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Review of Lift-off Models for Ground Based Buoyant Clouds

A Deliverable produced under Work Package 7 of the EC URAHFREP Project, Contract No. ENV4-CT97-0630

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Executive Summary

Models of lift-off for ground based buoyant clouds have been reviewed. The aim of the review is to provide a basis for enhancing existing hydrogen fluoride dispersion models to deal with possible plume lift-off in humid conditions. This requires that the models must ultimately apply to non-buoyancy conserving flows.

Few models exist which claim to deal with lift-off of ground based buoyant releases. Much of the published modelling work relates directly to experimental studies and therefore these studies are also discussed in this report.

The simplest lift-off models are based on lift-off occurring when a suitable non-dimensional cloud parameter exceeds a given critical value. Cloud Richardson Number (Briggs 1973) based on the atmospheric friction velocity is an appropriate lift-off parameter. Experimental studies indicate that lift-off depends on such a parameter, but in a continuous, rather than abrupt manner. Lift-off parameters based on local cloud scales are most appropriate for generalisation to HF clouds.

Correlations for distance to lift-off have been reported in the literature. Such distance to lift-off correlations are discussed in the report, but unfortunately are not directly suitable for generalisation to HF clouds.

A lift-off correlation based on wind tunnel data of buoyant releases from buildings has recently been published (Hanna et al 1998). This correlation and its suitability for describing HF clouds are discussed in the report.

Other models identified in the review include a three-dimensional computational fluid dynamic model for a buoyant wall jet (Sinclair et al 1990). The empirical mixing length turbulence closure used in this model may provide insight for entrainment in an integral model.

A simple integral model (Slawson 1990) is discussed in the report which has potential for further development. The model has similarities with the airborne plume model in HGSYSTEM 3.0 (Post 1994). The enhanced mixing and lift-off modelling capability of this type of model is far from demonstrated. However, such integral models are the most readily generalisable to include HF thermodynamics.

There is we believe scope to use the existing experimental data for further developing lift-off models for inclusion in integral dispersion models. However, new experimental data will also be required, particularly relating to source conditions closer to those expected for HF releases. Additionally, data on real HF clouds in humid atmospheres are necessary, in order to check lift-off predictions of integral models using HF thermodynamics. The planned URAHFREP experiments should provide invaluable data in this respect.

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1 Introduction

Anhydrous hydrogen fluoride (HF) is widely used in the petroleum and chemical industries, most notably as a catalyst in alkylation plants. A typical accidental release of HF will form a dense cloud of HF aerosol and vapour. HF droplets are hygroscopic reacting exothermically with liquid water, whereas in the vapour phase HF molecules form associations to form simple polymers called oligomers. Simple HF thermodynamic models indicate that, under sufficiently humid conditions, the heat generated by the interaction of HF with condensed atmospheric water can lead to the cloud, or at least parts of the cloud, becoming positively buoyant. The initially dense nature of the cloud means that it is quite likely to be dispersing at ground level before sufficient heat is generated to make the cloud positively buoyant.

Dense gas releases at ground level have received considerable attention over the past 10 to 20 years, leading to much improved models which have been validated against a number of laboratory and field experiments. However, only a limited number of dispersion experiments have been performed using HF, the most notable being the Goldfish Trials conducted in the US Nevada Desert. The observed cloud behaviour appeared to be consistent with a dense dispersing cloud. However, the low ambient humidity in these trials means that they tell us little about the influence of high humidity on HF dispersion. For humid conditions, reliance has therefore been placed upon the predictions of mathematical models incorporating thermodynamic models for HF.

As already mentioned, such models predict that under quite common atmospheric humidities the cloud becomes positively buoyant. Since the models treat the heat of mixing in the liquid phase as reversible, the positively buoyant phase may only be transitory. If the HF thermodynamic models are to be believed, the question then arises how the generated positive buoyancy modifies the subsequent dispersion of the gas cloud. It is possible that sufficient buoyancy may be generated for the cloud to “lift-off” the ground. Extending risk assessment models for such conditions requires an understanding of the behaviour of buoyant clouds at ground level. As a first step to this understanding, it is appropriate to review existing models of buoyant cloud lift-off. This is the subject of this review.

Although the review is motivated by an interest in the behaviour of HF clouds, buoyant lift-off is of much wider interest, being relevant to many areas including the dispersion of:

- fire plumes,
- intrinsically lighter than air gases released at ground level,
- gas clouds which may become buoyant due to heat transfer from the ground, latent heat, radioactive decay or chemical reaction processes and even volcanic flows.

We shall therefore try to discuss lift-off models fairly generally, making reference to the suitability for generalisation to HF where appropriate.

It is intended that the results of the review, together with new experimental data from the EC URAHFREP project[1], will be used as a basis for extending current risk assessment models to include the effects of buoyant plume lift-off.

[1] The URAHFREP project aims to reduce the uncertainties in understanding the behaviour of HF accidentally released into the environment. Under URAHFREP, a number of related activities are being undertaken by the participating organisations. These activities include chamber experiments to validate HF thermodynamic models, wind tunnel studies on buoyant lift off from the ground and reduced scale field trial releases of HF under humid conditions. AEA Technology is involved in the development and validation of integral models and conducting the thermodynamic experiments.

2 Early Theoretical Work

2.1 BRIGGS LIFT-OFF CRITERION

Briggs (1973) discussed lift-off of buoyant gas released on the ground. He suggested that a good indicator for determining lift-off might be the local parameter, L_p,

$$L_p = \frac{g\Delta\rho H}{\rho_a u_*^2} \tag{1}$$

where $\Delta\rho$ is the density difference $\rho_a - \rho$ of the cloud relative to the air density, ρ_a, and H is the effective depth of the cloud layer. L_p is a Richardson number for the cloud based on the atmospheric friction velocity.

When L_p is very small, Briggs argued that the gas remains at ground level and diffuses more or less as a passive gas. At somewhat larger L_p Briggs suggested that the vertical diffusion is enhanced but that the gas remains in contact with the ground. He argued that when the buoyancy driven vertical stretching is strong enough to pull in the lateral dimension of the gas cloud faster than it diffuses outwards, then L_p will increase and most of the material will (eventually) lift-off. The value of L_p at this point where lift-off just starts to occur was referred to by Briggs as a critical lift-off number. At larger L_p there is expected to be quicker, more well defined lift-off with less residual at ground level.

In the absence of experimental data on lift-off, Briggs (1973) attempted to estimate values for the critical L_p based on simple arguments. Firstly he compared the lateral inward velocity scale resulting from the buoyancy induced forces with the velocity scale for lateral (and longitudinal in the case of a puff) wind velocity fluctuations. The critical L_p value is when the velocity scales are comparable. Secondly he compared the lateral inward velocity with the outward diffusive velocity from buoyant plume theory. Both methods gave similar estimates of $L_p \approx 2.5$ to within a factor of four, for continuous point sources (plumes).

Briggs argued that the critical value for instantaneous point sources (puffs) should be about 50% higher due to the more diffuse inflow. For an instantaneous line source he thought it should be about 50% higher due to more vigorous longitudinal than lateral turbulence. The geometry of a continuous line source perpendicular to the wind is quite different since, in order to lift off the ground, a compensating down draft must develop. Briggs argued that this would leave some residual near the ground and that L_p might indicate the fraction of buoyant material organising itself as updrafts.

Briggs himself acknowledged that these estimates of critical L_p values were highly speculative and suggested investigating the problem in a boundary layer wind tunnel. Such studies were
subsequently performed and in the light of one of these studies (see below) Briggs revised his estimate of critical lift-off number to a value of around 30.

2.2 CLOUGH, GRIST AND WHEATLEY

Clough, Grist and Wheatley (1987) discuss, on theoretical grounds, HF clouds becoming buoyant in the later stages of dilution. Like Briggs, they refer to the two possible effects

1. Coherent lift-off of the cloud as a whole in the form of a rising thermal.
2. Enhanced vertical mixing caused by localised thermal effects.

They also agree with Briggs in that they conclude that L_p, (a layer Richardson number), determines whether coherent lift-off occurs in preference to mixing by ambient turbulence. Also, on dimensional grounds, they suggest that L_p is the relevant parameter in determining the importance of enhanced vertical mixing compared with ambient turbulence.

They suggest that a necessary, but not necessarily sufficient, criterion for coherent lift-off, or indeed for any significant buoyancy effect on vertical mixing, L_p should satisfy the following inequality

$$L_p \geq \left(\frac{w'}{u_*}\right)^2 \qquad (2)$$

where *w'* is the ambient vertical turbulence velocity, u_* is the friction velocity. In neutral atmospheres w'^2/u_*^2 is of order unity. In stable atmospheres w'^2/u_*^2 is ~1/5 and in unstable atmospheres $w'^2/u_*^2 \sim 2$. Hence density effects persist longest in stable atmospheres.

We should stress that Clough, Grist and Wheatley do not claim that (2) is a criterion for lift-off, rather it just registers the fact that density effects are important by virtue of the velocity scale for buoyancy induced vertical motions being greater than the atmospheric vertical velocity fluctuations.

Since it appears from observations (see below) in neutral boundary layers that significant lift-off does not occur until L_p is significantly greater than unity (Briggs quoting critical values around 30), the inequality (2) is well satisfied.

3 Experimental Studies

3.1 MERONEY'S WIND TUNNEL STUDY

Meroney (1979) conducted a study of continuous ground based buoyant releases in a boundary layer wind tunnel. Buoyant gas (helium and air) releases were at ground level from point, area and line sources at ground level. The point source was a small diameter tube releasing gas horizontally in the downwind direction. The area source was a vertical release through a porous plate. The line source was a release from a horizontal slot in the downwind direction. The wind profile was set up to correspond to a neutrally stable boundary layer. Distance to lift-off was estimated from visual records.

The experiments were carried out in a wind tunnel 16.7 m long and 1.8 m x 1.8 m in cross section. Spires and a barrier were placed upwind of the test section, to ensure a thick turbulent boundary layer.

Photographs taken at a volumetric flow rate of Q= 708 cc/s, and reference wind velocity $\overline{u}$ = 0.76, 1.22, and 1.83 m/s clearly show the helium plume lifting off the ground at lower ambient velocities, whilst the air plume remains touching the ground.

Meroney's experiments failed to identify a single critical value of L_p below which lift-off did not occur. For point sources the critical value appeared to be between 9 and 27, whilst for line sources it lay between 4.5 and 16000. Both these ranges are above that originally proposed by Briggs (1973). Hall et al (1995) report that as a result of considering Meroney's data Briggs revised his estimate of the critical L_p value to around 20-30 (his calculation giving a value of 29).

Meroney observed that the ground based plumes travelled some distance along the ground before apparently lifting off. Meroney plotted distance to lift-off, x, non-dimensionalised by a buoyancy length scale, l_b as a function of modified Froude number, Fr_s. The data for line and area sources (see Figures 1 and 2) indicated that the lift-off distance is correlated by

$$x / l_b \approx a\, Fr_s^{3/2} \qquad (3)$$

with a=0.24. The data for point sources lies well above this line (see Figure 3), but this was thought to be a result of high jet velocities through the narrow aperture source.

The buoyancy length scale in the above is given

$$l_b = F / U^3 \qquad (4)$$

with U taken to be the windspeed at a reference height of 25cm and

$$F = g\frac{\Delta\rho_s}{\rho_a}Q_s \qquad (5)$$

is the buoyancy flux which is conserved in these experiments. Q_s is the source volumetric flow rate.

Fr_s is referred to by Meroney as a modified Froude number. As indicated by Slawson et al (1990), Fr_s may be written simply as

$$Fr_s = L_s / l_b \qquad (6)$$

where L_s is the width of the source. In this sense, Fr_s can be viewed as a non-dimensional source width.

Meroney's results for line sources and area sources fall fairly near the empirical line given by (3). However the point sources all lie significantly above the line. Meroney attributes this to the forward momentum lengthening the distance to lift off.

Meroney's measurements indicate the following qualitative trends:

- increasing the source width of the source delays lift-off,
- increasing the source buoyancy promotes lift-off,
- decreasing the wind speed promotes lift-off.

Meroney's lift-off correlation (3) implies that any buoyant plume will eventually lift-off, although this may be so far from the source that it confers little benefit in reducing ground level concentrations. Hall et al (1995) felt that the initial attachment to the ground observed in Meroney's experiments was a curious result since the greatest buoyancy force in a plume occurs at the source. Also Hall and co-workers did not observe this delayed lift-off in their experiments (the plume either lifted off initially or not at all). Initial attachment to the ground may be a result of the source conditions in Meroney's experiments. There are mechanisms that might account for this attachment, for example momentum sources are known to adhere to solid surfaces by virtue of the Coanda effect[2]. According to Poreh and Cermak (1986), Briggs suggests in an unpublished note that the observed distances to lift-off could be a result of the plume needing some vertical growth before it can develop the internal flow circulation pattern required for introducing air underneath the plume to enable it to leave the ground.

3.2 POREH AND CERMAK'S WIND TUNNEL STUDY

Poreh and Cermak (1986) measured the concentration field and apparent lift-off of continuous buoyant horizontal emissions (of helium and air) in a neutrally stable boundary layer flow in a

[2] The Coanda effect is the tendency of jets to attach themselves to nearby solid boundaries, in this case the ground. The entrainment of air into the jet is restricted on one side by the boundary. This creates a reduced pressure so that the jet attaches to the surface. The same effect encourages jets to follow curved solid boundaries rather than to readily flow off at a tangent.

wind tunnel. As discussed above, Meroney (1979) found that results from his point source results were anomalous compared with his area and line sources. The purpose of Poreh and Cermak's (1986) study was to re-examine the case of horizontal emissions from point sources near ground level.

The tests were carried out in a wind tunnel of 1.95 m x 1.95 m cross section and length 29.3 m. The tunnel floor was roughened and spires were installed at the upwind end to ensure a thick turbulent boundary layer. The source was placed 13 m downwind of the spires.

Poreh and Cermak (1986) found that the source horizontal momentum flux, as well as buoyancy flux, had a considerable effect on the behaviour of the plume. Consequently both horizontal momentum flux and buoyancy flux were systematically varied. Some tests were carried out with elevated releases to see how elevation affected lift-off. Only flow visualisation was used to compare the elevated releases with ground level releases.

The results were analysed in terms of non-dimensional buoyancy flux and momentum flux parameters (F_* and M_*). F_* was defined as

$$F_* = \frac{F}{U^3 L}$$

with the buoyancy flux, F given by

$$F = \frac{g \Delta \rho_s Q}{\rho_a \pi};$$

and the reference length, *L,* and velocity, *U,* were taken to be the turbulent boundary layer height (δ=0.9m) and the wind velocity at that height. M_* was defined as

$$M_* = \frac{M_s}{\rho_a U^2 L^2} \qquad (7)$$

where the momentum flux M_s at the source is given from the volumetric source rate Q_s, density ρ_s and area A_s as

$$M_s = \frac{\rho_s Q_s^2}{A_s} \qquad (8)$$

Some of the releases were at approximately the same dimensionless buoyancy and momentum fluxes as in Meroney's point source tests, but unfortunately the results are not compared.

From the visual records and concentration measurements the following observations are noted

- increasing F_* decreased the distance to apparent lift-off,
- increasing M_* increased the distance to apparent lift-off,
- when M_* is small the plume rise at large distances depends on the downwind distance to the 2/3 power.

Poreh and Cermak state that comparison of the elevated releases with ground based releases having the same F_* and M_* indicate that they lift-off at similar distances from the source. Here lift-off is defined from the point where the bottom edge of the visible plume crossed the release height. We find this similarity of lift-off distance for plumes from elevated and ground level releases to be somewhat surprising. All other things being equal we would expect that the influence of the ground would lengthen the distance to lift-off for a ground based source compared with an elevated source. The presence of the ground makes it more difficult to introduce air under the plume (which is generally recognised as being necessary for lift-off) and also the relative motion of the plume is expected to favour initial attachment (Coanda effect). These effects may be offset somewhat by the increase in wind velocity with height which will initially keep higher releases more nearly horizontal. The observed behaviour could be due to such a wind speed effect.

Comparisons of visualisation results with concentration measurements show that the ground level concentration is certainly not zero at the point where the plume visually appears to lift-off. However, large negative gradients in $C(z=0)/C_{max}$ were recorded near this point. Such characteristically steep gradients only occur at near and intermediate distances from the source; at larger distances the ratio was observed to be almost constant. The almost constant ratio can be understood if the vertical plume extent and rise height grow with similar powers of distance.

Poreh and Cermak found at a given fixed downwind distance (x>δ) that $C(z=0)/C_{max}$ was a function of $F_*/\sqrt{M_*}$ only, and for large values of this parameter

$$\frac{C(z=0)}{C_{\max}} \;\alpha\; \frac{M_*}{F_*^2} \tag{9}$$

C/C_{max} is hence related to a densimetric Froude number based on the diameter and density of the plume at the source and on the chosen reference velocity.

There is a mistake in the x-axis in Figure 11 in Poreh and Cermak (1986) which demonstrates the relationship (9) and consequentially their quoted constant of proportionality is also incorrect, the correct value should be 0.64×10^{-3} rather than 0.64.

Poreh and Cermak found that for x>δ, the maximum concentration varied approximately as

$$C_{\max} \;\alpha\; M_*^{1/2} F_*^{-2/3} x^{-2} \tag{10}$$

Relation (10) must break down when F_* and M_* are sufficiently small that the plume diffuses passively.

3.3 SLAWSON'S WATER FLUME STUDIES

Sinclair et al (1990) describe experiments conducted in a water flume to simulate a three-dimensional hot jet released into a co-flowing turbulent boundary layer. The downstream behaviour of the jet was recorded by detailed temperature measurements, which were analysed to determine the jet trajectory, spread rate, and distance to lift-off from the surface.

The data are used to validate a three-dimensional, parabolic, finite volume model based on the time-mean equations for incompressible turbulent flow.

The experiments were conducted in a 13 m long water flume, with a test section 1.2 m wide and 0.9 m deep. The test section was visible for 2.4 m of its length through a Plexiglas wall. Probes were positioned throughout the test section to measure temperature and velocity. Hot water was injected through different sized slots of dimensions 0.01m x 0.01m, 0.057m x 0.0014m, and 0.114m x 0.0014m. The slots were oriented with their longest side parallel to the flume floor.

There are a number of inconsistencies in the source conditions specified in Table 2 of Sinclair et al (1990), particularly between volumetric flow rate and velocity and between aspect ratio and slot dimensions. These have been corrected in what follows.

A series of sixteen experiments were carried out at volumetric flow rates ranging from 6.2 to 33 cc/s, injection velocities from 4 to 41 cm/s, jet exit temperatures from 34.8 to 85.8 °C, and ambient water flume temperatures from 16.6 to 19.2°C. The integral average ambient velocity over the depth of the jet (0.03m) was 46.8 cm/s. The plume lift-off point was defined as the point where the 25 % isotherm of the non-dimensional temperature field separated from the floor of the water flume. Temperature cross section data were available for Tests 1 to 11; only visual observations were available for Tests 12 to 16.

Sinclair et al analyse their results in terms of a "Source Froude Number"

$$Fr_s = \left(\frac{u_s^3 L_s}{F} \right)^{1/2}$$

where u_s is the velocity at the orifice, L_s is a characteristic length scale defined as the square root of the orifice area, and F is the source buoyancy flux

$$F = \frac{\Delta\rho_s}{\rho_s} g Q_s .$$

Note that ρ_s rather than ρ_a is used in this definition.

Observed lift-off distances varied between 4 cm and over 1.4 m. The latter figure was for the two lowest Source Froude Number cases. In these tests, the distance to lift-off is influenced by jet momentum. Higher jet:ambient velocity ratios delay lift-off for low aspect ratio jets. High aspect ratio jets (long slots) are less jet-like, and a high exit velocity increases the buoyancy flux which enhances lift-off.

Meroney's correlation, which is based on the ambient velocity, grossly under-estimates the distance to lift off, even in the highest aspect ratio tests (See Figures 4- 6). If the ambient velocity is replaced by the source velocity in Meroney's correlation, then agreement with the high aspect ratio tests becomes quite good (Figures 7 and 8), but agreement with low aspect ratio tests remains poor (see Figure 9). This is in line with Meroney's own data, where agreement was poor for point sources.

Slawson et al (1990) used the same water flume to investigate plume behaviour from line sources of heat and momentum in a cross flow. Plume trajectory, growth and lift-off were recorded photographically, and by temperature measurements across the plume. Ten photographs taken at 10 s intervals were projected and traced onto paper, then digitised to obtain a single time averaged plume trajectory, growth and lift-off distance.

The elevated line source was simulated by a line of stacks 2.5 cm high, 0.28 cm exit diameter, separated by 2 cm. Elevated line lengths of 4, 8, 16 and 20 cm were investigated. The ratio of the stack exit velocity to the ambient velocity at the stack height was varied between 1.4 and 10, and the exit (source) Froude Number ranged from 4.7 to 30.

The results of the elevated line source tests largely confirmed that there is little trajectory enhancement for stacks aligned in a row perpendicular to the mean wind direction. This is because the spaces between the stacks prevent blockage of on-coming flow, and the plumes from individual stacks merge only after they have cooled, so there is little enhanced buoyancy. However, as the length of the line (i.e. number of stacks) increased, some reduced rates of rise were observed in the momentum dominated near field due to flow blockage, and slightly enhanced rates of rise in the early buoyancy dominated region.

The surface line sources were of length 6.15, 12.15, and 20.35 cm with a slot width of 0.25 cm. Attempts to analyse the plume trajectories for surface line sources were hampered by the strong shear layer near the surface and the different lift-off points for different sources.

For surface line sources, the distance to plume lift-off was measured from the source point to the point where the 25% non-dimensional isotherm detaches from the flume floor. The lift-off distance was found to correlate well according to an expression of the form (3). The value of a in equation (3) depends on the choice of reference velocity used for the buoyancy length scale l_b. Slawson et al state that the best (presumably in terms of collapsing data) choice of reference velocity was that associated with the free stream flow or region of flow above which a log-law velocity profile was valid. A value of a=0.84 gives a good fit to their data. Increasing the length of the line source was found to delay lift-off, whilst increasing the source heat flux hastened lift-off.

3.4 HALL'S WIND TUNNEL STUDIES

Hall et al have studied plume lift-off in connection with nuclear reactor accidents, HF releases, and chemical warehouse fires. A wind tunnel facility was used to carry out their experiments.

The study related to nuclear accidents (Hall and Waters, 1986) involved experiments carried out at a scale of 1:300, with a helium plume emitted uniformly from various faces of a typical reactor building. Heat release rates ranged from 1 to 100 MW, and wind speeds ranged from 1 to 10 m/s. Surface roughness was varied to cover full-scale values of 20- 60 cm. Plume concentration measurements were made at ground level and within the plume, and the influence of the presence of the building on plume behaviour was investigated.

Ground level concentrations reduced steadily as plume buoyancy increased. The plume started to lift clear of the ground when L_p reached a critical value of about 29, in agreement with Briggs' revised estimate. However, this did not generally result in an abrupt reduction in ground level concentrations except at very high initial buoyancies. The presence of the building was found to have a small effect on subsequent plume behaviour compared to buoyancy. Similarly, the results were insensitive to surface roughness. Plumes released from a whole building face quickly bifurcated, but reducing the release area or changing the wind direction from square-on to the building prevented this bifurcation taking place.

Hall et al (1995) describe the characteristics of dispersing plumes from fires in chemical warehouses, and investigate a variety of possible fire plumes experimentally in a wind tunnel. The plume was studied using tracer smoke and by measuring methane gas tracer concentration in the plume with flame ionisation detectors.

Calculations showed that the heat release rate from a largely intact warehouse will be constrained by the ventilation rate. A distinction is made between scenarios where the building ventilation is wind-driven and those where it is buoyancy-driven. In view of the wind speeds occurring in the UK, fire ventilation in largely intact buildings will usually be buoyancy driven. As regards plume lift-off, the conclusion was drawn that this would only occur at high heat release rates (> 10 MW) corresponding to the partial collapse of the building.

The results of the wind tunnel tests, were compared using four pieces of information, namely: the ground level concentration 10 m and 300 m downwind of the source, and the plume centreline height and maximum concentration 300 m downwind. Results are given for plumes with buoyancy only and plumes with momentum only. The results are shown in groups corresponding to plumes without buildings, plumes from building shells, plumes from building roof areas, and plumes from building doorways.

Instead of L_p, the results are analysed using a dimensionless buoyancy flux parameter

$$\hat{F} = \frac{F}{\bar{u}^3 L}, \qquad F = \frac{g \Delta\rho_0 Q}{\pi \rho_a}$$

and a dimensionless momentum flux parameter

$$\hat{M} = \frac{M}{\bar{u}^2 L^2}, \qquad M = \frac{\rho_0}{\rho_a} u_{exit} Q$$

where

$\bar{u}$ = wind speed at reference height
L= reference length scale (in this case, the height to the building eaves)
u_{exit}= plume exit velocity
Q= volumetric emission rate

The use of building height as a reference length is somewhat arbitrary, especially when this is also used in the analysis of plumes without buildings.

The data for plumes without buildings include tests involving point sources and area sources. The ground level concentration measurements show steady reductions with increasing values of buoyancy or momentum flux parameters. In the case of buoyant plumes, concentrations near the source were higher for the area sources than the point sources, but this effect had disappeared by 300 m. Distributing the source over a larger area increases the initial entrainment into the plume. The net effect in these experiments was to reduce plume rise.

The plumes show an accelerated increase in height at 300 m with higher discharge buoyancy and momentum. There is no difference between point and area sources at this distance. The details of the source become less distinguishable at larger distances.

The maximum concentration 300 m downwind falls markedly with increasing buoyancy, and to a lesser extent with increasing momentum. This effect is due to:

the change from a ground-based to an airborne plume,
the increase of wind speed with height,
enhanced mixing due to higher buoyancy or momentum.

No sharp reduction in airborne concentration was observed at a particular value of the buoyancy parameter which could readily be identified as plume lift-off. The plume started to lift clear of the ground at a buoyancy parameter value of 3 or more, and above values of 10 there was no longer any measurable concentration at ground level.

Hall compares his buoyancy parameter criterion with Briggs' lift-off criterion which is equivalent in the present experiments to a buoyancy parameter of around 0.1- 0.3. At these buoyancy parameter levels, ground level concentrations at 10 m have significantly decreased (particularly for point sources) but it is not possible to say that the plume has lifted clear of the ground. Increasing the Briggs' critical value by an order of magnitude would give a better indication of plume lift-off and reduce the sensitivity to source area.

Any discharge arrangement which distributes the plume across a building tends to reduce the chance of plume lift-off. In these circumstances, simple criteria such as those of Briggs are no longer appropriate.

3.5 SCHATZMANN'S WIND TUNNEL STUDY

Liedtke and Schatzmann (1997) studied releases of helium in a stratified wind tunnel. The main aim of the work was to investigate the behaviour of strongly buoyant plumes and the penetration of elevated inversion layers by such plumes. Most of the experiments are not directly relevant here, since they deal with very buoyant releases in low winds, which rise nearly vertically from the source. Some experiments were, however, conducted in a crosswind in the absence of an elevated inversion. Martin et al (1997) report that in these experiments the plume is quite often in contact with the ground. These experiments may have some relevance to lift-off modelling, although it seems more likely that this contact with the ground is as a result of vertical growth of the already elevated plume.

4 Lift-off Models

4.1 CRITICAL LIFT-OFF NUMBER

The simplest of all models is to use a critical lift-off number criterion such as proposed by Briggs (1973). For releases with a lift-off parameter (e.g. non-dimensional buoyancy flux) less than the critical value, then a ground based model could be used. For releases with a lift-off parameter higher than the critical value, a plume rise model could be used. However, there are potential problems with such a simplistic approach. Firstly, the apparently high value of critical lift-off number means that the ground based model should account for buoyancy enhanced mixing prior to lift-off. We are not aware of any such models. Secondly, although wind tunnel studies appear to support the use of a lift-off parameter to describe lift-off, in general the transition is smooth rather than occurring at a given critical value. Thirdly, a criterion based solely on critical lift-off number cannot account for the influence of plume width on lift-off. Another way of saying this is that the critical lift-off number should depend on some non-dimensional function of plume width. This function is not known.

4.2 DISTANCE TO LIFT-OFF

As reported above, various authors (Meroney 1979, Slawson et al 1990, Sinclair et al 1990) have correlated dimensionless distance to lift-off as a function of source Froude number raised to the power of 3/2. Experimental data seems to be quite well represented by such a dependence.

The value of the constant of proportionality differs between experiments. This is mainly attributable to the choice of different length and velocity scales for non-dimensionalising the results. Also different definitions of plume edge are used and there is a possibility that real differences result from different source geometries (eg release into a cross or co-flow).

Despite the different values of the constant of proportionality, lift-off distance as measured by the above workers does appear to scale with source Froude in this way.

We argue below that such a scaling is *plausible* for a plume in a uniform wind.

Suppose the height of the plume, H follows a 2/3 power law formula as for standard plume rise. This can be argued on dimensional grounds by analogy with the rise of line thermals (Turner 1973)

$$H \sim \frac{F^{1/3}}{U} x^{2/3}$$

where F is the conserved buoyancy flux.

In terms of the buoyancy length scale $l_b = F/U^3$ we find

$$\frac{x}{l_b} \sim \left(\frac{H}{l_b}\right)^{2/3}$$

If we postulate that *lift-off occurs when H* is a *fixed multiple of the plume width W*, then we obtain

$$\frac{x}{l_b} \sim \left(\frac{W}{l_b}\right)^{2/3}$$

For a line source of width W_0, when $W_0 >> x$, we can approximate the plume width as fixed and hence:

$$\frac{x}{l_b} \sim \left(\frac{W_0}{l_b}\right)^{2/3}$$

which is the observed behaviour.

Note that such scaling is unlikely to occur for a non-buoyancy conserving flow.

4.3 HANNA'S MODEL

Hanna et al (1998) propose a correlation for the effect of lift-off on ground level concentrations. In common with our ultimate interest of describing HF plumes, Hanna et al were also interested in the possibility of describing non-buoyancy conserving plumes. Their correlation is based on fitting a model to a selection of Hall et al's (1986, 1995) wind tunnel data on buoyant emissions from buildings. The model of Hanna et al (1998) is incorporated (Hanna and Chang 1997) in a modified version of HGSYSTEM called HGSYSTEM/UF_6.

Hanna et al (1998) correlate data using the *local* non-dimensional buoyancy flux, $\hat{F}$

$$\hat{F} = \frac{F}{u^3 W} \ ,$$

where

F = local plume buoyancy flux = $\dfrac{g \Delta \rho u H W}{\pi \rho_a}$,
u = effective wind speed over the height of the plume,
W = effective local lateral plume width,
H = effective local plume height.

$\hat{F}$ is a bulk Richardson number for the plume and can be thought of as a comparing the magnitude of the buoyancy induced plume velocity with that for the horizontal motion. As such $\hat{F}$ is a natural local parameter for investigating buoyant lift-off. $\hat{F}$ is directly equivalent to Briggs' L_p parameter.

As can be seen from the above definition, the plume width W dependence cancels when $\hat{F}$ is written in terms of density and height. This means that any correlation based *solely* on $\hat{F}$ will not distinguish between wide and narrow plumes having the same vertical density profiles.

Hanna et al (1998) assume that the reduction in ground level concentration due to plume lift-off (or buoyant vertical stretching) can be correlated as a function of $\hat{F}$ only. Their model for dispersion in the presence of a building is

$$\frac{CuR_B{}^2}{S} = \frac{\exp\left(-6\hat{F}^{0.4}\right)}{\left[\left(\frac{1}{3}\right)^3 + 0.03\left(\frac{x}{H_B}\right)^2 + \hat{F}^2\left(\frac{x}{H_B}\right)^4 + \left(\pi\frac{\sigma_y\sigma_z}{R_B{}^2}\right)^3\right]^{1/3}} .$$

C is the ground level mass concentration at distance x down wind of a building, S is the source strength (kg/s), σ_y and σ_z are the standard deviations in the distribution of a Gaussian passive plume in the y and z directions, H_B, W_B are the building height and width, and R_B is a length scale for the building,

$$R_B = H_B{}^{2/3}W_B{}^{1/3} \quad \text{subject to } R_B \le 2H_B .$$

The denominator is proportional to the cross-wind area of the plume which is taken to be the sum of components arising from existing dispersion models for positively or neutrally buoyant plumes.

The numerator is described as a "buoyant lift-off factor". According to the authors, the exponential form is chosen for its correct behaviour at large and small $\hat{F}$. The numerical parameters 6 and 0.4 were chosen to give the best overall, conservative fit to a selection of data from Hall's wind tunnel experiments. The lift-off factor is a simple continuous function of $\hat{F}$ allowing the continuous decrease of ground level concentration with buoyancy, as observed in the experiments of Hall et al, to be represented.

The exponential lift-off factor acts to reduce ground level concentrations. The factor does not distinguish between a reduction in concentration due to plume rise and that due to enhanced mixing. Indeed, such a distinction may be difficult to make for a ground level plume. However, at high buoyancies we expect the plume to lift clear of the ground and a significant reduction in ground level concentration will be due to plume rise. This reduction depends on the plume's vertical extent in relation to its elevation. It is possible that if the relationship between the trajectory and dilution were universal, the reduction due to plume rise might be represented as function of $\hat{F}$ alone. However, this seems unlikely to be the case generally, especially for a non-buoyancy conserving plume which might have quite a complex airborne trajectory.

In the absence of a building the model of Hanna et al reduces to:

$$\frac{Cu}{S} \approx \frac{\exp\left(-6\hat{F}^{0.4}\right)}{\left[\frac{F^2 x^4}{u^6} + \left(\pi\sigma_y\sigma_z\right)^3\right]^{1/3}} \qquad (11)$$

on replacing W_B by W (since the building width is not relevant). We note that the correlation is essentially untested in the absence of a building.

The first term in the denominator of equation (11) represents the buoyancy component of plume spread. As recognised by Hanna et al, this term implicitly assumes a point plume source and that buoyancy is conserved. The second term corresponds to the passive spread of the plume.

Hanna et al (1998) make the assertion that *in general* the same "buoyant lift-off" factor may be applied such that:

$$C(\text{with lift-off}) = C(\text{without lift-off})\ x\ e^{-6\hat{F}^{0.4}}$$

As far as the evidence presented in their paper goes this is conjecture.

To summarise. The correlation of Hanna et al (1998) has the merit of fitting a wide range of data for releases in the presence of buildings. The local dimensionless buoyancy flux *is* a physically relevant parameter for correlating plume lift-off, although the possibility of other influencing factors e.g. plume width should also be considered. Since the plume trajectory is not determined, the capability to deal with airborne plume trajectories differing in character from those of Hall's experiments must be questioned. Also, the presence of terms which implicitly assume buoyancy conservation makes the applicability of the correlation to non-buoyancy conserving flows questionable.

4.4 SLAWSON'S INTEGRAL MODEL

Slawson et al (1990) present a simple integral model for a plume resulting from a finite length line source. The model is a straightforward generalisation of a point source model.

The assumed cross-section shape is illustrated in Figure 13. The line length L_0 is taken to be fixed, whereas the radius R increases due to entrainment. Hence the plume cross-section will change from being linear near the source, to a circular shape further downstream. The model thus has the merit of being able to treat line and point sources on the same footing.

The plume equations for the plume attached to the surface are based on those for the free elevated plume. The equations are as described below.

The conservation equations for mass, vertical momentum and buoyancy for the elevated plume are:

$$\frac{d}{dx}(AU) = Cu_e$$

$$U\frac{d}{dx}M = F$$

$$\frac{dF}{dx} = 0$$

where A is the cross-sectional area, C the circumference, M is the vertical momentum flux and F is the buoyancy flux which are defined below.

The Boussinesq approximation has been made, together with the assumption that the plume velocity is very nearly equal to the ambient velocity, U. Top hat distributions of all plume parameters are assumed.

In common with other bent over plume models the entrainment velocity, u_e is assumed proportional to the vertical rise velocity, w:

$$u_e = \beta w$$

M is the vertical momentum flux of the plume

$$M = AUw$$

and F is the conserved buoyancy flux

$$F = AUg\Delta\rho / \rho$$

While the plume is elevated, the plume height, z, may be determined from the kinematic condition

$$U\frac{dz}{dx} = w$$

When the plume is attached to the ground, the plume height is determined by the increase in R due to *entrainment*.

The cross-sectional area A is given by

$$A = \pi R^2 + 2RL_0$$

and the perimeter C is

$$C = 2\pi R + 2L_0 .$$

For the ground based plume, C is reduced by an amount L_c to account for not all the surface being free to entrain fluid. Slawson et al (1990) assumes that L_c diminishes *linearly* with distance x from the source as:

$$L_c = L_0\left[1 - x / X_L\right]$$

where X_L is the distance to lift-off which must be determined empirically. Slawson et al (1990) use values of X_L which are based on their water tunnel experiments. Slawson et al (1990) acknowledge that their approach is very simplistic in its treatment of lift-off, but claim that it does serve to indicate some expected trends.

Slawson et al present analytic solutions of the model equations for a uniform ambient flow. The elevated plume trajectory data appear to confirm the model behaviour - showing a transition in power law behaviour from that appropriate for line sources to that for point sources. Numerical solution of the model equations gave the best results when compared with data, believed to be because the numerical model accounts for the variation of ambient velocity with height. Collapse of trajectory data for ground level sources was poorer than for elevated sources. The authors in part attributed this to the very strong shear layer near the surface and the variation of lift-off distance for different sources. The authors made few attempts to describe the observed trajectories using the presented integral models since they believed that further work was warranted.

Although the equations as presented above assume buoyancy conservation, this may be readily generalised by replacing buoyancy conservation by contaminant and energy conservation. The plume evolution is determined by local conditions - this is appropriate. An exception is the specification of the contact length on the ground which is dependent upon prior knowledge of the distance to lift-off. This feature of the model is least attractive from the point of view of generalising the model and an alternative local means to determine lift-off would be required.

4.5 SINCLAIR'S THREE-DIMENSIONAL MODEL

Sinclair et al (1990) describe a three-dimensional parabolic model for a buoyant wall jet released into a co-flowing turbulent boundary layer. One aim of the model was to evaluate the applicability of a Prandtl mixing-length hypothesis in the turbulence closure. The proposed mixing-length function varies continuously through the jet, buoyant plume and boundary layer regions and attempts to account for the local influence of buoyancy in enhancing or suppressing turbulence. The approach uses empirical relations based on Monin-Obukhov similarity theory for the atmospheric surface layer. Strictly speaking in the jet regime such similarity theory only applies to the constant stress layer very close to the wall, rather than to the whole jet. However, the authors claim the approach provides the correct tendencies, with the values of the constants adjusted to give best agreement with trajectory and spreading behaviour observed experimentally.

4.6 HGSYSTEM-MMES

Shell's HGSYSTEM 3.0 (Post 1994) options include extensions developed by Earth Tech. The HGSYSTEM model with these extensions is referred to as HGSYSTEM-MMES. One of the MMES extensions is a plume lift-off model.

Plume lift-off is dealt with as follows:

Once the plume is on the ground, it is taken to remain on the ground so long as the *local* $L_p<20$. Once the plume depth and buoyancy increase such that the local $L_p=20$, the plume centreline (or point of maximum concentration) is allowed to begin lifting off the ground. Plume rise after lift-off is dealt with differently, depending whether lift-off occurs within the jet model AEROPLUME or the advection dispersion model HEGADAS.

AEROPLUME's equations account for plume rise in that the model includes a buoyancy term in its vertical momentum equation. The air entrainment in AEROPLUME is taken to occur over the free perimeter of the plume.

In HEGADAS the plume rise is calculated separately according to a 2/3 power law with the buoyancy length scale, l_b, determined from the conditions at the start of rise. The buoyancy length scale is then treated as though the buoyancy were constant. The calculated plume rise is then applied by a post processor to the ground based HEGADAS results, although details of this post processing are not given. No mention appears to be made in the Technical Reference (Post 1994) of HEGADAS's treatment of dilution for the buoyant phase.

Plume rise in HEGADAS phase is terminated by a so-called "break-up" formula whereby the plume stops rising when the vertical velocity becomes comparable to the vertical velocity fluctuations.

5 Implications for Lift-off of HF Clouds

Of necessity, most studies of buoyant cloud lift-off are based on experiments using buoyancy conserving flows. As indicated in the introduction, in practice many clouds resulting from accidental releases of hazardous materials will not be buoyancy conserving. Evaporation and condensation, heat transfer from the ground and chemical interactions can all lead to non-conservation of buoyancy. HF is of particular interest because of its complex thermodynamic behaviour. In particular, HF oligomerisation and interaction with liquid water leads to the possibility of an initially dense cloud going buoyant and possibly becoming dense again.

If lift-off criteria and correlations as determined from buoyancy conserving flows are to stand a chance of being more generally applicable to a non-buoyancy conserving flow, we require an understanding based on the *local* conditions in the cloud. For this reason correlations based on non-dimensional momentum and buoyancy fluxes (eg Poreh and Cermak 1986) are **not directly** applicable. Obviously such non-dimensionalisation is appropriate for the experimental data, and the results may still be useful generally, so long as they can be used to established models which can in themselves be generalised. After such a generalisation, we should, if possible, check the model predictions against the more general non-conserving flow.

Despite such problems of interpretation, we believe that much of the observed behaviour of buoyancy conserving flows may apply more generally.

It seems likely that the observed result that buoyant plumes do not very readily lift clear of the ground (as indicated by the relatively large values quoted for Briggs critical lift-off number) will still be true for non-buoyancy conserving flows. It is therefore probably **not** adequate to simply assume that a cloud lifts free of the ground as soon as it becomes less dense than air.

Calculations of HF dispersion using integral models incorporating HF thermodynamic models indicate that in many cases the cloud is predicted to become buoyant when it has spread significantly on the ground and is quite low and flat. In such a case any dependence of lift-off on cloud width will be important. The studies on buoyancy conserving clouds reviewed above appear to indicate that lift-off of such a wide flat cloud will be inhibited compared with that of a narrow cloud. Indeed it is possible that the flat cloud will not lift-off but rather show enhanced vertical mixing due to convective mixing. Such convective mixing may be more likely if the cloud mixture obeys homogeneous equilibrium thermodynamics which will predict that the outer more well mixed parts of the cloud become buoyant before the less well mixed inner parts.

6 Summary and Discussion

During the course of our review we have found few published models which claim to deal with lift-off of ground based buoyant releases. Much of the current understanding of buoyant lift-off comes from various wind and water tunnel studies on buoyant plumes. Even amongst the different wind tunnel studies there are few results which may be directly compared.

Indications of the experimental studies are that ground based buoyant plumes in an ambient flow do not readily lift clear of the ground. Briggs proposed that lift-off is determined by a parameter referred to as L_p, which is a bulk Richardson number for the cloud. In the light of wind tunnel measurements Briggs suggested a critical value of L_p or about 30 as a measure of when plume lift-off starts to occur. Subsequent wind tunnel studies appear to support lift-off depending on L_p, although lift-off appeared to vary continuously with this parameter, rather than occurring at a precise critical value. Fairly obviously, lift-off is enhanced for light winds and high source buoyancies. Increased plume width appears to suppress plume rise.

Lift-off parameters based on non-dimensional fluxes are of limited use for non-buoyancy conserving flows unless they can be interpreted in terms of local cloud conditions.

Various studies have correlated the dimensionless distance to lift-off as a function of source Froude number. The correlations are difficult to compare because of the different source geometries and the different non-dimensionalisations adopted. The lift-off distance correlations are unlikely to be valid for non-buoyancy conserving flows.

Hanna et al (1998) proposed a correlation for lift-off based on a continuous function of a local lift-off parameter. The correlation of Hanna et al is based on wind tunnel data of buoyant releases from buildings. The correlation appears in part to assume buoyancy conservation, and since the plume trajectory is not separately accounted for, it is unlikely to be applicable to plumes having differing trajectories, as might be expected for a buoyancy changing HF plume.

We have not considered in detail the three-dimensional model of Sinclair et al (1990) since it is more complex than the one-dimensional models more typically used in risk assessment. However, the empirical mixing-length turbulence closure could provide insight for entrainment models. The use of Monin-Obukhov similarity functions in the mixing model, although questionable, does highlight a possibly useful analogy between mixing of buoyant gas layers near the ground and mixing under unstable convective atmospheric conditions.

The model of Slawson et al (1990) has some attractive features and is in principle generalisable to an HF plume. The model allows evolution from an elongated source, which is probably required for wide flat HF clouds becoming buoyant. The model grows the vertical height of the plume when on the ground and restricts entrainment to account for the contact of the cloud with the ground. In these respects the model is similar to, albeit simpler than, HGSYSTEM's airborne jet/plume model. The trajectory of the lifted-off plume is calculated using an integral model with a vertical momentum equation. Parts of the model would require modification for HF, in particular, the empirical distance to lift-off would have to be replaced by something more appropriate. The entrainment model is based on standard plume rise models which may not be most appropriate for the grounded phase. Prior to new data becoming available, there is, we believe, scope in using existing wind tunnel data (e.g. Hall et al 1995, Poreh and Cermak 1986) for investigating further the lift-off behaviour of a model like Slawson's.

In our opinion, due to the complexity of the interaction between the cloud and the ground, it is almost inevitable that any integral model of plume lift-off will be highly empirical. Such an empirical model will more than likely rely heavily on results from wind tunnel studies using buoyancy conserving flows. Although, there is scope for further model development and validation using the existing data identified in this review, new wind tunnel studies are required to address the following points.

More information about enhanced mixing and lift-off is required, using source conditions approximating those expected of HF clouds when they go buoyant. L_p or equivalently $\hat{F}$ are clearly important parameters for lift-off models, it would therefore be very useful if such a local cloud parameter could unambiguously be determined from measurements. Measurement of the vertical concentration profile as a function of distance would be useful. Some measure of plume width is also desirable, although this is likely to be difficult to determine, and could possibly be estimated from vertical profiles and contaminant conservation. Additionally, data on real HF clouds in humid atmospheres is necessary, in order to check lift-off predictions of integral models using HF thermodynamics. The planned URAHFREP experiments should provide invaluable data in this respect.

7 Acknowledgements

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9 Figures

FIGURE 1

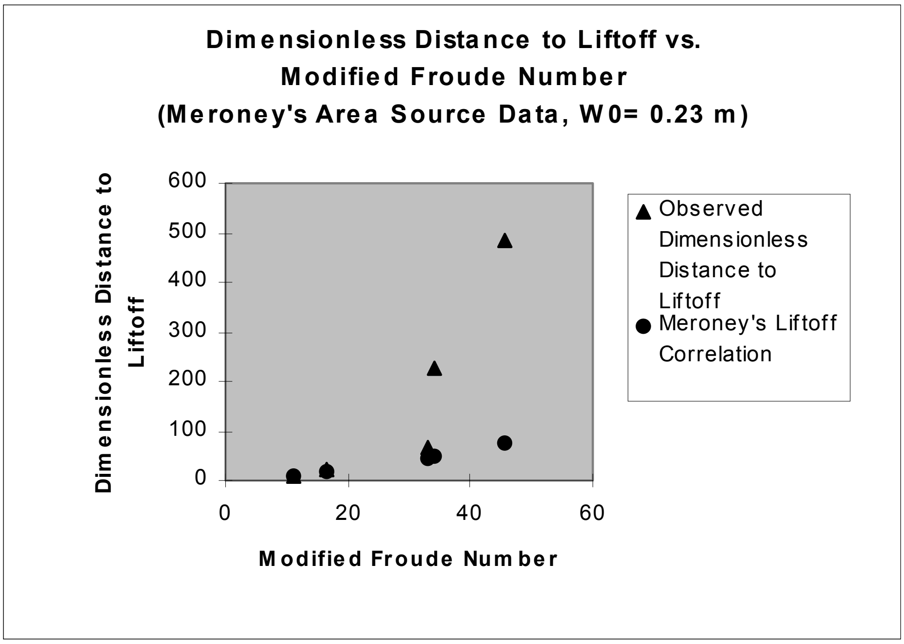
Dimensionless Distance to Liftoff vs.
Modified Froude Number
(Meroney's Area Source Data, W0= 0.23 m)
Dimensionless Distance to Liftoff
600
500
400
300
200
100
0
0
20
40
60
Modified Froude Number
Observed Dimensionless Distance to Liftoff
Meroney's Liftoff Correlation

FIGURE 2

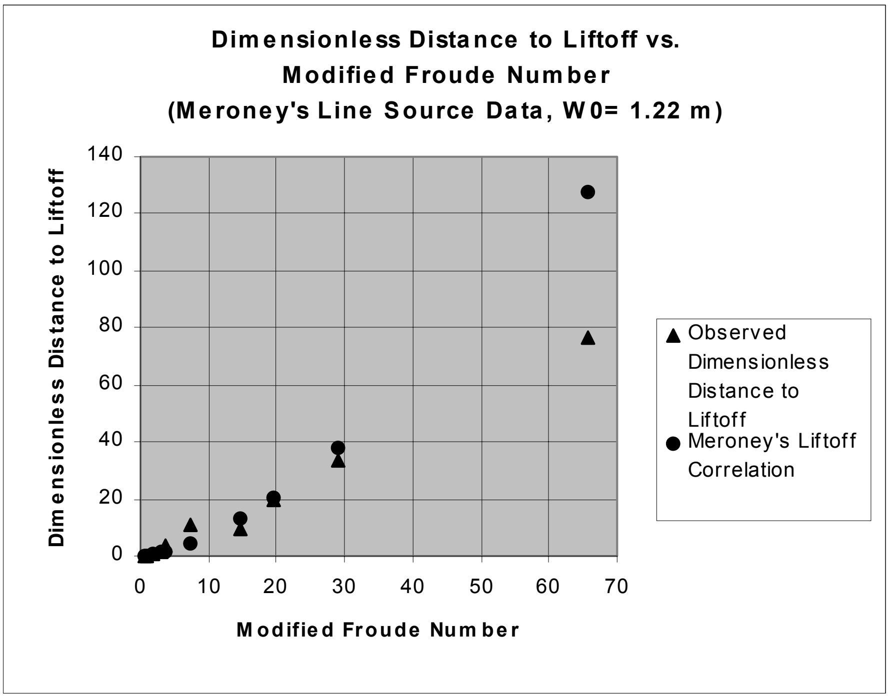
Dimensionless Distance to Liftoff vs.
Modified Froude Number
(Meroney's Line Source Data, W0= 1.22 m)
Dimensionless Distance to Liftoff
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
Modified Froude Number
Observed Dimensionless Distance to Liftoff
Meroney's Liftoff Correlation

FIGURE 3

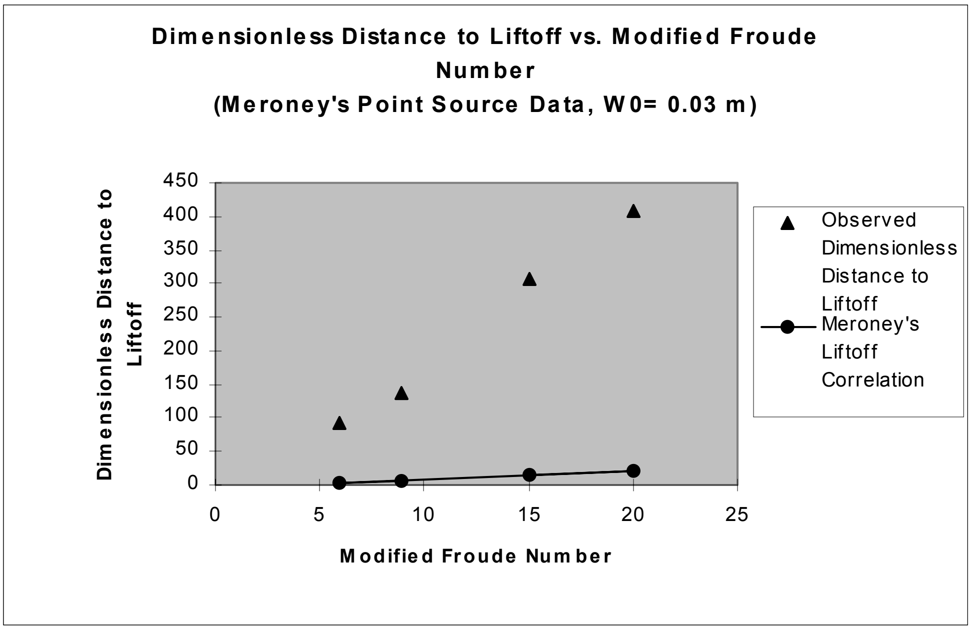
Dimensionless Distance to Liftoff vs. Modified Froude Number
(Meroney's Point Source Data, W0= 0.03 m)
Dimensionless Distance to Liftoff
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
Modified Froude Number
Observed Dimensionless Distance to Liftoff
Meroney's Liftoff Correlation

FIGURE 4

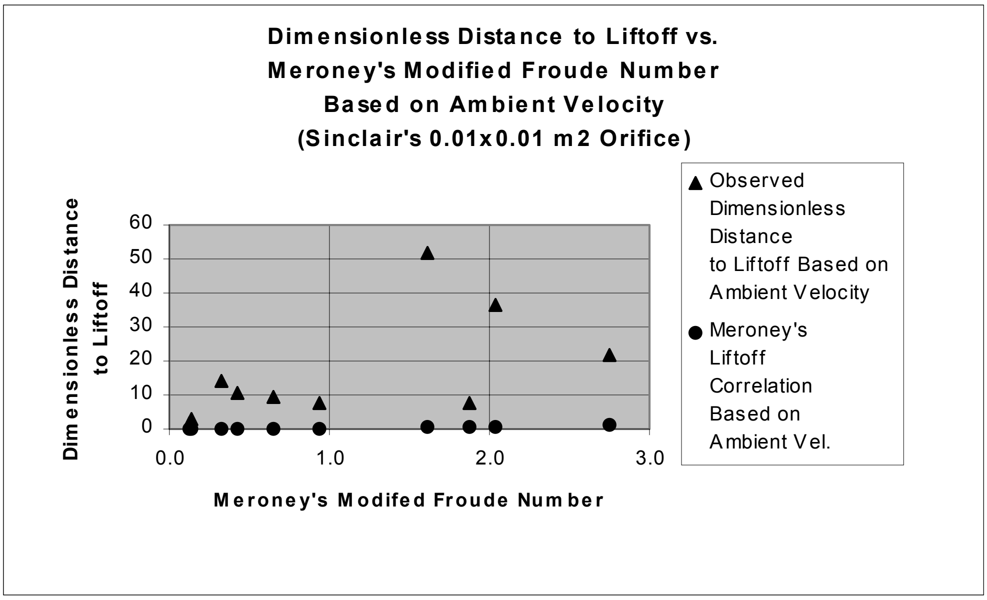
Dimensionless Distance to Liftoff vs.
Meroney's Modified Froude Number
Based on Ambient Velocity
(Sinclair's 0.01x0.01 m2 Orifice)
Dimensionless Distance to Liftoff
60
50
40
30
20
10
0
0.0
1.0
2.0
3.0
Meroney's Modifed Froude Number
Observed Dimensionless Distance to Liftoff Based on Ambient Velocity
Meroney's Liftoff Correlation Based on Ambient Vel.

FIGURE 5

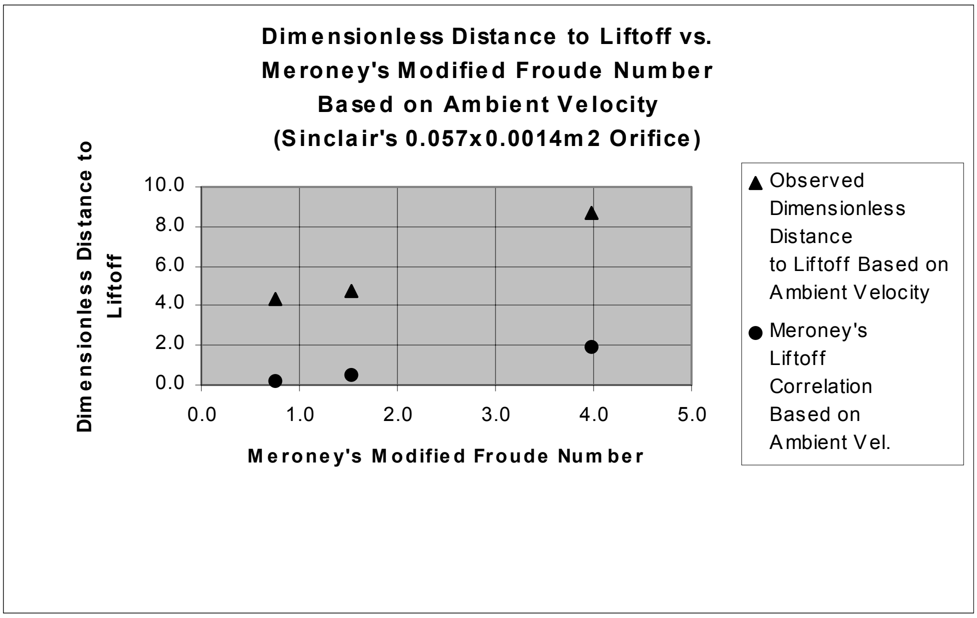
Dimensionless Distance to Liftoff vs.
Meroney's Modified Froude Number
Based on Ambient Velocity
(Sinclair's 0.057x0.0014m2 Orifice)
Dimensionless Distance to Liftoff
10.0
8.0
6.0
4.0
2.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
Meroney's Modified Froude Number
Observed Dimensionless Distance to Liftoff Based on Ambient Velocity
Meroney's Liftoff Correlation Based on Ambient Vel.

FIGURE 6

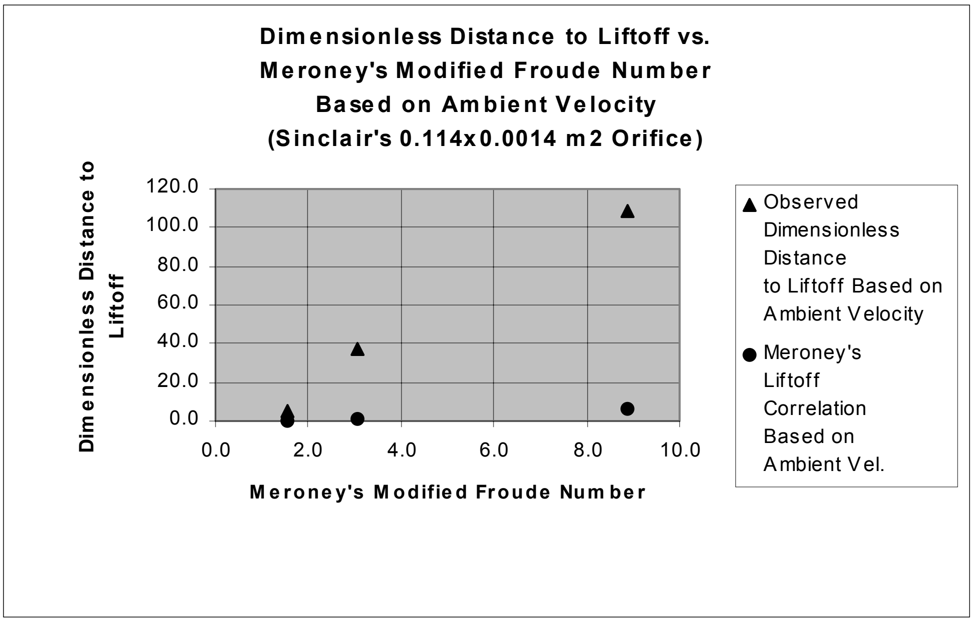
Dimensionless Distance to Liftoff vs.
Meroney's Modified Froude Number
Based on Ambient Velocity
(Sinclair's 0.114x0.0014 m2 Orifice)
Dimensionless Distance to Liftoff
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
Meroney's Modified Froude Number
Observed Dimensionless Distance to Liftoff Based on Ambient Velocity
Meroney's Liftoff Correlation Based on Ambient Vel.

FIGURE 7

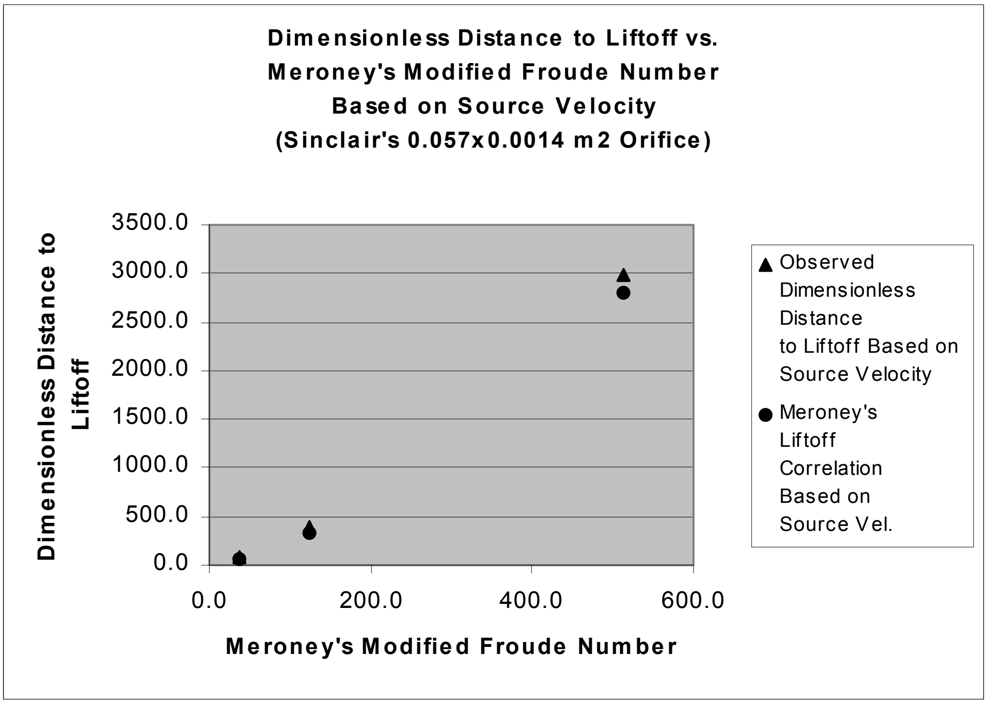
Dimensionless Distance to Liftoff vs.
Meroney's Modified Froude Number
Based on Source Velocity
(Sinclair's 0.057x0.0014 m2 Orifice)
Dimensionless Distance to Liftoff
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
200.0
400.0
600.0
Meroney's Modified Froude Number
Observed Dimensionless Distance to Liftoff Based on Source Velocity
Meroney's Liftoff Correlation Based on Source Vel.

FIGURE 8

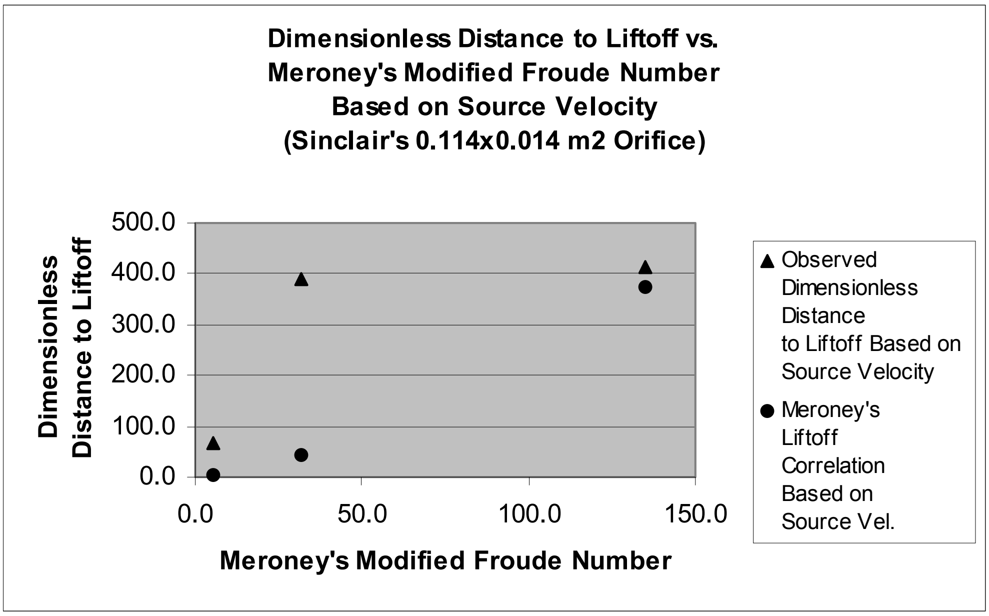
Dimensionless Distance to Liftoff vs.
Meroney's Modified Froude Number
Based on Source Velocity
(Sinclair's 0.114x0.014 m2 Orifice)
Dimensionless Distance to Liftoff
500.0
400.0
300.0
200.0
100.0
0.0
0.0
50.0
100.0
150.0
Meroney's Modified Froude Number
Observed Dimensionless Distance to Liftoff Based on Source Velocity
Meroney's Liftoff Correlation Based on Source Vel.

FIGURE 9

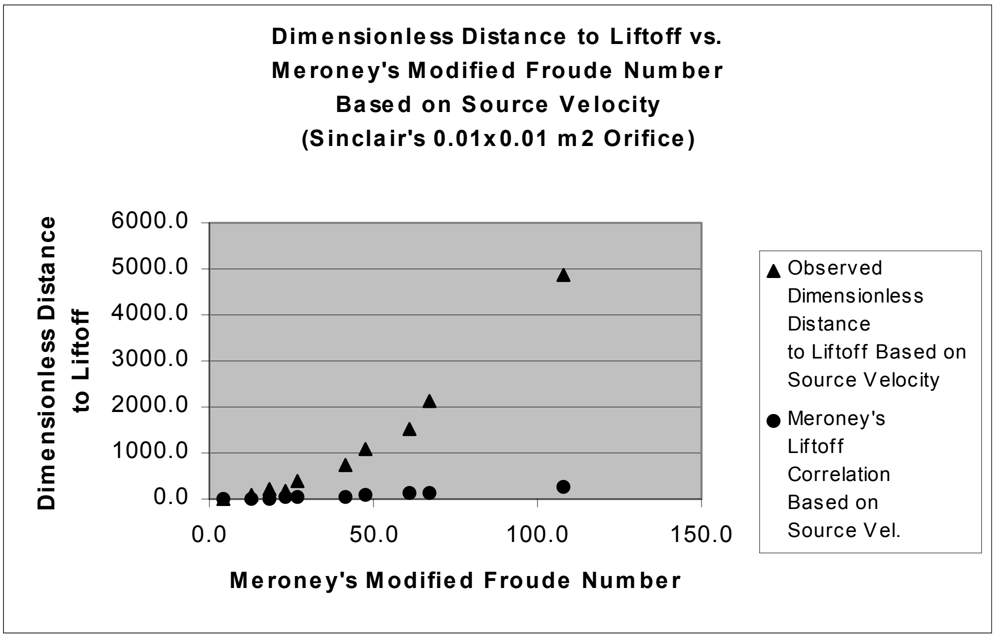
Dimensionless Distance to Liftoff vs.
Meroney's Modified Froude Number
Based on Source Velocity
(Sinclair's 0.01x0.01 m2 Orifice)
Dimensionless Distance to Liftoff
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
0.0
50.0
100.0
150.0
Meroney's Modified Froude Number
Observed Dimensionless Distance to Liftoff Based on Source Velocity
Meroney's Liftoff Correlation Based on Source Vel.

FIGURE 10

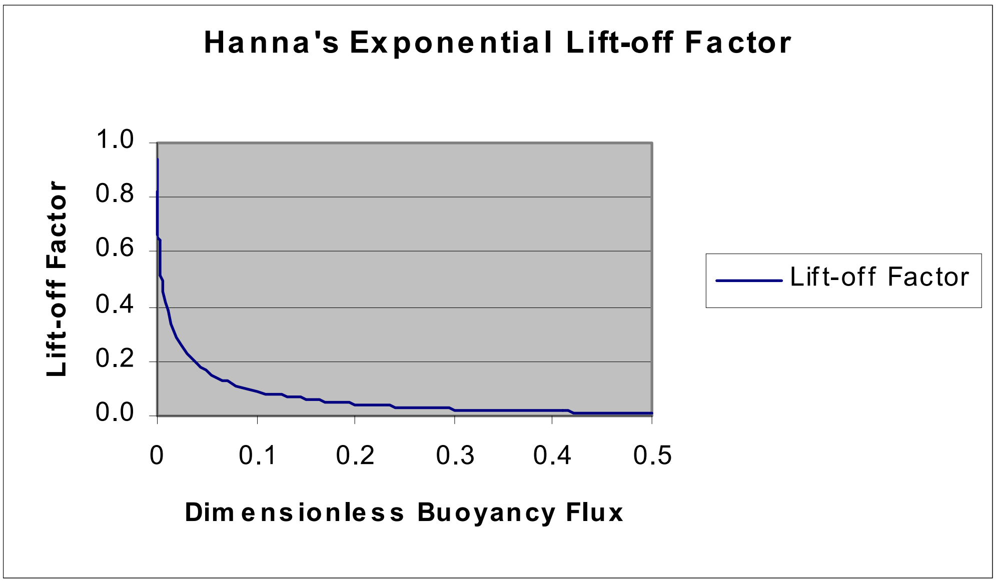
Hanna's Exponential Lift-off Factor
Lift-off Factor
1.0
0.8
0.6
0.4
0.2
0.0
0
0.1
0.2
0.3
0.4
0.5
Dimensionless Buoyancy Flux
Lift-off Factor

FIGURE 11

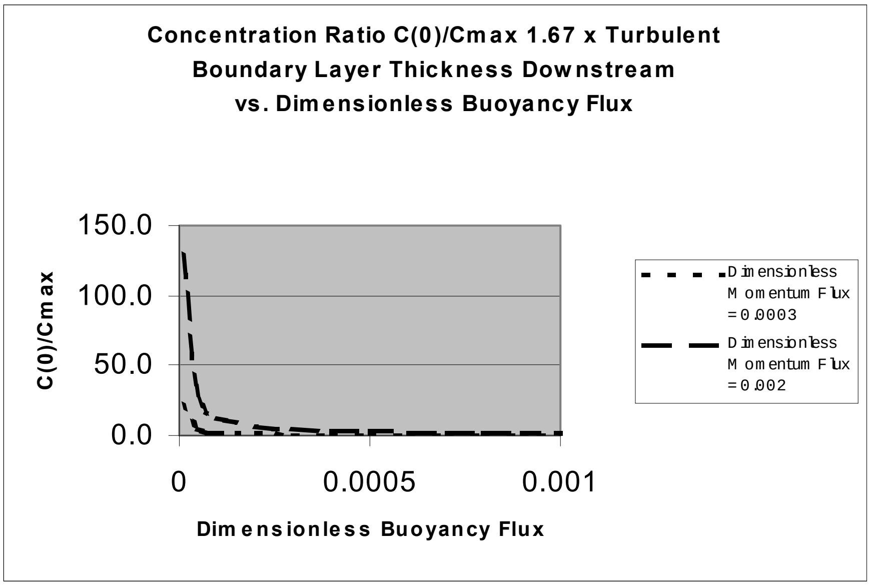
Concentration Ratio C(0)/Cmax 1.67 x Turbulent Boundary Layer Thickness Downstream vs. Dimensionless Buoyancy Flux
150.0
100.0
50.0
0.0
C(0)/Cmax
0
0.0005
0.001
Dimensionless Buoyancy Flux
Dimensionless Momentum Flux =0.0003
Dimensionless Momentum Flux =0.002

FIGURE 12

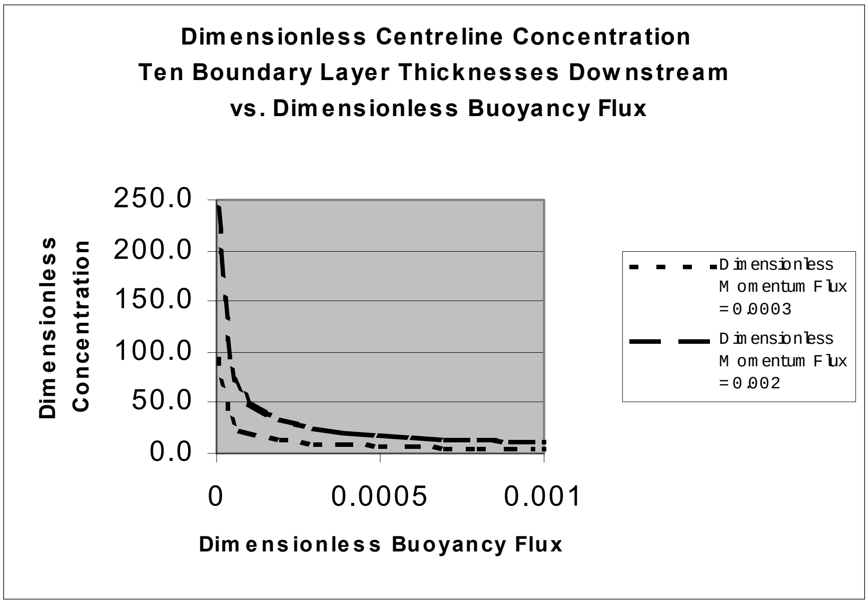
Dimensionless Centreline Concentration
Ten Boundary Layer Thicknesses Downstream
vs. Dimensionless Buoyancy Flux
Dimensionless Concentration
250.0
200.0
150.0
100.0
50.0
0.0
0
0.0005
0.001
Dimensionless Buoyancy Flux
Dimensionless Momentum Flux = 0.0003
Dimensionless Momentum Flux = 0.002

FIGURE 13

PLUME CROSS-SECTION USED BY THE INTEGRAL MODEL OF SLAWSON ET AL (1990)