases, and concentrations decrease, all clouds become

effectively neutral. Here we assume that Eq. (8) is valid for all densities, and the dense gas effects can be accounted for by increasing σ_o . Substituting Eq. (8) into Eq. (6), we obtain:

$$C(t_{d2})/C(t_{d1}) = (ut_{d1} + 2.5(\sigma_o + 0.1x))/(ut_{d2} + 2.5(\sigma_o + 0.1x)) \quad (9)$$

Since x/u is simply the travel time, t_t , from the source to the position x , Eq. (9) can be written:

$$C(t_{d2})/C(t_{d1}) = (ut_{d1} + 2.5(\sigma_o + 0.1ut_t))/(ut_{d2} + 2.5(\sigma_o + 0.1ut_t)) \quad (10a)$$

or

$$C(t_{d2})/C(t_{d1}) = (t_{d1}/t_{d2} + 2.5(\sigma_o/(ut_{d2}) + 0.1t_t/t_{d2}))/ (1 + 2.5(\sigma_o/(ut_{d2}) + 0.1t_t/t_{d2})) \quad (10b)$$

Thus Eq. (10b) has the format suggested by the dimensionless Eq. (2) [$C_{d2}/C_{d1} = f(t_{d1}/t_{d2}, t_t/t_{d2}, \sigma_o/ut_{d2})$].

The near-field limiting solution of this equation is $C(t_{d2})/C(t_{d1}) = (t_{d1}/t_{d2} + 2.5\sigma_o/ut_{d2})/(1 + 2.5\sigma_o/ut_{d2})$. For situations where σ_o/ut_{d2} and σ_o/ut_{d1} are $\ll 1$, $C(t_{d2})/C(t_{d1}) = t_{d1}/t_{d2}$ (since for continuous source releases, the release rate $= Q/t_d$). The far-field limiting solution of the equation is $C(t_{d2})/C(t_{d1}) = 1$, since as travel time increases, the cloud σ_x increases so that eventually it becomes much larger than either ut_{d1} or ut_{d2} and both clouds are effectively “puffs” of nearly the same size.

Following the general formulation of the dimensional analysis in Eq. (2), we prepared the example nomogram in **Fig. 1**. Since a complete solution to Eq. (10b) would require a three-

dimensional plot, our example nomogram assumes a value of $\sigma_o/ut_{d2} = 0.0125$ (i.e., the release duration t_{d2} equals 80 times the time taken for the air to traverse a distance σ_o). σ_o/ut_{d2} was close to 0.0125 during Trials 2 and 6 at the Jack Rabbit I field experiment involving releases of pressurized liquefied chlorine discussed in the next section. Note that the vertical axis in **Fig. 1** is t_{d1}/t_{d2} and the horizontal axis is $t_t/t_{d2} (= x/(ut_{d2}))$. For the JR I field trials involving releases of pressurized liquefied chlorine from a hole in a one or two ton tank, there is uncertainty regarding the value of t_d , since the videos did not show a sharp cessation of the two-phase jet, and some of the dense chlorine cloud remained in the depression around the source and was subsequently detrained into the ambient air flow. The following asymptotes are seen on the figure: 1) as t_{d1}/t_{d2} approaches unity, $C(t_{d2})/C(t_{d1})$ approaches unity; and 2) as t_t/t_{d2} increases, the ratio $C(t_{d2})/C(t_{d1})$ approaches unity. The latter fact was previously explained as being the result of the fact that both clouds are effectively puffs of the same size at such large times or distances.

Fig. 1. Contours of the $C(t_{d2})/C(t_{d1})$ solution to Eq. 10b for $\sigma_o/ut_{d2} = 0.0125$.

4. Application to the Jack Rabbit I field experiment

The 2010 Jack Rabbit I (JR I) field experiment provides some useful observations for testing the above formulations. In JR I, releases of one or two tons of pressurized liquefied chlorine or anhydrous ammonia took place over the flat desert at Dugway Proving Ground, Utah, USA. Fox and Storwold (2011) provide a detailed description of the JR I experiment and Hanna et al. (2012, 2016) describe analyses of the downwind dispersion observations. A depression (basin) 50 m in diameter and 2 m deep was dug in the desert surface. A two-ton tank was placed in the center of the depression, with a release valve, with diameter 8 cm, located at the bottom of the tank about 2 m above ground (see **Fig. 2**). The jet was intentionally directed downwards, to maximize the near-field cloud impact. Releases took place just after dawn on clear summer mornings, when the ambient atmosphere was stable. Wind speeds during the five chlorine trials were usually low (about 2 m/s or less), except for one trial with 6.2 m/s. The downward pointing jet and the depression would tend to keep the chlorine close to the source location for as long as possible, especially during periods with light winds.

In the five JR I experiment trials involving chlorine, the tank emptied in about 30-60 s, with a powerful momentum jet seen on the videos. The flashing near the valve resulted in a two phase mixture containing about 20 % vapor and 80 % liquid (by mass), with the liquid in the form of small drops with diameters likely in the range from about 20 to 100 μm . As described by Hanna et al. (2012), a significant fraction of the airborne mass (gas and small aerosol mixture) that was

released did not initially escape the depression (i.e., it was “held-up”) when the ambient wind speed was less than 2 or 3 m/s. **Fig. 2** contains two photographs of the cloud during Trial 2, which had the smallest wind speed, 0.6 m/s, during JR I. The top photograph shows the initial momentum jet, which lasted about 30 s, and the bottom photograph illustrates the calm dense cloud held-up in the depression. The videos show that the chlorine gas was subsequently detrained into the overlying ambient flow over a time period of about 32 min (1920 s) for this Trial. Thus, from the point of view of transport and dispersion in the overlying ambient boundary layer, the release duration time, t_d , for Trial 2 was actually 1920 s, even though most of the chlorine was released from the tank in only 30 s.

Fig. 2. Jack Rabbit I Trial 2 ($u = 0.6$ m/s) visible chlorine cloud behavior at 22 s (top) and at 180 s (bottom) after the release began. The pressurized release from the tank ceased at about 30 s.

Another of the JR I chlorine trials (Trial 6) took place during a period with larger ambient wind speeds (6.2 m/s) and minimal “hold-up” in the depression was observed in that case (see **Fig. 3**). The chlorine cloud appeared as a typical plume that moved off downwind. This behavior agreed with fundamental theory for detrainment of dense clouds held up in a depression (Hanna et al., 2012). In this case, the videos of the jet suggest that t_d is about 30 to 60 s, with some uncertainty concerning the time that the jet release ended.

Fig. 3. Jack Rabbit I Trial 6 ($u = 6.2$ m/s) visible chlorine cloud behavior at 34 s after the release began.

In the next section we apply Eq. (10b) to JR I Trials 2 and 6. We also compare the results for Trial 6 with calculations by the widely-used dense gas dispersion model, SLAB (Ermak, 1990).

5. Effects of duration of release on JR I Trial 2 and 6 simulated concentrations

As discussed above, JR I trial 2 had the lowest wind speed, 0.6 m/s, of all the trials. Consider two possible assumptions for release duration – t_{d1} of 30 s (corresponding to the time taken to empty the tank and the duration of the strong two-phase momentum jet), and t_{d2} of 1920 s (corresponding to the time taken for all the gas in the depression to be entrained into the overriding ambient air; see Hanna et al., 2012). Assume that the initial standard deviation σ_o , is

14.4 m (the standard deviation of a uniform distribution over the 50 m width of the depression seen in **Fig. 2**). Intuitively, it is expected that concentrations will be larger for the smaller t_d than for the larger t_d , since the mass emission rate is larger for the smaller t_d . The analytical Eq. (10b) yields the results listed in **Table 1** for the ratios of the concentrations for the $t_{d1} = 30$ s and the $t_{d2} = 1920$ s release.

As suggested in the previous section, Table 1 shows that the calculated (analytical) ratio $C(t_{d2} = 1920 \text{ s})/C(t_{d1} = 30 \text{ s})$ is smallest (about 0.05 in this case) at the edge of the depression ($x = 25$ m) and slowly approaches unity at large distances. Eq. (10b) suggests that, at small distances, where t_{d1} has a large influence, for all other conditions the same, the concentration ratios are approximately proportional to t_{d1} . For example, for $t_{d1} = 15$ s instead of 30 s, the ratio in Table 1 at $x = 25$ m would decrease by almost a factor of $30\text{s}/15\text{s} = 2$.

Table 1. Analytical ratios of concentrations for $t_{d2} = 1920$ s release to concentrations for $t_{d1} = 30$ s release for JR I Trial 2 scenario ($u = 0.6$ m/s and $\sigma_o = 14.4$ m).

x (m)	$C(t_{d2} = 1920 \text{ s})/C(t_{d1} = 30 \text{ s})$
	<u>analytical solution</u>
25	0.051
50	0.054
100	0.065
200	0.084
500	0.136
1000	0.211
2000	0.328
5000	0.535
10000	0.694

Note that, for the two Trial 2 t_d values considered in **Table 1**, the distance at which $t_d = t_t$ is 18 m for the $t_{d1} = 30$ s case and is 1152 m for the $t_{d2} = 1920$ s case. This is the distance where the length of the central core or slug (ut_d) equals the downwind distance, x , and can be thought of as where the cloud is transitioning from being “like a plume” to being “like a puff”.

For Trial 2, $\sigma_o/ut_{d2} = 0.0125$, which is the value assumed in preparing the nomogram in Fig. 1. The solution for Trial 2 on Fig. 1 would be a horizontal line at $t_{d1}/t_{d2} = 0.0156$. The four order of magnitude range in t_t/t_{d2} on the horizontal axis corresponds to downwind distances from 11.5 m to 115 km.

The analytical Eq. (10b) was also applied to JR I Trial 6, where the wind speed was relatively large (6.2 m/s) and there was much less “hold-up” in the depression. Still, there was about a factor of two uncertainty in the duration of the release (from $t_{d1} = 30$ to $t_{d2} = 60$ s), based on review of the videos. As seen in **Fig. 3** for Trial 6, the initial cloud spread σ_o is smaller than seen in **Fig. 2** for Trial 2. We assume that σ_o is 5 m for Trial 6. **Table 2** contains the Eq. (10b) estimates of the concentration ratio for these t_d options and for $u = 6.2$ m/s and $\sigma_o = 5$ m. Here the ratio is larger (closer to unity) than in **Table 1**, because the difference between the two t_d values is smaller. The analytical formula predicts a ratio of 0.52 at the edge of the depression ($x = 25$ m) and a ratio of 0.94 at a distance of 10 km. The SLAB dense gas model predictions of the concentration ratios for $t_{d1} = 30$ s and $t_{d2} = 60$ s are also listed in **Table 2**, and are consistently only about 10 % smaller than the ratios calculated with the analytical formula. Note that the

analytical and SLAB solutions in the near-field are close to 0.5, which is the asymptotic limit of Eq. (10b) for $t_{d1} = 30$ and $t_{d2} = 60$ s.

Table 2. Analytical and SLAB modeled ratios of concentrations for $t_{d2} = 60$ s release to concentrations for $t_{d1} = 30$ s release for JR I Trial 6 scenario ($u = 6.2$ m/s and $\sigma_o = 5$ m).

x (m)	C($t_{d2} = 60$ s)/C($t_{d1} = 30$ s)	
	<u>analytical</u>	<u>SLAB</u>
25	0.52	0.47
50	0.53	0.47
100	0.55	0.47
200	0.57	0.49
500	0.64	0.60
1000	0.72	0.68
2000	0.79	0.71
5000	0.89	not available
10000	0.94	not available

The nomogram in Figure 1 has been prepared assuming a value of 0.0125 for σ_o/ut_{d2} . For trail 6, $\sigma_o/ut_{d2} = 0.0134$, which is close enough to the value assumed for Figure 1 that we can assume that the nomogram can be applied to Trial 6. The solution for Trial 6 would therefore be the horizontal line at $t_{d1}/t_{d2} = 0.5$ in Figure 1, and the four orders of magnitude on the abscissa would represent downwind distances from 3.8 m to 37.8 km.

Observations of arc-maximum observed concentrations during Trial 6 are compared with SLAB predictions for $t_{d1} = 30$ and $t_{d2} = 60$ s in **Fig. 4**. As suggested by comparing the analytical

formula and SLAB concentration ratios listed in **Table 2**, the fractional difference in the SLAB predictions for $t_{d1} = 30$ and $t_{d2} = 60$ s are seen to gradually decrease as distance increases. At large distances, both clouds are dispersing essentially as puffs, since $t_t = x/u \gg t_d$ for both release durations.

Fig. 4. Concentrations predicted by SLAB for JR I Trial 6 for $t_d = 30$ s and 60 s, compared with sampler (JAZ, Canary, MiniRAE) observations. The SLAB predictions were used to calculate the ratios presented in **Table 2**.

6. Practical guidance and caveats

The scenario of interest in this paper is the accidental release of a pressurized liquefied gas from a hole in a storage tank or pipe. There is a fixed mass, Q , in the tank or pipe segment. In the JR I experiments, with Q of one or two tons and hole sizes of 8 to 10 cm, the initial high-momentum jet release lasts for about 30 s to 60 s. The analytical solution and the SLAB dense gas dispersion model agree that, for a constant mass released, Q , and all other conditions the same, an increase in the duration of release, t_d , can significantly decrease the predicted cloud maximum concentration in the near-field. However, for concentrations at large distances or travel times ($t_t = x/u \gg t_d$), the reductions in concentration steadily decrease. At such large distances or travel times, the cloud looks like a puff with nearly the same σ_x no matter what the release duration.

We have been assuming that the mass release occurs at ground level. Otherwise, if there is a significant stack height or plume rise (due to momentum effects), the cloud may remain aloft for a while near the source. As a result, the near-field ground-level concentrations would likely be nearly zero until the base of the elevated cloud reaches ground level farther downwind.

As discussed in the section describing differences between the cloud spreads of puffs and continuous plumes, there may be an additional increase in concentration for the case with smaller t_d due to the fact that the spread (e.g., σ_y) of a puff is less than that of a continuous plume. We have not accounted for that difference in the analytical solution. Furthermore, we have arbitrarily assumed an initial spread, σ_o , based on visual inspection of the JR I videos and photos. That assumption could have a large effect on the maximum C difference very near the source.

The analytical approach is less useful if the release scenarios are significantly different for the two t_d options (e.g., if one t_d is primarily associated with a two-phase momentum jet and the other with a liquid spill and subsequent evaporation). However, as for the examples used above, at large downwind distances, even the release scenario may become unimportant, since, for the same total mass released, the resulting cloud in either case is a well-dispersed puff and is essentially neutral or passive.

Despite the caveats, the fundamental result appears to be supported by theory and by operational model application – for typical large releases of pressurized liquefied gases, the differences in cloud centerline C due to differences in t_d are largest near the source and become insignificant at distances of 5 to 10 km and beyond.

The same general approach regarding effects of release duration would also apply to non-reactive releases of other chemicals for other scenarios and scales. The sizes of hazard areas could be vastly different depending on the magnitude of the release and the hazard threshold. For example, suppose there was a large release, near ground level, of radiological pollutants

from a nuclear power plant incident. The two release durations in question might be $t_{d1} = 6$ hours and $t_{d2} = 6$ days. Although a comprehensive modeling approach might involve a detailed numerical weather prediction model and a Lagrangian particle or puff dispersion model, a first-cut estimate of the ratios of expected arc-maximum concentrations can be made with Eq. (10b). The concentration ratio is likely to be 0.042 (6 hrs/144 hrs) at cloud travel times less than 6 hrs (or downwind distances less than 216 km for a wind speed of 10 m/s). At travel times much greater than 6 days (or distances greater than about 5200 km), the concentration ratio approaches unity.

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Fig. 1. Contours of the $C(t_{d2})/C(t_{d1})$ solution to Eq. (10b) for $\sigma_o/ut_{d2} = 0.0125$.

Fig. 2. Jack Rabbit I Trial 2 ($u = 0.6$ m/s) visible chlorine cloud behavior at 22 s (top) and at 180 s (bottom) after the release began. The pressurized release from the tank ceased at about 30 s.

Fig. 3. Jack Rabbit I Trial 6 ($u = 6.2$ m/s) visible chlorine cloud behavior at 34 s after the release began.

Fig. 4. Concentrations predicted by SLAB for JR I Trial 6 for $t_d = 30$ s and 60 s, compared with sampler (JAZ, Canary, MiniRAE) observations. The SLAB predictions were used to calculate the ratios presented in **Table 2**.

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Table 1. Analytical ratios of concentrations for $t_{d2} = 1920$ s release to concentrations for $t_{d1} = 30$ s release for JR I Trial 2 scenario ($u = 0.6$ m/s and $\sigma_o = 14.4$ m).

Table 2. Analytical and SLAB modeled ratios of concentrations for $t_{d2} = 60$ s release to concentrations for $t_{d1} = 30$ s release for JR I Trial 6 scenario ($u = 6.2$ m/s and $\sigma_o = 5$ m).