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DEVELOPMENT OF CRUNCH: A DISPERSION MODEL FOR CONTINUOUS RELEASES OF A DENSER-THAN-AIR VAPOUR INTO THE ATMOSPHERE

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Development of CRUNCH: A dispersion model for continuous releases of a denser-than-air vapour into the atmosphere

by

S. F. Jagger

SUMMARY

Further consideration is given to the computer code CRUNCH – a model to describe the dispersion, in the atmosphere, of 'continuous' releases of denser-than-air vapours. The duration of the release must be such that a steady state plume results. Model equations are reviewed and a guide to source term calculation given. Attempts to validate the model against available experimental data are described and analytical solutions to the model equations, for certain limiting conditions, are provided. CRUNCH is also compared with other similar working models.

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1. INTRODUCTION

The recent study of industrial installations on Canvey Island[1] has identified the wide variety of ways in which failure of a process plant or a transport container could release a potentially hazardous material to the environment. Similar circumstances apply throughout the chemical industry. There is increasing use and storage, in industry, of materials which, when released, lead to the formation of a denser-than-air gas or vapour. Since many of these are highly-toxic or flammable, there have been many attempts to compute the dispersal of such a material. The hazards due to any particular incident are determined by the nature of the contaminant, the release mechanism and the environment into which it is released. However, it is possible to envisage such a wide range of release modes that it would be difficult to consider each case individually, so it has become usual to provide models for two limiting situations

(i) a release in which the source forms 'instantaneously'

(ii) a release from a continuous steady source.

The former can result from the 'flash' vaporisation of a liquid stored under pressure above its boiling point. With catastrophic release of containment a large fraction of the stored material can vaporise in a fraction of a second to form a gas cloud of well-defined cylindrical shape. This has been the subject of an earlier model.[2] This report is concerned with the second situation, for which the characteristic release time, over which the release rate is constant, is long compared with the time for dispersion. Such circumstances may result from broken pipework or, when a pool of volatile liquid is formed, with consequent boil-off or evaporation. The gas is assumed to advect with the ambient wind at all times and situations in which the gas emerges with appreciable momentum in any direction, influencing the flow can only be modelled downstream of the source when this is dissipated. The intermediate case of a transient source strength has been considered by several authors[3,4] but still awaits satisfactory treatment. However, for some situations either of the two limiting models may offer an adequate approximation of source behaviour.

2. A DISPERSION MODEL FOR 'CONTINUOUS' RELEASES

The situation modelled is depicted in Fig. 1. A dense gas emerges from a source such that it can be considered to emerge through a rectangular area, placed in the vertical plane and perpendicular to the plume direction, which assumes that of the ambient wind. The rectangular co-ordinate system is aligned so that this is along the x-axis. The gas flux at the source, and in every plane perpendicular to the plume direction, is constant in time and a stationary flow field has been attained. For this to apply, the characteristic time of release must be much larger than that for dispersal of the contaminant. The plume can be thought to consist of a number of rectangular elements or 'puffs' emerging from the source at regular time intervals. the model follows the development of these puffs at a series of downwind points as illustrated in Fig. 2. These puffs are immediately assumed to advect with the ambient wind at their half-height. Acceleration of the plume to the wind velocity is not considered, since an analysis of inertial effects has shown[5] that the time for which these are important is short, compared to the dispersion time. Additionally, wind shear effects on cloud structure are not included; for a puff release producing a cloud of finite extent, this may not be valid but for a plume, extending to large downwind distances, they can be argued to have only a minor influence at the advancing front. The plume also slumps due to the action of gravity and is allowed to entrain air through its sides and top surface. A considerable simplification is obtained by allowing the plume to slump only in the lateral direction. Spreading of a fluid element is caused by pressure differences across this element and since the pressure gradient in the wind direction is small, the resulting pressure differences and slumping velocities are small also, thus permitting this convenient approximation. Initially, as the plume slumps, its vertical dimension decreases and with it the slumping velocity and advection velocity. Thus the plume advection velocity varies as a function of downwind distance. With the present steady state modelling, and to satisfy continuity constraints, there must be consequent adjustment of plume height. Calculation of this parameter from the volume flux ensures this occurs. As the cloud height begins to grow, the advection velocity increases and the plume height decreases accordingly. With advection downwind, the cloud gains buoyancy by entraining air and, if the cloud is cold, by absorbing heat from the ground. Eventually the plume begins to disperse as would a passive pollutant, through the action of ambient atmospheric turbulence, and to follow the dispersion processes down to low concentrations, especially important for toxic gases, a virtual source passive dispersion model is fitted to the slumping plume.

2.1 Equations for the plume

For a steady plume entraining air, the mass of a small plume element, width 2L, density ϱ_c and height h, a distance x from the source is:

$$M(x) = M_a + M_g = 2L(x)\, h(x)\, \varrho_c\, (x)\, dx \qquad \text{... (1)}$$

Differentiating Equation (1) and putting $u_c = dx/dt$ gives the gaseous mass flux

$$\dot{M}_a + \dot{M}_g = 2L(x)\, h(x)\, \varrho_c\, (x)\, u_c(x) \qquad \text{... (2)}$$

A similar analysis for the gaseous vo!ume flux gives:

$$\dot{V} = 2L(x)\, h(x)\, u_c(x) \qquad \text{... (3)}$$

Combining these expressions with the equation of state for the plume, yields expressions for the major cloud parameters; plume density and volume flux, at any point downwind of the source, in terms of the species mass fluxes, temperatures and densities:

$$\varrho_c = \frac{\dot{M}_a + \dot{M}_g}{\dot{V}} \qquad \text{... (4)}$$

$$\dot{V} = \frac{T_c\, \dot{M}_a}{\varrho_a\, T_a} + \frac{T_c\, \dot{M}_g}{\varrho_g\, T_g} \qquad \text{... (5)}$$

Concentrations of contaminant, assumed everywhere, during the gravity-dominated phase, to be uniform, are computed from

$$C\,(x, y, z) = \dot{M}_g/\dot{V} \qquad \text{... (6)}$$

2.2 Plume motion

While the plume is denser than air, it is assumed to slump everywhere in a direction perpendicular to the plume travel direction. No slumping is considered along the direction of the wind and the model is thus more appropriate to high ambient wind speeds, and in the far field, where advection dominates over gravitational spreading. An expression, used in many models,[2,5,6] for the rate of growth of a dense cloud, due to gravitational spreading, has been obtained by analogy with the collapse of a liquid column. It can also be obtained from consideration of the pressure differences across a fluid element. Thus the rate of growth of cloud half-width is:

$$\frac{dL}{dt} = K\,(g'h)^{1/2} \qquad \text{... (7)}$$

In this steady-state situation, it is more appropriate to regard the plume as a density intrusion and express the growth of the plume in terms of downwind travel distance x, and the gaseous volume flux $\dot{V}$. Thus using Equation (3)

$$\frac{dL}{dx} = K\,(g'\dot{V}/2Lu_c^{3})^{1/2} \qquad \text{... (8)}$$

where

$$g' = g\,(\varrho_c - \varrho_a)/\varrho_a$$

and

$$u_c = dx/dt.$$

Here K is the gravitational slumping constant to be inferred from appropriate theory and experiment.

The cloud is assumed to be advected downwind at a velocity given by the wind at the cloud half-height. A simple logarithmic wind profile is assumed for all atmospheric stability conditions and, hence, if the measured wind velocity at some reference height, z_r is u_r, then the velocity of the cloud, u_c, is given by:

$$u_c = u_r \frac{\ln (\dot{V}/4Lu_c z_o)}{\ln (z_r/z_o)} \quad \ldots (9)$$

2.3 Entrainment of air

Entrainment is the process by which the cloud is diluted. The present model incorporates entrainment both at the edges and over the top surface of the cloud.

During initial phases of dispersion, when the cloud is growing rapidly, both field trials[7] and laboratory experiments[8] indicate that the leading edge resembles the front of a gravity current, with a raised head, where there is considerable mixing with ambient air. This mixing is a complicated three-dimensional effect[8] but here a much simplified scheme is adopted, in which the entrainment is related to the area of the cloud edge and an entrainment velocity, proportional to the rate of advance of the edge. Hence considering a small plume element of edge area 2h dx, then the air inflow through this area occurs at a velocity α_1 dL/dt. Thus the rate of air mass entrainment

$$\frac{dM_a}{dt} = 2hdx\, \varrho_a\, \alpha_1 \frac{dL}{dt} \quad \ldots (10)$$

and in terms of air mass flux through the plume and downwind distance

$$\frac{d\dot{M}_a}{dx} = 2h\, \varrho_a\, \alpha_1 \frac{dL}{dt}\ . \quad \ldots (11)$$

Specification of top entrainment requires an understanding of processes operative at a stable density interface. Germeles and Drake[17] have suggested an entrainment velocity, for the top surface, proportional to the local difference of cloud slumping and ambient wind velocities. Such velocity shear generates mechanical turbulence and through this entrainment to the cloud. However, top entrainment is of most importance when such velocity shear is small and the ambient atmospheric turbulence is dominant. In this case, the form of entrainment velocity of Cox and Roe[5] is more appropriate.

$$U_e = \alpha_2\, U_t\, Ri^{-1}$$

$$Ri = (gl/U_t^2)\, \Delta\varrho/\varrho_a \quad \ldots (12)$$

Ri is a Richardson number characteristic of the ambient atmosphere. Equation (12) is valid so long as $U_e << U_t$ but clearly breaks down for small values of Ri, when very large entrainment velocities are predicted. In these circumstances, as the density of the cloud approaches that of air, mixing is determined, not by the density difference, but by the ambient turbulence and is Richardson number independent, the entrainment velocity tending to some constant fraction γ (originally thought to be close to one) of the turbulence velocity. The values of turbulence length scale l, and longitudinal turbulence velocity, U_t, required for Equation (12), are obtained from tabulations. l is given as a function of stability and height above ground by Taylor et al,[9] and U_t is computed from

$$U_t = \left(\frac{U_t}{u_*}\right) \cdot \left(\frac{u_*}{u_r}\right) \cdot u_r$$

The first and second bracketed quantities are given as functions of only Pasquill stability category and surface roughness respectively. This has been presented in Table 1. However, some variation of (u_*/u_r) with stability is also observed. α_2 is a further constant, for top entrainment, to be fixed by assessment of experimental and theoretical investigations of density interfaces. As for edge entrainment, a rectangular element of width 2L and length dx is considered. The rate of entrainment of air through this area is

$$\frac{dM_a}{dt} = 2L\, dx\, \varrho_a U_e$$

Thus the change of air flux with distance along the plume is given by,

$$\frac{d\dot{M}_a}{dx} = 2L\, \varrho_a U_e \qquad \ldots (13)$$

By combining Equations (12) and (13) and substituting an expression for gaseous volume flux, Equation (3), an expression for the total change of air mass flux, due to simultaneous edge and top entrainment, can be obtained:

$$\frac{d\dot{M}_a}{dx} = 2L\, \varrho_a U_e + \frac{\varrho_a \dot{V} \alpha_1}{L} \frac{dL}{dx} \qquad \ldots (14)$$

2.4 Cloud heating

Dense gas clouds are often produced at temperatures far below ambient and hence absorption of heat, from the ground and from entrained air, is an important process by which they may gain positive buoyancy. In principle, heating mechanisms, such as solar radiation, can be incorporated in the model but only the above two are considered here. Heat exchange with the ground is assumed to occur by turbulent natural convection. If the cloud is colder than the ground, the heating rate per unit area for this process is given by[2]

$$Q = \alpha_3 (T_{gr} - T_c)^{4/3} \qquad \ldots (15)$$

where

$$\alpha_3 = 0{\cdot}1457\, K' \left[\frac{\varrho_f^2\, g\beta_f}{\mu_f^2} \left(\frac{C_p \mu}{K'} \right)_f \right]^{1/3}$$

In some cases the dominant heat transfer mode will be forced convection. This occurs when the Richardson number, Ri, is small and, by using the Reynolds analogy for heat and mass transfer, the local heat transfer rate can be computed from

$$Q = 1/2\, C_f\, \varrho_c\, C_p\, u' (T_{gr} - T_c) \qquad \ldots (16)$$

where

u' = local difference of the wind and the cloud slumping velocity,

and

C_f = friction factor, given by $2(u_*/u_c)^2$. $C_f \sim 10^{-3}$ for sea and 10^{-2} for rough open terrain.

Application of a simple heat balance to a cloud element then gives the rate of temperature rise of the cloud due to ground heating and entrained air. Thus

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* *Strictly speaking, the quantity used for U_t should be the vertical component of the turbulence velocity and not the longitudinal component. The confusion of these quantities in Equation (12) has arisen from experimental reports in which the longitudinal component is most quoted because it is much more easily measured.*

$$\frac{dT_c}{dx} = \frac{1}{\dot{M}_a C_{pa} + \dot{M}_g C_{pg}} \left[\underset{(a)}{(T_a - T_c) C_{pa} \frac{d\dot{M}_a}{dx}} + \underset{(b)}{2LQ} \right] \qquad \ldots (17)$$

Here (a) and (b) represent heating due to entrainment and ground heating respectively. The parameter, Q, appearing here, is computed from expression (15) or (16). For each situation, it is not immediately clear which is the dominant heat transfer mechanism and both must be computed before a decision is reached. In general, forced convection seems to be more effective for most cases on rough terrain. For a release on a smoother surface such as sea, transfer is by natural convection for all but the highest wind speeds.

2.5 Transition to the passive phase

As the cloud gains buoyancy, either through entraining air or by cloud heating, its density approaches that of its surroundings, and at some distance downwind it may be considered to disperse as would a neutrally-buoyant cloud. This distance is specified, in the model, by the application of two criteria. Satisfaction of **either** of these criteria deems the plume immediately passive. Thus the transition, though in reality continuous, is assumed instantaneous.

2.5.1 Test 1

This consists of two tests, both of which must be satisfied simultaneously before the cloud is considered to be neutrally-buoyant.

The rate of lateral growth of the plume, due to atmospheric turbulence, must be greater than that due to gravity spreading, i.e.

$$\frac{dW}{dx} > \frac{dL}{dx} \qquad \ldots (18)$$

where W is the 'half-width' of a Gaussian plume, conventionally taken here to be at the 10% of peak concentration level, and so given by $2 \cdot 14\, \sigma y$. σy is the usual lateral standard deviation of the plume and is dependent on stability category and downwind distance.

Additionally, the relation $U_e > U_t$ must be satisfied and Equation (12) still applies. This ensures that turbulence is dominant in fixing the height of the cloud, with mixing determined by ambient turbulence and not controlled by the interface density difference.

2.5.2 Test 2

The plume is also considered to be neutrally-buoyant when the density difference between the cloud and the surrounding air has become less than some arbitrarily chosen small value. In the present model this is given the value 1×10^{-3} kg m^{-3}. Hence

$$(\varrho_c - \varrho_a) < 1 \times 10^{-3} \text{ kg m}^{-3} \qquad \ldots (19)$$

2.6 Passive diffusion

The idealised variation of plume width with distance downwind is shown in Fig. 3. When the plume is neutrally-buoyant, at distances downwind of the transition[11] point, the concentration profile, taken to be Gaussian, is given by

$$C(x,y,z) = \frac{\dot{M}_g \exp\left(-y^2/2\sigma_y^2(x)\right)}{2\pi\sigma_z(x)\,\sigma_y(x)\,u_c} \cdot S(x,z) \qquad \ldots (20)$$

where

$$S(x,z) = 2\exp\left(-z^2/2\sigma_z^2(x)\right)$$

and

$$C(x,O,O) = \dot{M}_g/(\pi\sigma_z(x)\ \sigma_y(x)\ u_c)$$

The width and height of the plume during this phase are specified by the lateral and vertical standard deviations, $\sigma_y(x)$ and $\sigma_z(x)$, functions of atmospheric stability category, roughness length and downwind distance. The initial conditions of the passive phase are defined using continuity of plume height h_t, and half-width L_t, at the transition point. Not all plume parameters can be continuous at $x = x_t$, since the Gaussian distribution has only two degrees of freedom. Thus, assuming the cloud edges are defined by the 10% of peak concentration contour, the equivalent passive dispersion parameters, at the transition point, are

$$\sigma_{yt} = L_t/2\cdot 14$$
$$\sigma_{zt} = h_t/2\cdot 14 \qquad \ldots (21)$$

During the slumping phase, the width and height of the plume respectively grow more and less rapidly with downwind distance than would the width and height of a passive plume, released under the same conditions. Thus, at the transition point, the plume width is equivalent to the width of a neutral plume released from a point X_{vy} upwind of the actual source, and the height is that of such a plume originating at a distance X_{vz} downwind of the source. These are shown on Fig. 3, the plan and elevation views of the plume.

The problem remains to take account of this initial plume development on dispersion downwind of the transition point. There are several ways of allowing for this. Cox and Carpenter[5] have used a virtual line source to match plume width and ground level concentrations at the transition and the plume height is discontinuous. In CRUNCH two separate virtual sources are used, one for lateral plume spread and another for height variation.

The positions of these virtual sources are shown in Fig. 3 and are determined from the relations:

$$\sigma_y(X_{vy}) = \sigma_{yt}$$
$$\sigma_z(X_{vz}) = \sigma_{zt} \qquad \ldots (22)$$

Here the values of σ_{yt} and σ_{zt} are those of Equation (21) and σ_y and σ_z are dependent on atmospheric stability and roughness length, being calculated according to the scheme of Hosker.[10] These values, obtained by consideration of experimental releases, are appropriate to emissions of 10-60 minutes duration. Use of the Hosker parametrisation for σ_y and σ_z in Equation (22) produces two complex equations for X_{vy} and X_{vz}. These are solved using Newton's method of successive approximations. Knowledge of X_{vy} and X_{vz} then allows computation of dispersion parameters downwind of the transition point by substitution of the distance to the virtual source, for the downwind distance, in the formulae detailed in Tables 1 and 2.

The use of such a virtual source formulation to take account of initial source size seems to produce very similar results to other techniques used, for example, by Cox and Carpenter.[5] However, the method predicts faster growth of plume dimensions than using the sum of squares of the variances formulation used in the similar instantaneous source code DENZ. Thus this produces a swifter decay of contaminant concentration.

2.7 Source specification and model summary

Equations (8), (14) and (17) form a set of coupled non-linear differential equations in the independent variables L, $\dot{M}_a$ and T_c. While the plume is denser-than-air, the computer code CRUNCH integrates these equations numerically and, with the aid of equations for the plume parameters and wind speed, 4, 5, 6 and 9, the growth of the plume at distances downwind can be determined. When either Tests 1 or 2 have deemed the plume passive, the concentration profile is assumed Gaussian with cloud concentration given by 20 and the width and height determined from 22. Application of the relation 21 ensures continuity of cloud height and width. To start the integration, however, initial values of the program variables are required. This involves specifications of the source strength, and size of the initial rectangular window through which the gas emerges. In the model this can be done in two ways:

(a) If only the initial gaseous flux is known, assumptions must be made regarding source configuration. The source, in this case, is taken to be a rectangle of equal height and half-width. This parameter, L_o, must initially be computed by hand and input to the code. The procedure for this is to use the relationship between the initial gas volume flux and source dimensions, i.e.

$$\dot{V}_o = 2 L_o^2 u_c (L_o/2) \qquad \text{... (23)}$$

Here $u_c (L_o/2)$ is the wind velocity at the source half-height. Thus, assuming a logarithmic wind velocity profile, substitution in Equation (23) for u_c gives

$$\dot{V}_o = 2 L_o^2 u (z_r) \frac{\ln (L_o/2z_o)}{\ln (z_r/z_o)} = u (z_r) F (L_o). \qquad \text{... (24)}$$

This equation is not easily solved for L_o but an approximate solution can be obtained using Fig. 4. This shows the variation of $F (L_o)$ with L_o, using z_r = 10 m and z_o = 0·01 – 1 m. Similar curves can be constructed for other values of z_r and z_o. Thus knowledge of the initial volume flux $\dot{V}_o$ and $u (z_r)$ allows computation of $F (L_o)$, the abscissa of Fig. 4. L_o is then the corresponding ordinate. As a check CRUNCH reconstructs the gaseous mass flux using Equation (23) and the equation $\dot{M} = \varrho\dot{V}$. This must approximate to the actual release rate.

(b) One common release mode in which a steady-state model may be applied is in the calculation of dispersion of a dense vapour emitted from a boiling liquid pool. In this case the source may be of very large areal extent and possess a small vertical dimension. The assumption of equal height and half-width becomes invalid and application of the method above for calculation of L_o can lead to a distorted plume.

In such a situation, the initial half-width of the plume, L_o is known and it is necessary to calculate the initial height, h_o. Thus Equations (23) and (24) become:

$$\dot{V}_o = 2 L_o h_o u (h_o/2) \qquad \text{... (25)}$$

$$\dot{V}_o = 2 L_o h_o u (z_r) \frac{\ln (h_o/2z_o)}{\ln (z_r/z_o)} = L_o u (z_r) F' (h_o) \qquad \text{... (26)}$$

The function $F' (h_o)$ is shown in Fig. 5. Using a similar technique to that above, the initial height, h_o, can be obtained from this plot using the gaseous volume flux, the wind speed at the reference height and the known source width to compute $F' (h_o)$. Again, the code CRUNCH reconstructs the gaseous mass flux as an accuracy check of this procedure.

Some choice of empirical constants K, α_1, α_2 and γ must also be made from both experimental data and theoretical arguments. The values currently used in the model are respectively 1, 0·20, 0·60 and 1. K, the gravity-spreading constant was originally thought to be $(2)^{1/2}$. Correlations with recent experiments[7,8] suggest this to be an overestimate and have indicated a value closer to unity. These same experiments have also suggested that, close to the source, there is vigorous mixing at the cloud edge and this can be an important dilution process. Consequently, values of the edge mixing coefficient have risen to account for this and that given above was obtained from examination of Picknett's Porton data. A similar reassessment of top entrainment has taken place with α_1 now taking the value indicated above, lower than was initially used in the code. This was determined from analysis of both Porton and Gadila data.[13] The constant γ contains the limiting value of entrainment velocity through the cloud top, when the difference in density between inside and outside the cloud is small. For lack of any data on such situations γ has been set at 1·0, thus putting this limiting entrainment velocity equal to the longitudinal turbulence velocity.

3. VALIDITY OF THE MODEL

3.1 Analytic solutions of model equations

To enable comparison of predictions with analytic models and verify numerical results, it is useful to have some simple formulae for cloud development. This becomes possible if cloud heating is neglected and only ambient temperature releases considered. Thus the governing equations are reduced to the two Equations (8) and (14), for the growth of plume half-width and entrained air mass flux. It is possible for particular situations and by means of some simplifying assumptions to integrate these equations analytically. Coupling of Equations (8) and (14) is through u_C, the velocity of the cloud, which is a function of plume height and thus gaseous cloud volume flux. A considerable first approximation is to take the cloud velocity as constant, removing the coupling and allowing successive integration of Equations (8) and (14). Details of such a procedure and further assumptions used are found in Appendix 1. In this case the plume width grows according to Equation (A3) which simplifies to:

$$L \alpha x^{2/3} \qquad \ldots (27)$$

Such a result has also been obtained by Britter,[11] for a constant velocity plume with no mixing and seems to be a well-founded relation. The mass of air entrained to the plume follows (Equation (A4)).

$$\dot{M}_a \alpha x^{2\alpha_1/3} . \exp (x^{5/3}) \qquad \ldots (28)$$

where the first index above shows the variation of edge entrainment and the second refers to air entrainment through the cloud top. The predictions of such equations have been compared with code results for identical situations. Figure 6 shows this comparison for a release of 1 $m^3 s^{-1}$ of chlorine into neutral weather conditions (Pasquill category D), with a constant wind velocity of 5 ms^{-1}. The close agreement indicates the satisfactory numerical accuracy of the computational solution procedures. Such simplified equations can also be used to indicate the sensitivity of plume predictions to the choice of windspeed. Some dispersion models use a single windspeed, sometimes measured at a height of 10 m, whereas the method used here assumes a logarithmic wind profile. For a small release, in which the cloud slumps to low heights, use of a constant 10 m windspeed is unrealistic, and produces very inaccurate dispersion predictions, as the additional curve of Fig. 6 shows. Dispersion predictions seem sensitive to this parameter and care must be exercised in its choice.

It is also possible to obtain analytic solutions of model equations for a varying cloud velocity, at certain limiting stages of cloud growth. This is presented in Appendix 1 for occasions when edge and top entrainment are separately dominant, respectively close to the source and when the cloud/air density difference is small.

3.2 Comparison with experimental data

There is a distinct lack of good experimental data on dense gas dispersion and there is a critical need for activity in this field. Prior to release of data from the Shell Maplin Sands results, the only suitable spill for validation of a continuous release steady-state dispersion model remains that carried out from the SS Gadila.[13] The majority of tests so far carried out have involved boil-off from small liquid pools, resulting in a time-dependent vapour emission rate. However, those from the SS Gadila were of such size and duration that such difficulties were overcome. In these experiments, large quantities of liquefied natural gas (LNG) were ejected from the stern of a large LNG carrier. The plume was observed by surface and airborne cameras, the extent of the visible plume indicating the 0·5% molar concentration contour. No measurements were made within the cloud.

Checks indicated that, of the series of spills reported by Kneebone and Prew,[13] numbers 4 and 6 provided steady-state vapour emission rates. Figures 7a and 7b show a comparison of the measured variation of plume width with downwind distance, inferred from overhead photographs, and CRUNCH predictions, for these two experiments. With due account of the uncertainties both in the model and measurements, agreement must be considered highly adequate, especially for run 4 and widths of both plumes. The underestimation of plume persistence for the larger spill has also been observed with the similar model of Cox and Carpenter[5] and less markedly so by that of te Riele.[15] The reason for this is not yet clear but could be due to an overestimated surface roughness parameter used in the model or failure to account for any entrained water droplets. The only other parameter reported from the Gadila spills was an estimate of plume height. This, in agreement with the observations of Britter, yet in contrast with instantaneous source release experiments, showed little variability with downwind distance, for example, the plume of spill 6 remaining at 10-12 m throughout its travel. Such a constant height could be due to large and dominant edge mixing and is not well predicted by the model of the CRUNCH type, which give a slumping cloud.

3.3 Assessment of model assumptions

In such a simple model many assumptions and simplifications are necessary and it is not possible to justify each one separately. However, here some of the major simplifications will be assessed to indicate the approximate range of model validity. A justification of the use of slumping formula can be found in Fryer and Kaiser.[2] An examination of the little entrainment information is also presented, though it can be argued that, in a continuous source model, edge entrainment has relatively greater importance.

In so far as it provides a flow of contaminant, from a vertically-placed rectangular window, the model assumes the source has no influence on the subsequent dispersion. For a source to attain a steady-state, as is required by the model, variations in source strength must take place on a time scale large compared with the dispersion time. An estimate of the time required for dispersion can be obtained from the time taken for a plume element to advect downwind to a point where it reaches the lower flammable limit (LFL). In practice, however, this condition need not be so stringently adhered to and, if the release time and dispersion time are of similar order, then the continuous source model can be used. For cases, intermediate between an instantaneous and a continuous steady source, few models are available, but CRUNCH may be used in conjunction with an instantaneous release model, to give some estimate of the dispersion. For a specified source, CRUNCH can be applied by first computing the total mass of vapour emitted. A representative constant release rate and release duration can then be obtained and used in the model. The dispersion estimates obtained must, however, be qualified by similar estimates obtained from assumptions that the same material is released instantaneously and use of a suitable model. A dispersion estimate for a time-varying source should fall between the 'continuous' and 'instantaneous' figures since, for the release of a given mass of contaminant, the shortest and longest distances to LFL are produced by respective assumptions of a constant continuous and instantaneous source. Cox and Carpenter[5] have produced criteria for the problem of when to apply instantaneous and continuous release models. However, their choice seems somewhat ad hoc, having little physical basis.

The model also takes no account of source configuration or possible initial momentum of the contaminant as, for example, from a jet release. Present methods of allowing for such influences use only empirical factors to account for the initial dilution of the plume. Near-field flow effects are ignored. Such an approach is valid providing source momentum does not affect the ambient flow field. Thus source momentum is unimportant providing the efflux velocity of the contaminant u_S satisfies the relation

$$u_S << u_C \, (\varrho_a/\varrho_g)^{1/2} \quad \ldots (29)$$

Such a relation can be parameterised in terms of source flux and applied to both vertical and horizontal source momenta. Thus for a butane emission at an efflux velocity typical of evaporation from a liquid pool on land, say $0 \cdot 5$ ms^{-1}, then CRUNCH gives an accurate picture of dispersion for wind velocities (at the cloud height) greater than ~ 2-3 ms^{-1}. The plume will also spread upwind, a factor not computed by the present model. The penetration upwind of a dense gas plume seems dependent on the buoyancy flux and has been experimentally investigated by Britter.[11] It is during initial stages that cloud acceleration effects are most important. However, Cox and Carpenter[5] have argued that these are minor because times over which the cloud is accelerated to the ambient windspeed are very short. The effect of omission of these processes, though difficult to assess would tend to produce a conservative estimate of the hazard range.

Along the wind, advection is assumed to dominate gravitational spreading, another simplification which appears better at high wind speeds. The rate of cloud slumping is greatest at the source and decreases with downwind travel, so any neglect of gravitational effects must be most important close to the source. The parameter controlling slumping of a plume element is the pressure difference across it and this is determined, in turn, by the density gradient along the plume. Using the expressions of Appendix 1, the variation with downwind distance of such quantities can be determined and, for particular releases, the validity of assuming advection only along the wind, examined. Such an analysis shows that the model is most suitable for application in high wind speed conditions and that, for the smallest releases, advection velocities at the height of the cloud ~ 1 ms^{-1} are necessary for the model to apply at distances within 10-20 m of the source. For lower wind velocities, the model will not give satisfactory predictions until the plume reaches downwind distances of 50-100 m.

Effects of wind shear are difficult to estimate and are of small importance for a continuous plume extending large distances downwind. With increasing height in the cloud, different horizontal sections may advect at different rates but since this merely causes displacement and no overturning then there can be little additional mixing. Choice of an invariant cloud velocity only appears to become critical for very small cloud heights but, providing the cloud height everywhere appreciably exceeds the surface roughness length, then wind shear effects are unimportant.

4. OTHER CONTINUOUS RELEASE MODELS

4.1 Alternative treatments

There have recently been several other examinations of the continuous release dense gas problem and though different approaches have been adopted their predictions are remarkably similar.

The model of Cox and Carpenter[5] is closely related to CRUNCH, describing simultaneous spreading, advection, heating and entrainment, with transition to final passive behaviour. Differences arise in the treatment of cloud heating, as forced convection is considered to be dominant, and advection, which is assumed to occur at a constant 10 m height windspeed. Such factors may slightly increase predictions of downwind plume travel. The major differences lie in the treatment of later stages of dispersion. When the density of the cloud is close to that of air, a lower limiting value of entrainment velocity is used. Also a finite length crosswind line source has been applied, with matching to the dense phase by assuming continuity of plume centre line concentration and width, for the passive cloud. Again such factors, though tending to slightly increase the downwind length of the plume, must be considered minor.

Britter[11] has developed a model based on experiments in water flumes. A highly simplified semi-empirical approach was adopted in which neither mixing of ambient fluid, passive phase, variable advection velocity nor cloud heating were considered. It is thus a close approximation to the situation for which analytical solutions to model equations are obtained in Appendix 1. Britter examined the effects of source size and momentum, and compared plume lateral growth with laboratory and full-scale data. Good agreement was obtained at medium ranges, but such a model cannot predict dispersion near contaminant LFL's, since dilution of the plume is not considered. In comparison with CRUNCH, Britter's approach predicts a wider plume due to the neglect of mixing and, consequently, a faster rate of lateral spread.

The approach of Eidsvik[6] is strikingly similar to that in CRUNCH, though it has recently been extended to account for time dependent vapour sources[14] and a continuous transition between dense and passive phases. However, edge entrainment is only considered during initial stages of cloud growth, and the plume is advected at a constant windspeed, independent of cloud height. In addition, the only heat transfer mode computed is forced convection. The top entrainment mechanism chosen attempts to include both the effects of organised convection, due to temperature gradients across the cloud, and of mechanically produced turbulence (as in CRUNCH). The former appears more important for small ambient wind speeds and during early stages of cloud development. Thus for high wind speeds, the two models should show good agreement and differences should be most marked in low ambient wind speeds.

A more complex model is that of Colenbrander[4] which accounts for continuous releases from transient vapour sources and allows for vertical and lateral variation of concentration within the plume, though this assumes a given shape. Vertical expansion of the plume is computed using an eddy diffusivity model, with some allowance for density and stability effects. In the lateral direction, an eddy diffusivity approach is again used and there is the usual liquid column analogy for gravitational spreading. Any relation of such a model to the relatively simple approach used in CRUNCH in difficult to assess and must await suitable experimental data. All effects considered in CRUNCH appear in Colenbrander's formulation with greater rigour, excepting that of heating of the cloud both from the ground and entrained air.

4.2 Comparissons with CRUNCH

Preliminary comparisons of release predictions of CRUNCH with some of the alternative approaches outlined above, have been made.

Table 3 contains estimates given by CRUNCH and two other models of the distance and width at the 0·5% methane concentration level for the Gadila experiments 4 and 6. CRUNCH appears at the lower end of the range of values presented, but the variaton may be due to differences in model input parameters due to the lack of experimental measurements. In general, however, there are no order of magnitude disagreements and, with due allowance for the lack of understanding of processes modelled, such differences are understandable at the present time.

The simpler models of Britter and Eidsvik have been compared with formulae of Appendix 1. Thus all models show that the plume width is proportional to x^n, where $n \sim 2/3$, and CRUNCH and the Eidsvik model indicate that downwind variation of concentration should approximately vary with the inverse square of the downwind distance. Thus although differing in details such simple models appear to produce similar overall behaviour.

5. CONCLUSIONS

The computer code CRUNCH, embodying the modelling described above, must be regarded as a first step in the construction of a physically realistic dispersion model for long-period releases of a dense gas. Several possible improvements to the existing model could be considered. These include automation of the calculation of the initial plume dimensions and possible modification of the limiting top entrainment velocity at low Richardson Numbers.

The dense/passive transition remains a little understood part of such models. The present ad hoc method employed because of the few degrees freedom of the Gaussian model, results in discontinuities of plume parameters at the transition point. A few of the present models do allow for a more realistic continuous transition but, in order that this should be possible, other unproven constraints are applied to the plume, such as an assumed density distribution. It is possible only 3D hydrodynamic models may treat this problem satisfactorily.

The code requies a steady continuous source which severely limits its applicability. However, some estimate of the hazard range of a time-varying release can be obtained by sensible assessment of hazard range predictions computed assuming the same quantity of material is released from a constant continuous source (using CRUNCH) and instantaneously (DENZ).[2] The range for a transient source should fall between these two predictions, since an instantaneous release case has been shown to give the greatest dispersion distances.

Other assumptions of the model would seem to make it more suitable for high wind speed conditions over rough surfaces with low roughness length, z_0. Thus it is most accurate at windspeeds $\gtrsim$ 5 ms^{-1} and terrain with $z_0 < 20$ mm. However, to take account of slumping in the wind direction, initial source momentum and shear effects would require a much more complex formulation and a complete new model. A set of good experimental data remains a great need in this field and would provide invaluable validation of the approach and assumptions used. Also it is possible that entrainment coefficients, set with reference to both instantaneous and continuous release experiments, would be modified with reference to such data.

6. APPENDIX 1

Analytic solutions of model equations

6.1 Using a constant cloud velocity

Equations (8) and (14) can be rewritten, when an ambient temperature release is considered, in the form

$$\frac{dL}{dx} = A\,(Lu_c^3)^{-1/2} \qquad \text{... (A1)}$$

$$\frac{d\dot{M}_a}{dx} = BL\,(\dot{M}_a + C) + [\alpha_1\,(\dot{M}_a + C)/L]\,dL/dx \qquad \text{... (A2)}$$

where

$$A = K\,[g\dot{M}_g\,(1 - \varrho_a/\varrho_g)/2\varrho_a]^{1/2}$$

$$B = 2\,\varrho_a\,\alpha_2\,U_t^3/gl\,\dot{M}_g\,(1 - \varrho_a/\varrho_g)$$

$$C = \dot{M}_g\varrho_a/\varrho_g$$

Thus providing a constant turbulence length scale and longitudinal turbulence velocity are assumed then A, B and C are constants for any particular release and weather conditions. Such assumptions seem valid for a small release for which the cloud height remains small and shows little variation. Integrating Equation (A1) under these conditions gives

$$L = [L_o^{3/2} + A'\,x]^{2/3} \qquad \text{... (A3)}$$

where

$$A' = \frac{3}{2}\,Au_c^{-3/2}$$

and

$$L = L_o \text{ at } x = 0$$

Thus in this case the lateral spreading depends only on the buoyancy flux. $\dot{V}_g g'$ and is independent of the entrainment processes.

Substitution of Equation (A3) allows direct integration of Equation (A2) producing the variation of the air mass flux with downwind distance. Thus

$$\dot{M}_a = C\,[X^{2/3\alpha_1}\,\exp\big(3B\,(X^{5/3} - L_o^{5/2})/5\,A'\big)/L_o^{\alpha_1} - 1] \qquad \text{... (A4)}$$

where

$$X = (A'\,x + L_o^{3/2})$$

and

α_1 is the edge entrainment coefficient.

The downwind variation of contaminant concentration can then be inferred from relation Equation (6). Expression (A4) shows the dominance of two different processes – edge and top entrainment, at different distances from the source. At short ranges the exponential factor is small and $\dot{M}_a \sim CX^{2/3\alpha_1}/L_o^{\alpha_1}$ (edge entrainment). At greater distances top entrainment, represented by the exponent of (A4), becomes more important.

Using this approach it is possible to assess the validity of neglecting gravitational spreading in the direction of the ambient wind. Considering a linear equation of state and steady motion only, a variation of the gravitational slumping velocity, with plume density, and thus downwind distance, can be obtained. The following approximate relation applies:

$$u \sim (4RT/M_a)^{1/2} \, [\ln(\varrho_a/\varrho_c) + (\varrho_c/\varrho_a) - 1]^{1/2} \quad \text{... (A5)}$$

Thus, near the source, for the 1 $m^3 s^{-1}$ release of chlorine, (considered in Section 3.1), slumping velocities $\sim 0 \cdot 25$ ms^{-1} are expected at $\sim$ 10 m from the source. Consequently, the advection velocity of the cloud must greatly exceed the value predicted by Equation (A5) for CRUNCH to produce an accurate picture of the dispersion.

6.2 Using a variable cloud velocity

Describing the wind profile by means of a logarithmic relation as in CRUNCH renders the equations difficult to solve. However, some progress can be made using a power law form of the wind profile. In the lowest parts of the atmosphere this can be written as:

$$u_c = u_r \, (h/2z_r)^m \quad \text{... (A6)}$$

with m $\sim 0 \cdot 2$ Equations (A1) and (A2) can now be considered when top and edge entrainment are separately dominant, respectively close and far away from the source.

(a) During the first stages of cloud growth, for all but the smallest releases $\dot{M}_g >> \dot{M}_a$ and $\dot{V} \sim \dot{M}_g/\varrho_g$. Using this approximation, Equations (A1) and (A2) can be integrated For initial cloud growth, therefore, the variation of lateral width is described by:

$$L = (L_o^{5/4} + Dx)^{4/5} \quad \text{... (A7)}$$

where D is a constant dependent on release and atmospheric condition, being computed from

$$D = K[g \, \dot{M}_g \, (1 - \varrho_a/\varrho_g)/2\varrho_a u_r \times (4z_r \, \varrho_a/\varrho_g \, \dot{M}_g)^{1/5}]^{1/2}$$

Close to the source only edge entrainment need be considered. Thus the RHS of Equation (A2) need only consist of the first term. Substitution of the relation above for L and the full expression for $\dot{V}$ permits integration of Equation (A2). The variation of air mass flux with downwind distance is again a power law relation and takes the form:

$$\dot{M}_a = C \, [(X^{\cdot 8}/L_o)^{\alpha_1} - 1] \quad \text{... (A8)}$$

Thus $\dot{M}_a$ varies approximately as $x^{\cdot 56}$ close to the source with $\alpha_1 = 0 \cdot 70$. Here C is as previously defined and $X = (L_o^{1.25} + Dx)$.

(b) At larger distances downwind the lateral width of the cloud increases only very slowly and top entrainment, which increases the cloud height is the most important process. In the region where $(\varrho_c - \varrho_a) \rightarrow 0$;

$$\frac{dh}{dx} = \frac{U_e}{u_c} \sim \frac{\varepsilon U_t}{u_c}$$

where ε is a constant, in this case taken to be unity. Thus.

$$h = [(u_t \, (2z_r)^m/u_r) \, (x - x') + h'^{1+m}]^{1/1+m} \quad \text{... (A9)}$$

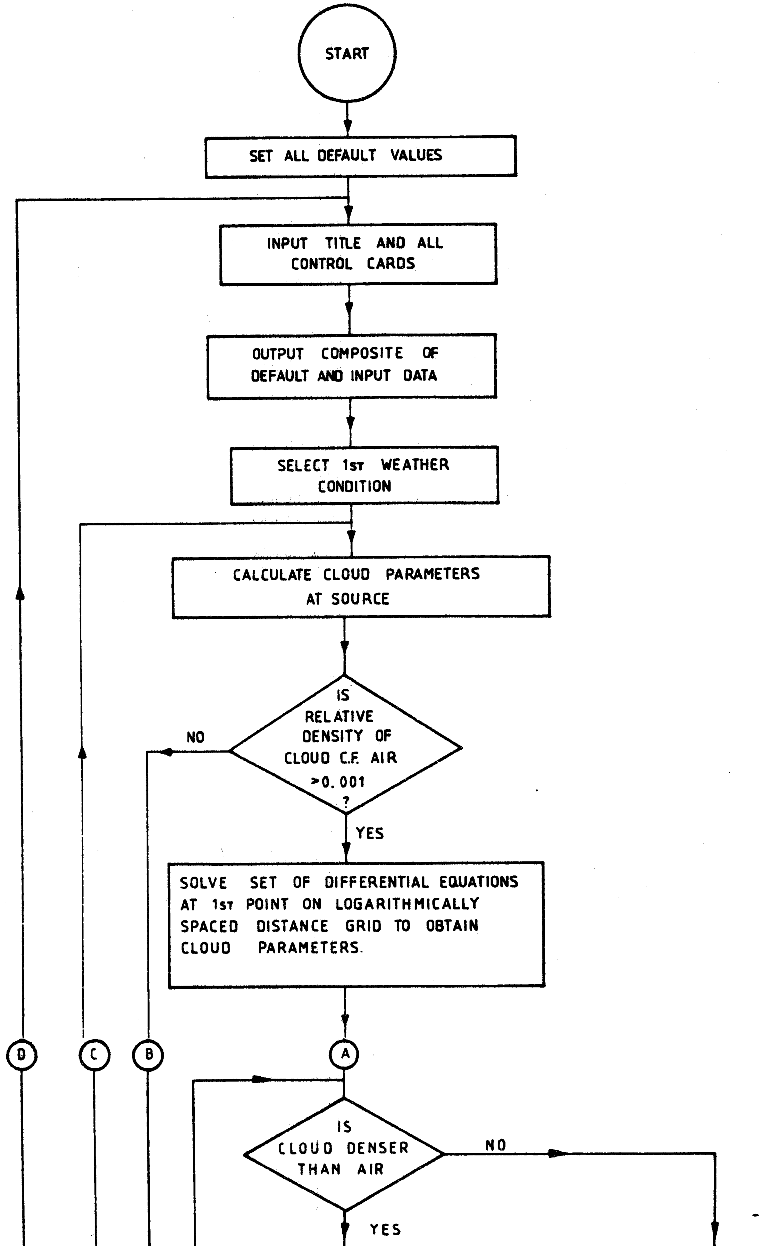
describes the growth of the cloud in the later gravity-dominated stages, x' and h' denoting the downwind distance and height of the plume when top entrainment becomes dominant. Equation (A9) can be used to provide a solution to Equation (A1) for the growth of the plume. With $m = 0 \cdot 2$, this can be written in the form

$$L^{3/2} = A'' \left(x^{3/4} - x'^{3/4}\right) + L'^{3/2} \qquad \ldots \text{(A10)}$$

and

$$A'' = A \left[u_r \, u_t \, (2z_r)^{1/5}\right]^{-1/4}$$

The air mass flux can be then found by substitution and integration of Equation (A2) as previously shown. In this case, it can be shown to vary as $x^{3/2}$.


START
SET ALL DEFAULT VALUES
INPUT TITLE AND ALL CONTROL CARDS
OUTPUT COMPOSITE OF DEFAULT AND INPUT DATA
SELECT 1st WEATHER CONDITION
CALCULATE CLOUD PARAMETERS AT SOURCE
IS RELATIVE DENSITY OF CLOUD C.F. AIR >0.001 ?
NO
YES
SOLVE SET OF DIFFERENTIAL EQUATIONS AT 1st POINT ON LOGARITHMICALLY SPACED DISTANCE GRID TO OBTAIN CLOUD PARAMETERS.
D
C
B
A
IS CLOUD DENSER THAN AIR
NO
YES

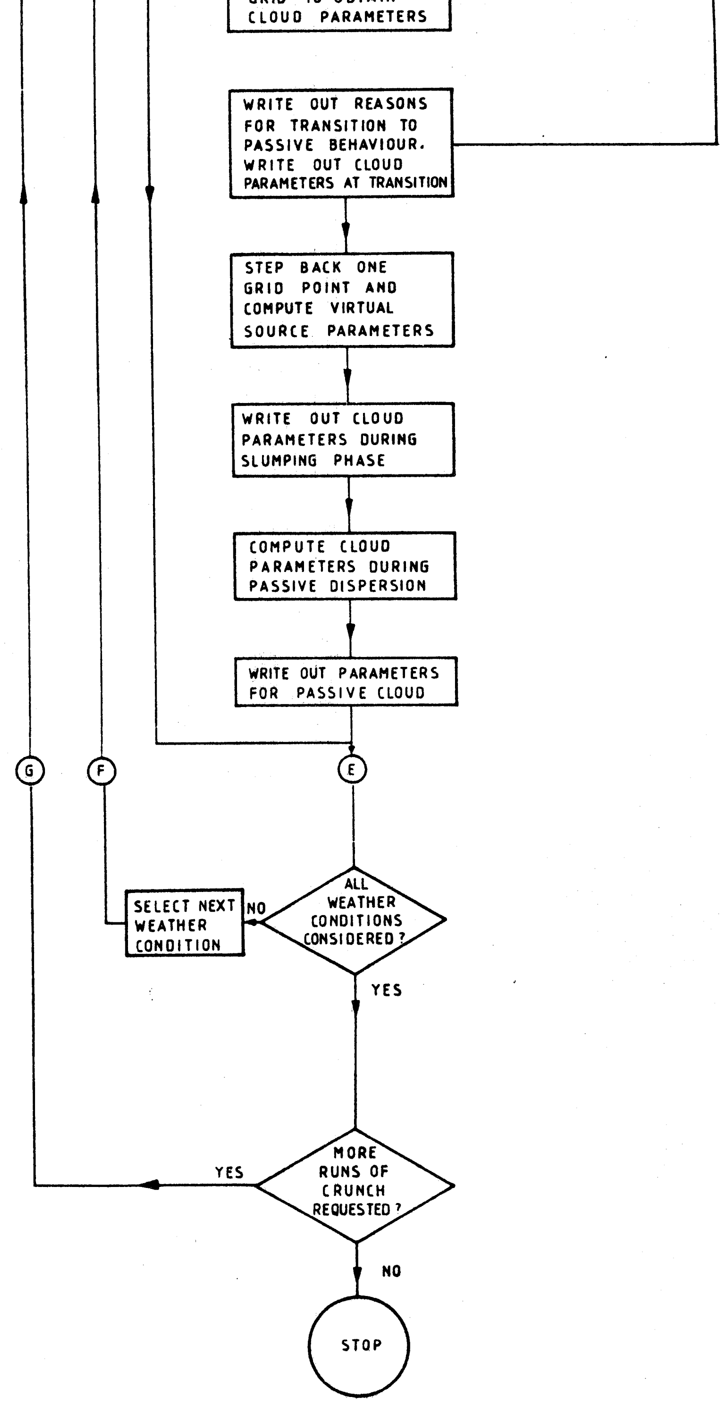


FIG. A1 FLOW CHART FOR CRUNCH

7. APPENDIX 2

Notation

C	Species concentration
cf	Friction factor
C_p	Specific heat at constant pressure
g	Acceleration due to gravity
h	Height of the cloud
K'	Thermal conductivity
K	Proportionality constant in the slumping formula
L	Cloud half-width
M	Gaseous mass
$\dot{M}$	Mass flux
Q	Heat transfer rate
Ri	Richardson number
T	Temperature
t	Time
u	Velocity
U_s	Gaseous efflux velocity
U_t	Longitudinal turbulence velocity
u_*	Friction velocity
V	Gaseous volume
$\dot{V}$	Gaseous volume flux
W	Half-width of a Gaussian plume
x	Downwind distance
z	Height above the ground
z_o	Meteorological roughness length
α_1	Edge entrainment constant
α_2	Top entrainment constant
α_3	Constant in the heat transfer equation
γ	Constant ratio of U_e/U_t for small Richardson number
β	Coefficient of volume expansion
ϱ	Density
μ	Coefficient of dynamic viscosity
σ_z, σ_y	Horizontal and vertical standard deviations of a Gaussian plume

Subscripts

a	Indicates reference to air
c	Refers to a cloud parameter
e	Entrainment values
f	This indicates a parameter computed at the interface between two species
g	Source gas quantity
gr	Ground value
o	Refers to parameters at the source
r	Denotes a reference height at which wind speed is measured
t	Can refer to a turbulent quantity or parameters at the transition from dense to neutrally-buoyant diffusion
v	Indicates a quantity referenced to a virtual source

8. APPENDIX 3

Program details

8.1 Calculational scheme

A flow chart illustrating the calculational scheme within CRUNCH is given in Fig. A1. Briefly, the equations from which the various cloud parameters can be obtained, described earlier, are solved at a series of logarithmically-spaced points on a pre-set distance grid given by,

$$x = \exp\left(0{\cdot}2\,(i - 1)\right) \qquad\qquad i = 1 \text{ to } 50$$

The calculations are performed for each of the weather conditions specified by the user.

The program does not as yet calculate the consequences of the release of the surrounding population. Extension of CRUNCH to perform these calculations should be relatively easily achieved by "transplanting" into CRUNCH routines already developed for this task in DENZ.[2]

8.2 Input and control instructions

Methods for entering data into CRUNCH and selecting different types of calculation are described below. The input instructions are written for users submitting data via cards; data may also be input via VDU's or other devices, provided that they are presented to the code in the fixed format notation described in this section: All instructions to CRUNCH are made via key words, which are in A8 format and left justified, unless otherwise stated all numbers are in E10.3 format and right justified. Columns 9 and 10 are blank on most control cards.

The following symbols will be used throughout this section:

__	to indicate a blank column
( )	to indicate a group of ten blank columns
| |	to enclose a group of ten columns

8.2.1 Title cards

Each new run of CRUNCH must start with one or more title cards. The first four columns of each card must not be left blank; anything appearing in these columns will be ignored and all characters appearing in the remaining 76 columns treated as part of the title and reproduced, verbatim at the beginning of the output. After the last title card there must be one blank card.

8.2.2 Input and control cards

The following cards may appear in any order after the blank card signifying the end of the title cards.

(a) The 'Van Ulden' card

VAN_ULDEN	K	( )	( )	( )	( )	( )	( )

The card specified in colums 11-20, the value to be assigned to the constant K, in the equation governing growth in cloud width (Equation (7)).
Default: If the card is omitted, K = 1.

(b) The 'Alpha' card

ALPHA	α_1	α_2	α_3	( )	( )	( )	( )

The values to be used by CRUNCH for the constants, α_1, α_2 and α_3 in the equations concerned with edge entrainment, top entrainment and heating by turbulent natural convection from the ground (Equations (11), (12) and (17) respectively) are input via this card.
Default: If the card is omitted, $\alpha_1 = 0 \cdot 6$ $\alpha_2 = 0 \cdot 2$, $\alpha_3 = 0$

(c) The 'Air' card

AIR	ϱ_a	T_a	C_{pa}	( )	( )	( )	( )

The card specifies the density ϱ_a Kg/m³, and specific heat capacity, C_{pa}J/Kg/°K, of air at ambient temperature, T_a°K.
Default value: If the card is omitted, $\varrho_a = 1 \cdot 205$ *Kg/m³,* $C_{pa} = 990$ *J/Kg/°K,* $T_a = 293$*°K.*

(d) The 'Gas' card

GAS	ϱ_g	T_g	C_{pg}	( )	( )	( )	( )

ϱ_g is the density of the gas released (Kg/m³) and C_{pg} its specific heat (J/Kg/°K) at temperature T_g(°K).
Default value: None

(e) The 'Ground' card

GROUND	z_o	z_r	a_1	cf	( )	( )	( )

The meteorological roughness length, z_o (m), and height, z_r (m), at which any windspeeds given by the 'weather' card are assumed to be measured, are set by this. The index a_1 should be set to 1 if ground temperatures are to be specified; in this case, further cards containing values for the ground temperature in the various weather conditions are required, where the ith ground number of the jth card refers to the temperature (°K) in the ith velocity subdivision of the jth weather category (A=1, B=2 ... F=6) as defined either by the WEATHER card, which must precede this card if it is used, or the default weather data (Table 2). cf is the friction factor of the underlying surface.
Default value: If the card is omitted $z_o = 0 \cdot 1$, $z_m = 10$, $a_1 = 0$, *cf* $= 0$ *and the ground temperature is 293°K in all weather conditions.*

(f) The 'Weather' card

WEATHER	n_1	n_2	n_3	n_4	n_5	n_6	( )

The card defines the weather conditions around the site. The number of velocity subdivisions in each Pasquill stability category are specified by n_1 to n_6, ($n_i < 4$), where n_i reference to the ith stability category. The following data are then required:

On a new card, n_1 numbers corresponding to the velocity subdivisions (m/s) appropriate to the 1st weather category (A) . Repeat for each weather category for which $n > 0$.
Default value: If the card is omitted values are as on Table 1.

(g) The 'Source' card

SOURCE	L_o	h_o	( )	( )	( )	( )	( )

L_o and h_o are the half-width (m) and height (m) of the cloud at the source.
Default value: None

8.2.3 Cards ending a run of CRUNCH

The following cards are compulsory and most appear after those described above.

(i) The 'Continue' card

CONTINUE	( )	( )	( )	( )	( )	( )	( )

Further runs of CRUNCH may be initiated by this card. It should be followed by the title and control cards described above. Any new data following this card will overwrite all values set on previous similar dated card.

(j) The 'End' card

END	( )	( )	( )	( )	( )	( )	( )

This card is used to define the end of data block. If further runs are required, then it should be followed by a CONTINUE card, otherwise it should be followed by another END card (i.e. the complete set of data are terminated by two END cards), in which case control jumps to the STOP instruction in CRUNCH.

8.3 Output

The output from CRUNCH commences with a title containing information supplied by the user. This if followed by data on the values assigned to:-

(i) The constant, K, in the slumping formula (Equation (1)).

(ii) The constants, α's, in the equations governing edge entrainment (Equation (2)), top entrainment (Equation (4)) and heating by the ground (Equation (9)).

(iii) The roughness length and the reference height of the windspeed.

(iv) The initial temperature, density and specific heat capacity of air and pollutant gas.

The following output is then given for each weather condition:-

(i) The mass flux of pollutant gas at the source.

(ii) The reason for the cloud's transition from negative to neutral buoyancy, the downwind distance at which it occurs and the values of parameters associated with the determination of the transition point.

(iii) The cloud height, half-width and velocity at each point on the logarithmically-spaced distance grid (for points where the cloud is neutrally-buoyant the values output as height and half-width represent the 10% contours of the Gaussian concentration profile).

(iv) At downwind distances at which the cloud is negatively-buoyant, the cloud temperature, density and pollutant gas concentration are given, in addition to data on the volume flux and air mass flux at each grid point.

(v) The ground level centre-line concentration of pollutant gas is output at all distances where the cloud is neutrally-buoyant.

8.4 Coding

CRUNCH is written in FORTRAN 4 for the Risley ICL 2980. Data may be input via data cards or VDU's providing they adhere to the format stipulated. It requires about 10 Kb of store with an extra 25 Kb for data storage. No magnetic tapes or disc files are required.

The program uses a standard NAG library routine (DO2 YAF) for integration of the equations with a Runge-Kutta Mersion integration scheme.

TABLE A.1

Default meteorological data

Stability category	**A**	**B**	**C**	**D**	**E**	**F**
Default wind speed, m/s	1·5	3·0	3·0	3·0 6·0	3·0	2·0

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TABLE 1

Parameters used for computation of longitudinal turbulence velocity and length scale

(a) $l = 5 \cdot 88\ h^{0.48}$

(b) $U_t = X.\ Y.\ u$ where $X = (U_t/u_*)$ and $Y = (u_*/u)$

Y is taken as 0·1 in the code and X, which varies with stability category, is shown below.

Stability category	**A**	**B**	**C**	**D**	**E**	**F**
X	3·0	3·0	2·4	2·4	1·6	1·6

TABLE 2

Calculation of passive dispersion parameters after Hosker(10)

(a) $\sigma_y(x) = c_1 x/(1 + 0 \cdot 0001x)^{1/2}$

Here c_1 is a constant dependent on stability category as shown below.

Stability category	**A**	**B**	**C**	**D**	**E**	**F**
c_1	0·22	0·16	0·11	0·08	0·06	0·04

(b) $\sigma_z(x) = g(x)\ F\ (z_o,x)$

where

$$g(x) = c_2 x^{d_1}/(1 + c_3 x^{d_2})$$

and

$$F(z_o,x) = \ln\left[c_4\ x^{d_3}\ \left(1 + (c_5\ x^{d_4})^{-1}\right)\right] \quad z_o > 0 \cdot 1\ \text{m}$$

or

$$F(z.,x) = \ln\left[c_4\ x^{d_3}\ (1 + c_5\ x^{d_4})\right] \quad z_o < 0 \cdot 1\ \text{m}$$

Here c_2, c_3, d_1 and d_2 are dependent on stability category as given below.

Stability category	**A**	**B**	**C**	**D**	**E**	**F**
c_2	0·112	0·130	0·112	0·098	0·0609	0·0638
d_1	1·060	0·950	0·920	0·889	0·895	0·783
$c_3 \times 10^4$	5·38	6·52	9·05	13·5	19·6	13·6
d_2	0·815	0·750	0·718	0·688	0·684	0·672

and c_4, c_5, d_3 and d_4 are dependent on roughness length.

Roughness length, m	c_4	d_3	c_5	d_4
0·01	1·56	0·048	$6 \cdot 25 \times 10^{-4}$	0·45
0·1	–	0	0	0
1	7·37	−0·0957	$4 \cdot 29 \times 10^{3}$	−0·60
4	11·7	−0·128	$4 \cdot 59 \times 10^{4}$	−0·78

TABLE 3

Comparison of three model predictions of Gadila experiments

Model	**Crunch**		**Cox et al**		**Shell**	
Release	4	6	4	6	4	6
Range (m)	900	1540	–	1730	1160	2100
Width (m)	140	300	–	240	210	375

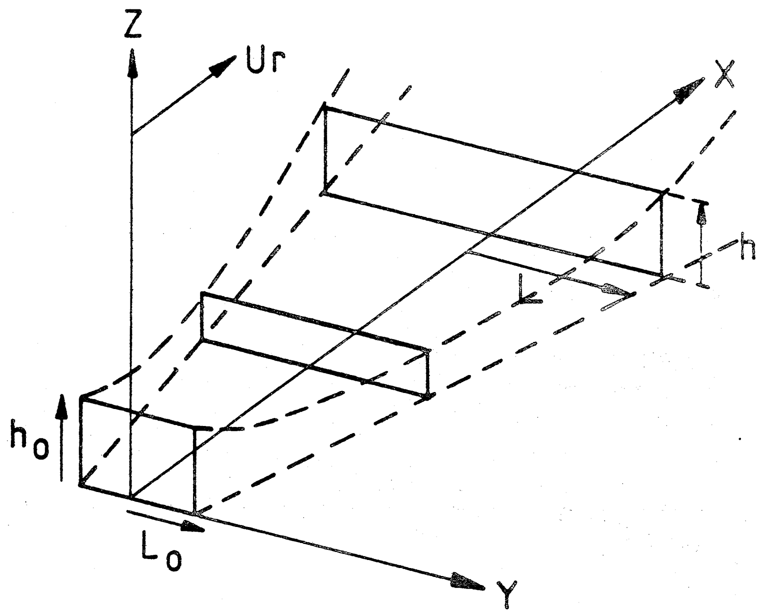


Figure 1 **The configuration of the steady state continuous plume. The source is represented by the plane of dimensions L_o and h_o, and the ambient wind direction is along the x-axis.**

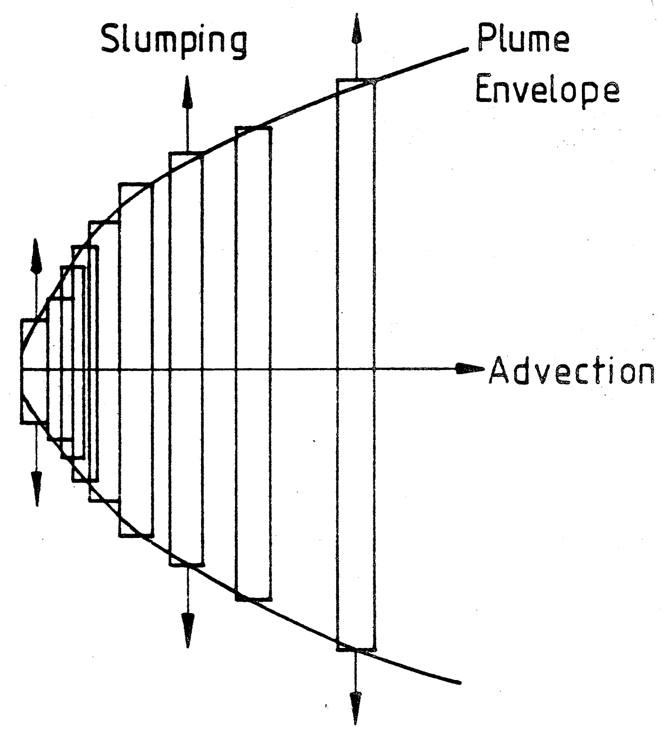


Figure 2 **The development of the dense gas cloud by slumping and advection.**

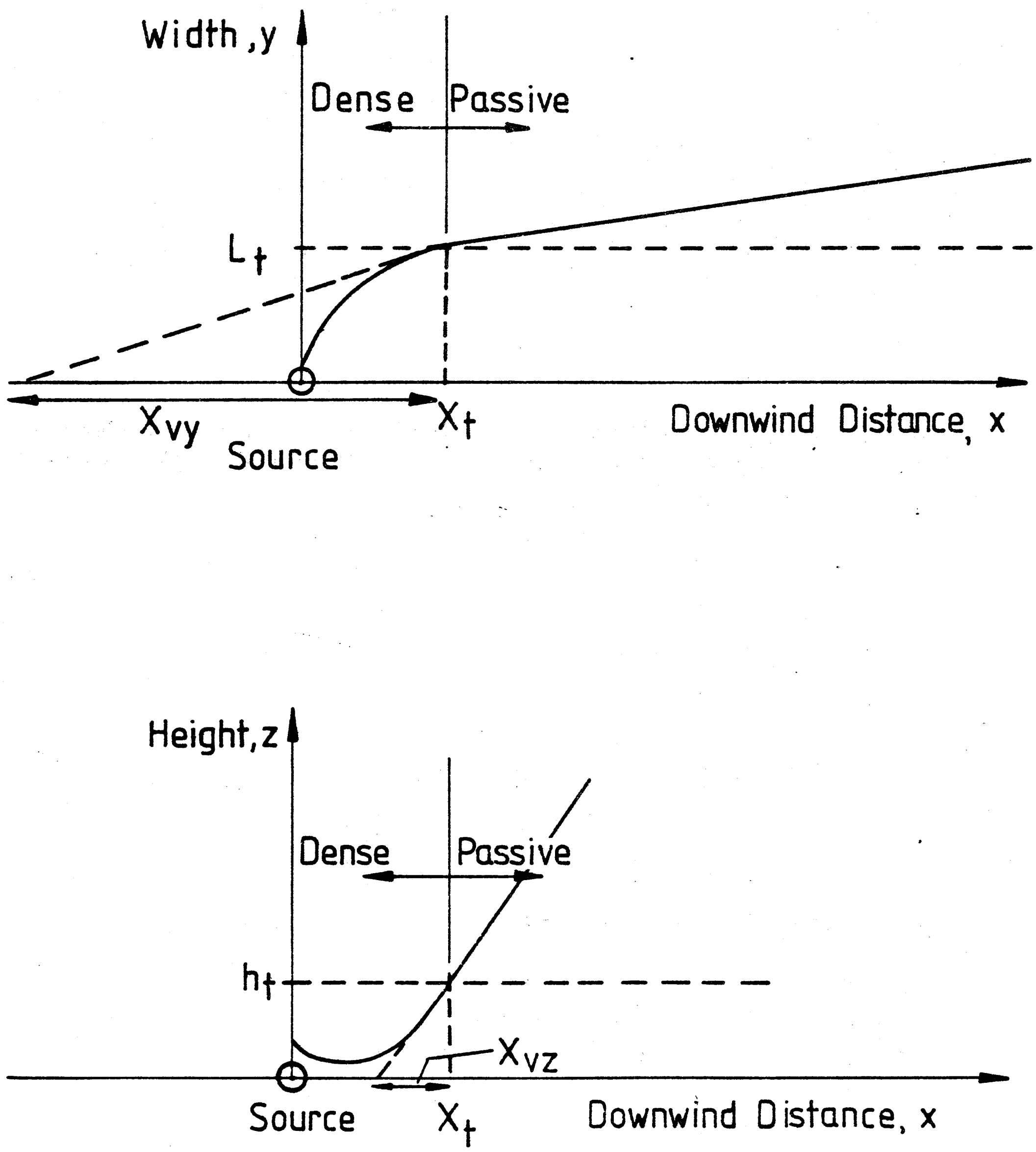


Figure 3 The growth of plume width across the transition from dense to passive phases.

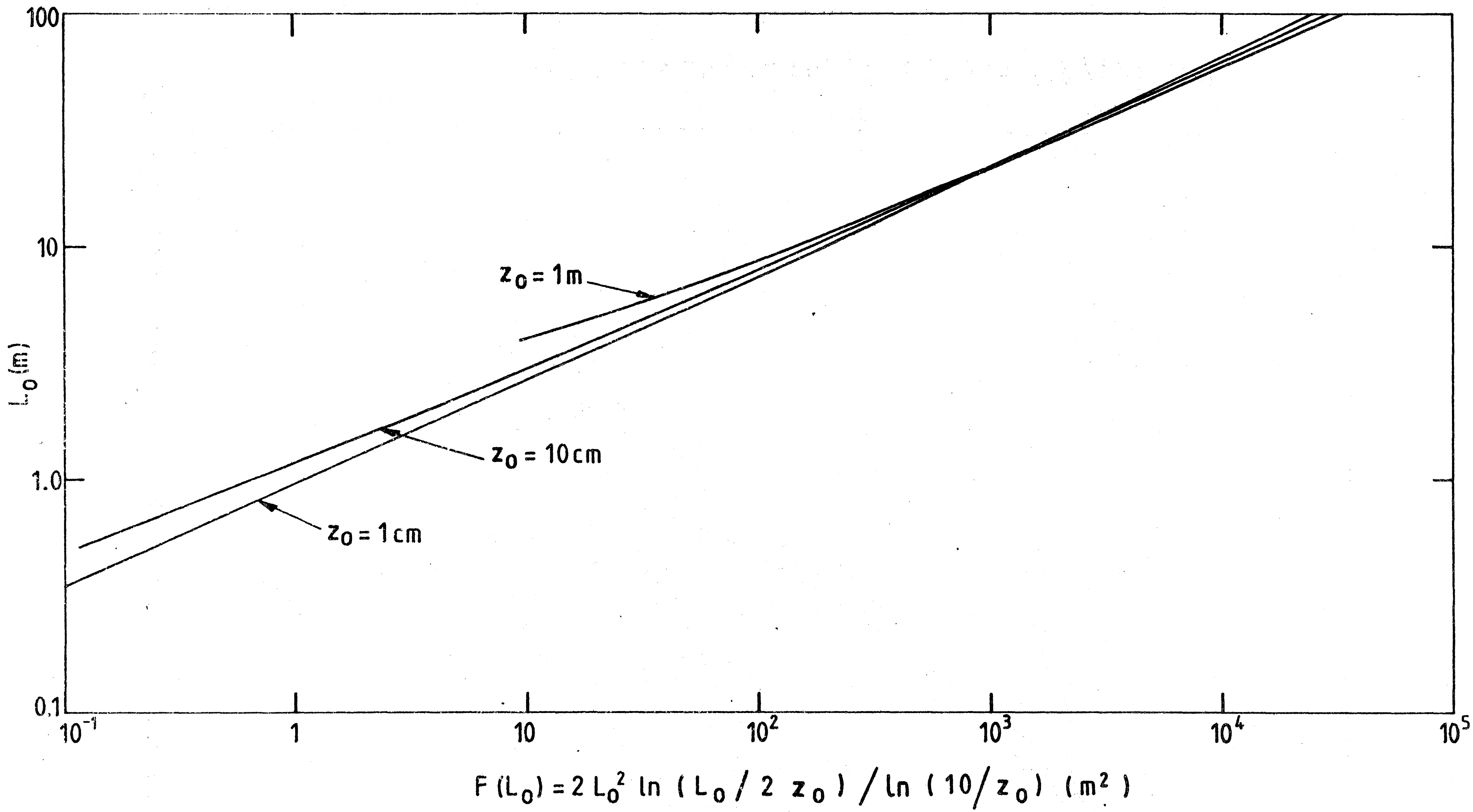


Figure 4 Variation of the function $F(L_o)$ with L_o for different representative roughness lengths.

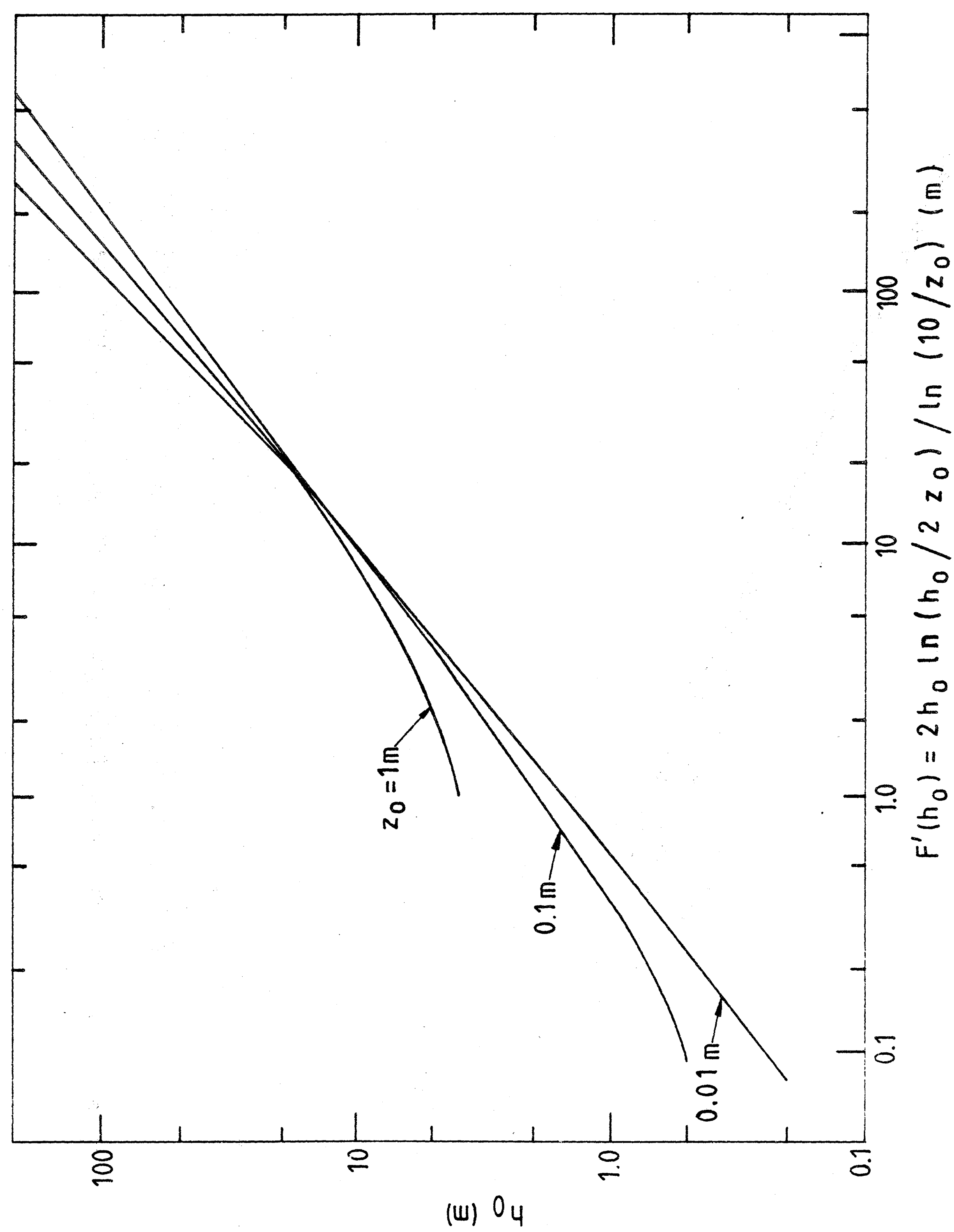


Figure 5 Calculational procedure for the plume height from the function $F'(h_o)$

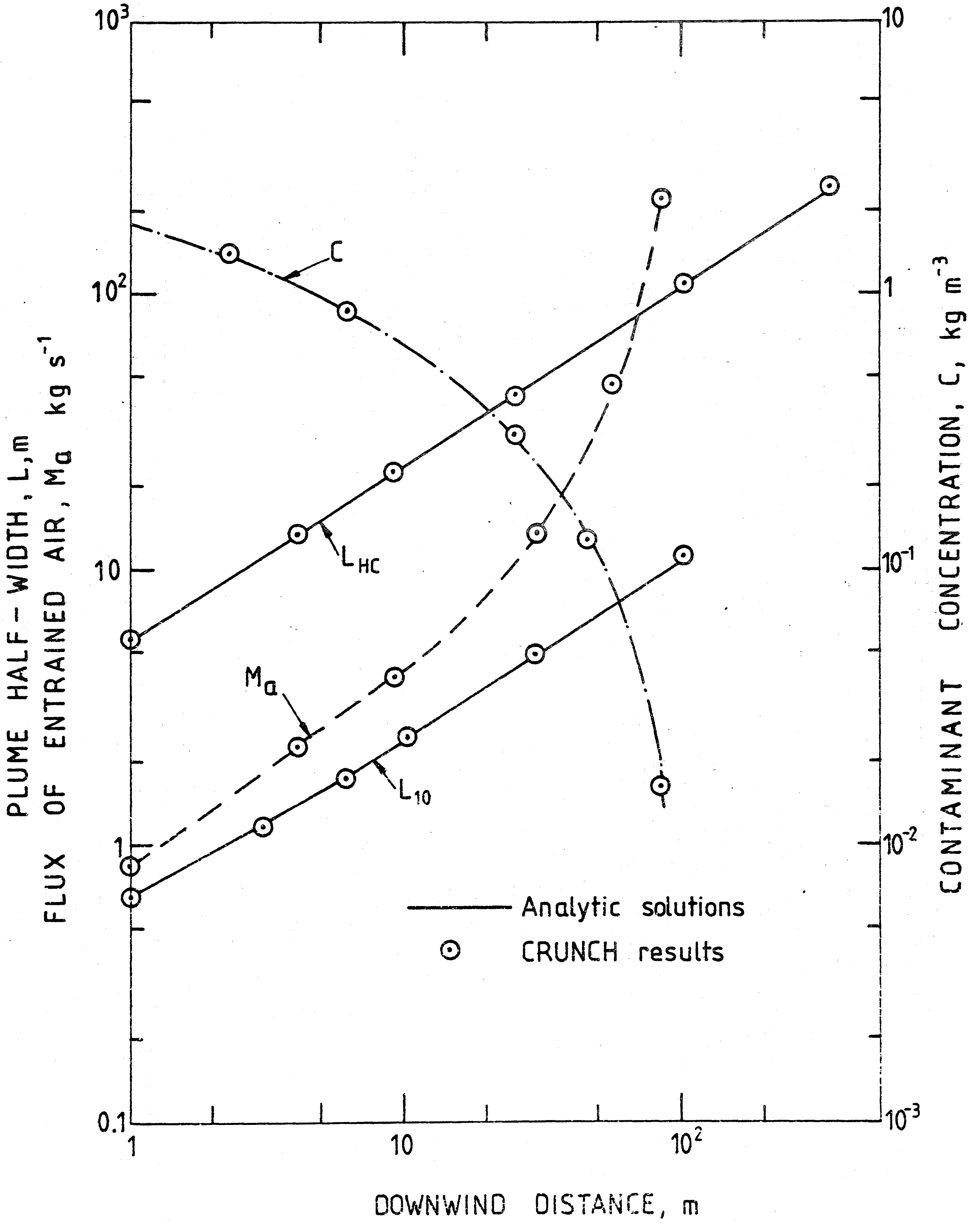
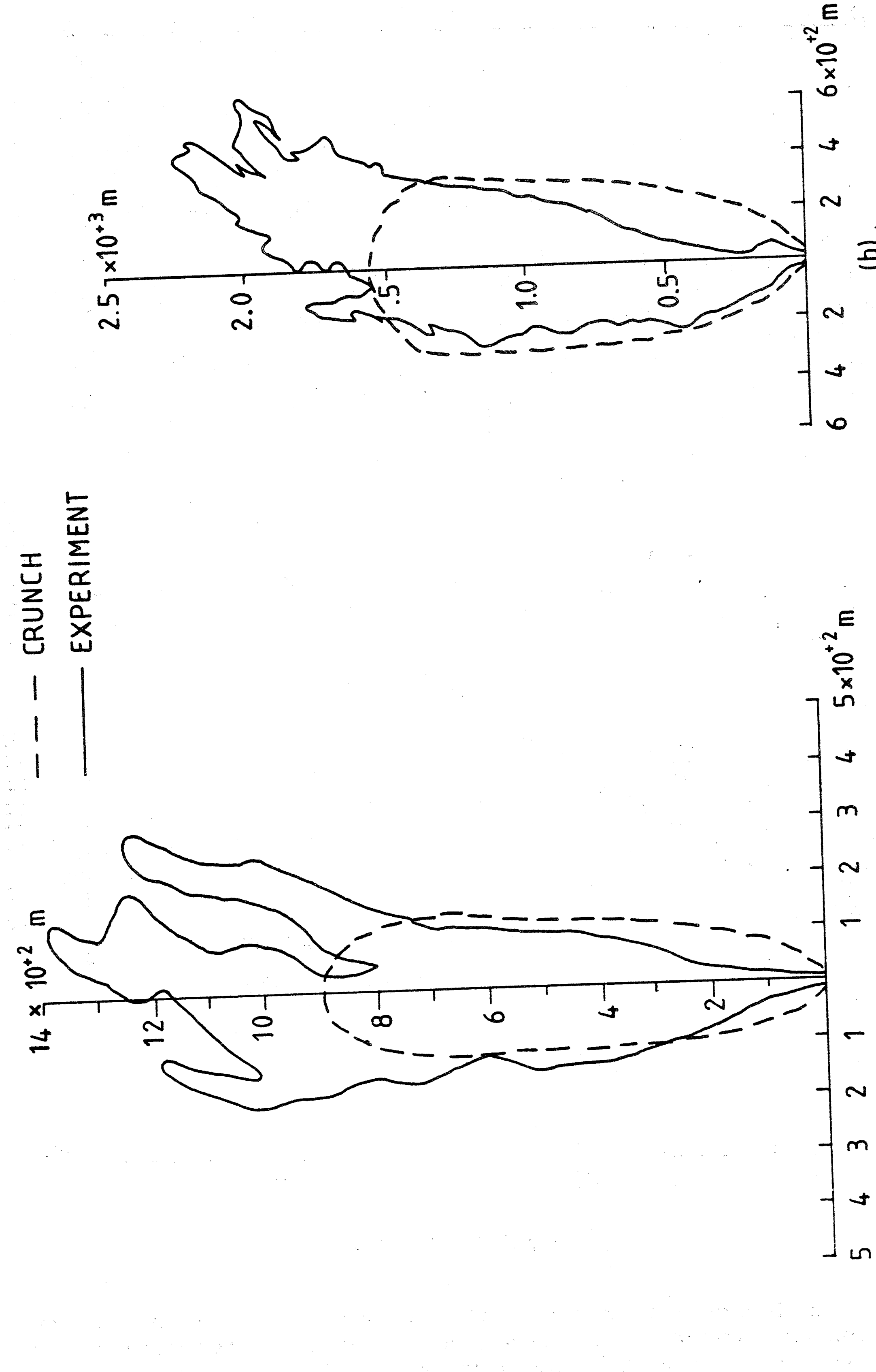


Figure 6 Comparison of numerical and analytic solutions of the model equations for a chlorine release of 1 $m^3 s^{-1}$ into category D-weather. Parameters compared are the lateral plume width (L_{10}), the downwind variation of air in the cloud and the decay of contaminant concentration. The predicted width is also shown using a windspeed measured at the approximate average height of the plume (L_{HC}), instead of that usually adopted at the standard measurement height of 10 m.



Figures 7(a) and 7(b) CRUNCH predictions and observed extent of methane plumes from SS GADILA spills 4 and 6.

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