THE ATMOSPHERIC DISPERSION OF HEAVY GASES: AN UPDATE

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Models for atmospheric dispersion of heavy gas clouds are reviewed. Wind tunnel and mathematical models are discussed, and their respective limitations are outlined. Similarity mathematical models are emphasized. Laboratory experimental data correlations for gravity spreading and air entrainment, and vertical mixing rates in stably stratified flows are summarized. A general purpose similarity model is illustrated by comparison with selected field data which have recently become available.

INTRODUCTION

A review of mathematical models of heavy gas atmospheric dispersion was presented in the previous symposium in this series (Havens, 1982). The mathematical modeling approaches in use today are essentially the same, with two main types: three-dimensional hydrodynamic models and similarity models. The former provide solutions of the partial differential Navier-Stokes and energy balance equations for input and boundary conditions representing heavy gas releases into an atmospheric flow. Similarity models assume a self-similar form for the gas concentration (and other properties) in a heavy gas cloud or plume. The assumption of a cloud "shape" (the similarity form) provides a mathematical definition of the cloud boundary. The models require specification of entrainment (mixing) of air into the cloud and account for lateral movement of the cloud boundary due to density driving forces and interaction with the wind. The specification of the movement due to density driving forces (gravity spread) and the prescription of air entrainment into the cloud are essential determinants of the location of the predicted cloud boundaries and the hazard extent. Although there has been some refinement of the mathematical modeling approaches, the primary effort in the last three years has been in the critical review of the methods and evaluation against experimental data which have become available. Many of the questions raised in previous reviews (Havens, 1982; Webber, 1983) required testing against experimental data. Some such testing had already been reported, but the results were not conclusive, and important questions remained about the accuracy and applicability of the several models which had been proposed. During the last three years extensive laboratory data which address some of the main questions raised in the previous review have become available. Also,

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extensive field data from the Burro/Coyote LNG releases at China Lake, California (Cederwell, 1981; Koopman, 1982; Goldwire, 1983), LNG-LPG releases at Maplin Sands, UK (Blackmore, 1982; Colenbrander, 1983, 1984; Puttock, 1982), and the Freon-air releases at Thorney Island, UK (HSE, 1982-1983; McQuaid, 1983) provide data covering a wide range of conditions whose effects on heavy gas dispersion can be compared with model predictions.

THE METHODS

The general problem is prediction of the dispersion, by mixing with air, of a mass of heavy gas released during a finite time period into the atmospheric boundary layer. The typical development and movement (including dispersion) of such a heavy gas "cloud" is illustrated in Figure 1. At time t_1, a heavy gas cloud has formed over the source, from which the gas issues at the rate $E(x,y,t)$. Characteristic profiles of the cloud boundary at times t_2 and t_3 after completion of the source are depicted. The cloud is described by specification of its height or depth $H(x,y,t)$, local concentration $c(x,y,z,t)$, density $\rho(x,y,z,t)$, enthalpy $h\ (x,y,z,t)$, and velocity $u_j(x,y,z,t)$. Vertical profiles of c, H, ρ, and u which reflect assumptions of air entrainment through the top and front (side) boundaries of the cloud (entrainment velocities w_e and u_e respectively) as well as shear stress at the cloud top and bottom surfaces (τ_0 and τ_δ respectively), are depicted. The local velocity u_j may be the result of both density-driving forces and the atmospheric flow. The cloud depicted in Figure 1 reflects a formation phase with duration small compared to the travel time to the maximum distance exposed to the concentration of interest, as might occur following the rapid evaporation of a spilled cryogenic liquid. Such a cloud is three-dimensional and highly transient, and a general model of the momentum, mass, and energy transfer processes which determine its development is complex and difficult.

There are three approaches currently being considered for simulation of heavy gas dispersion scenarios such as that depicted in Figure 1:

--3-D hydrodynamic mathematical models
--wind tunnel models
--similarity mathematical models.

3-D hydrodynamic models can, in principle, be used to simulate the three-dimensional and temporal cloud development and dispersion processes. With suitable turbulence closure techniques, it may be possible to account for effects of nonuniform terrain and flow obstacles such as may be present in an industrial environment. It may also be possible to estimate concentration fluctuations around the predicted mean (time average) values. Four of these 3-D mathematical models--SIGMET-N, MARIAH, ZEPHYR, and FEM3--are being evaluated by our research group under a contract with the Gas Research Institute (Havens, 1983). The present limitations on the use of such models are both practical and fundamental in nature. Although computer hardware (and time) requirements for 3-D model simulation of practical heavy gas dispersion problems may not be prohibitive, they are very substantial. The only method of insuring an accurate solution of the partial differential equations being approximated, by investigating the consistency and convergence properties of the numerical techniques used, is time consuming and expensive. Furthermore, the complexity of the models and the present state of methodology of computer solution of large systems of partial differential equations strongly suggest their use only by persons with substantial training. A more fundamental limitation (and the greatest cause of uncertainty about the result) is in the methods used for the turbulent mixing prescriptions, i.e. the turbulence closure (Farmer, 1983). It is likely that the applicability of mathematical turbulence closure methods to the description of density-stratified mixing in a shear flow, and consequently to many heavy gas dispersion scenarios of interest, can be demonstrated. However, the verification of turbulence closure techniques applicable to the prediction of the organized structure observed in strong density-driven flows, mixing in non-isothermal flows, and mixing induced by flow obstacles is only now being researched (Schreurs, 1983).

The potential advantage of wind tunnels is that, in principle, the spatial and temporal variations in a heavy gas cloud can be physically simulated and the phenomenological relations which must be postulated in mathematical models (the prime example being the turbulence closure) are not required. Instead, a small scale physical model of the flow is constructed in the laboratory. When the characteristic mass, length and time scales, and the physical variables (such as temperature, pressure, velocity, etc.) important in the process can be completely identified, these variables can be arranged into dimensionless groups whose functional relationship is the same in the model and "prototype" processes. Hence the functional dependence of the prototype process on the physical variables can be determined from measurements made in the wind tunnel model. However, a complete simulation (i.e. with equality of all of the dimensionless groups which determine the flow) is not possible for the large majority of practical problems. "Partial" simulations, in which the requirements for similarity are relaxed in some characteristics of the flow, must be resorted to. A prime example is the necessity to relax the requirements for Reynolds number equality between model and prototype flows. It is characteristic of heavy gas dispersion wind tunnel models that "good" simulation of the density-driven flow component of large scale heavy gas releases requires operation of the wind tunnel at low velocity. Operation at such low Reynolds number makes the similarity between the turbulence spectra of the model and prototype flows uncertain, and there are practical difficulties in operating large wind tunnels at low velocity (say < 0.5 m/s). Heavy gas dispersion wind tunnel models have been reported by Meroney (1982) and Hall (1982), and the limitations of wind tunnels for modeling heavy gas dispersion are being studied in the U.S. at Colorado State University (Meroney, 1983). Apart from the use of wind tunnel experiments as physical models of heavy gas dispersion processes, the data obtained are also useful for evaluation of mathematical models.

It is in those scenarios where the heavy gas cloud can be represented as having a regular shape that similarity models are applicable. Such approximations are justified for certain types of heavy gas releases at ground level on uniform terrain (or water) into an unobstructed atmospheric boundary layer flow. If the cloud formation phase, t_F, is very large compared to the time of cloud travel to the maximum distance exposed to the concentration of interest, t_T, a stationary "plume" representation of the cloud is applicable; if $t_F << t_T$, an "instantaneous" source representation is indicated. In either case the structure is represented in the form

$$\phi_i(x,y,z) = \phi_{i_s}(x)\ f(y/y_s,\ z/z_s) \tag{1}$$

where ϕ_i represents concentration, velocity, or temperature (enthalpy), and y_s, z_s are characteristic cloud dimensions.

Figure 2 depicts cloud shapes which have been most frequently used in "similarity" heavy gas dispersion models, and illustrates the perfect mixing model assumption. The perfect mixing model represents the structure of the cloud as being spatially uniform. This method has been used to represent both instantaneous and steady releases. For instantaneous releases an initial volume of gas, usually represented as a vertically oriented cylinder, is placed in the flow field at time zero. The dimensions of the cylindrical *cloud subsequently change as a result of gravity spreading and air entrainment*, and the cloud is moved downwind with a velocity determined from the wind vertical profile. Steady releases are represented as rectangular (and uniform) in cross-section with properties (concentration, temperature, etc.) varying with downwind distance. In both cases the principal dimensions of the cloud change as a result of gravity spreading (assumed to occur crosswind only in the plume representation) and entrainment of air across the top and side boundaries. A more complex self-similar representation of the concentration structure of a heavy gas plume from a ground level area source (Figure 7) was proposed by teReile (1977) and Colenbrander (1980). The concentration profile has a center section which is represented as dispersing only in the vertical direction, to account for the relatively uniform concentration field which develops over a uniform area source. Horizontal diffusion processes are associated with gas concentration gradients at the edge of the uniform central section. Other similarity forms, most of which are variations on the ideas just described, have been proposed (Flothmann, 1980; Fannelop, 1980; Rosenzweig, 1980; Morgan, 1983).

PHENOMENOLOGY OF HEAVY GAS DISPERSION

The typical heavy gas dispersion scenario involves three more or less distinct regimes of fluid flow. Following release, especially for rapid release of a large quantity of heavy gas, a cloud having similar vertical and horizontal dimensions (near the source) may form. The initial behavior of such a cloud is relatively independent of the characteristics of the ambient wind field until the strength of the buoyancy-driven flow (slumping and lateral spreading) decreases sufficiently that the cloud motion begins to be controlled by the ambient atmospheric flow. When the cloud motion begins to be determined by the atmospheric flow, the dispersion process can be described as a stably stratified plume (or cloud) embedded in the mean wind flow. As the dispersion proceeds, the stable stratification due to the heavy gas decreases until the process can be represented as a neutrally buoyant plume (or cloud) in a neutral or stratified mean wind flow. The three regimes,

--buoyancy-dominated flow
--stably stratified flow
--passive dispersion,

which may overlap and be present in various degrees in different heavy gas dispersion scenarios, must be accounted for if a model is to be generally applicable. 3-D hydrodynamic models, in principle, can account for all three regimes simultaneously. Similarity heavy gas models make provision for separate description of the regimes. However, the specific treatment of each of these flow regimes in the early models, as well as the methodology used to provide transition between the regimes, is quite varied and explains in large part the differences observed when the various models have been applied to the same heavy gas dispersion scenario (Havens, 1977, 1979).

Buoyancy-Dominated Flow Regime

For heavy gas releases with initially similar vertical and horizontal dimensions there is now conclusive evidence that the rapid gravity-driven flow which ensues results in large scale turbulent structures which effect considerable dilution of the cloud (Picknett, 1978; Hall, 1982; Meroney and

Lohmeyer, 1982; Havens and Spicer, 1983; Spicer and Havens, 1984). Since this initial turbulent motion can in some conditions result in dilution of the cloud by a factor of ten to one hundred, it must be accounted for in heavy gas dispersion predictions.

Gravity Spreading. *The gravity spreading motion that follows such* releases has been modeled as a gravity-driven intrusion of the heavy gas into the surrounding atmosphere. Such currents are formed in many natural situations (Simpson, 1982), including thunderstorm outflows, sea breezes, and cold fronts in the atmosphere, and a variety of ocean currents driven by density differences. The transient gravity front that occurs in heavy gas releases has most often been described as a quasisteady flow in which the buoyancy and inertial forces are assumed to be in balance. The front velocity is usually calculated from the relation

$$u_f = C_E (g \Delta H)^{1/2} \tag{2}$$

with the constant specified somewhat differently by different modellers but within the range 1.0 - 1.414. Havens and Spicer (1983) have reported laboratory instantaneous releases, in calm air, of right cylinders (height/diameter = 1.0) of Freon-12 with initial volumes from 0.035 to 0.51 m^3. Dimensional arguments suggest that such releases should scale with the characteristic length scale $V^{1/3}$ and time scale $T = V^{1/6} / \sqrt{g\Delta}$. Figure 3 summarizes the measured cloud front position (radius/$V^{1/3}$) vs. time (t/T). The cloud front position is well represented, for t > ~20 T, by the solution of Equation 2 with the constant $C_E = 1.16$. Equation 2, which reflects the assumption of quasisteady exchange of cloud potential and kinetic energy, indicates a step change of the front velocity to its maximum value at the instant of release. The heavy gas volume must, of course, accelerate from rest. van Ulden (1979), Meroney and Lohmeyer (1982), and van Ulden (1983) have proposed methods for modeling the acceleration phase of a transient heavy gas gravity current. Figure 3 also indicates the predicted cloud frontal position vs. time for the conditions of the experimental releases reported by Spicer and Havens (1984) obtained using the model of van Ulden (1983), adapted for application to radially symmetric heavy gas releases.

Air Entrainment. Although model treatments of air entrainment have in many cases given widely disparate results (Havens, 1977; Webber, 1983), most of the differences are attributable to the various specifications for air entrainment velocities. Similarity models usually incorporate air entrainment into the heavy gas cloud via an expression of the form

$$\dot{V}_a = w_e A_T + u_e A_F \tag{3}$$

where $w_e A_T$ and $u_e A_F$ are vertical and horizontal entrainment rates represented as the product of a characteristic area and velocity. Entrainment at the cloud front, which is expected to be important only during the gravity-dominated stages of the cloud development, has most often been modeled by specifying the entrainment velocity as proportional to the front velocity:

$$u_e = C_1 u_f \tag{4}$$

Fay (1984) has shown that Equation 4 (with sufficiently large C_1) will predict a cloud released in the absence of wind to grow in vertical extent, in contradiction to energy balance requirements.

Figure 4 shows ground level, peak-measured concentration as a function of distance from the release center for the instantaneous Freon-12 releases reported by Havens and Spicer (1983). The volume-averaged concentration of the cloud corresponding to the position of the cloud front, determined by spatial integration of vertical and horizontal cloud concentration profiles (Spicer, 1985; Havens and Spicer, 1985) are shown in Figure 5, along with predictions obtained using the box models of van Ulden (1974), Germeles and Drake (1975), Cox and Carpenter or Fryer and Kaiser (1979), Eidsvik (1980), Fay (1980), Meroney and Lohmeyer (1982), Fay (1983), and van Ulden (1983). The data of Spicer and Havens are consistent with a coefficient $C_1 = 0.6$ in Equation 4.

Stably Stratified Flow Regime

An intermediate phase of the typical heavy gas dispersion process (between the buoyancy-dominated flow regime and the latter stages where dispersion is passive) is similar to a variety of naturally occurring flows in which a stably stratified plume is embedded in a mean flow. This regime is characterized by the persistence of a lateral (crosswind) gravity-driven flow and vertical density stratification which damps turbulent mixing. The lateral gravity spread can be modeled using Equation 2. The vertical mixing is usually modeled with a vertical entrainment velocity which is a function of the friction velocity of the flow and the stabilizing effect of the density gradient. The stabilizing effect of the density gradient is determined from a bulk Richardson number for the flow:

$$w_e = u_* / \psi(Ri_*) \tag{5}$$

The function ψ in Equation 5 is chosen to agree with laboratory experimental measurements of mixing in density-stratified flows. Figure 6 shows vertical entrainment velocity data vs. the bulk Richardson number of the flow from the experiments reported by Lofquist (1960), Kantha, Phillips, and Azad (1977), and McQuaid (1976). The plotted line represents a curve fit of the three data sets, which cover a Richardson number range from near zero to about 10^5. This range should encompass heavy gas dispersion scenarios of interest. Questions have been raised about the interpretation of both KPA's and McQuaid's experiments, and there exist data reported earlier by Ellison and Turner (1959) and more recently by Deardorff (1982), Kranenberg (1983), and Stretch (1983) which may justify some modification of the entrainment velocity specification shown in Figure 6.

Passive Dispersion Regime

Vertical passive dispersion from ground level sources is conventionally modeled as a gradient transfer process by application of similarity principles developed by Monin (1959) and Batchelor (1964) and extended for stratified flow by Gifford (1962). The velocity profile in a shear flow against a rough wall boundary is determined from

$$\frac{du_x}{dz} = \frac{u_*}{kz} \psi_M \,(z/\lambda) \tag{6}$$

where the function ψ_M has been determined from experimental measurements of vertical momentum transfer (Businger, 1971). For the limiting case of neutral stratification, $\psi_M = 1$, and Equation 6 indicates a logarithmic velocity profile with roughness height z_r. The corresponding vertical diffusivity, defined as the ratio of momentum flux to the mean velocity gradient, is given by

$$K = \frac{k u_* z}{\psi_M} \tag{7}$$

and, (invoking the Reynolds analogy) the equivalent vertical entrainment velocity is

$$w_e = \frac{K}{z} \tag{8}$$

For neutral stratification, $\psi = 1$ and $w_e / u_* = k$, the von Karman constant, which is about 0.4. This result is consistent with the extrapolation of data summarized in Figure 6 to zero Richardson number.

ILLUSTRATION OF A GENERAL APPLICATION SIMILARITY MODEL

Havens and Spicer (1985) have developed a general purpose heavy gas dispersion similarity model for incorporation by the U.S. Coast Guard in its Hazard Assessment Computer System (HACS). The model is designed for simulating dispersion from ground level sources over water or level, unobstructed terrain. The DEGADIS (DEnse GAs DISpersion) model is an adaptation of the Shell HEGADAS model described by Colenbrander (1980, 1983). The buoyancy-dominated flow regime is simulated using a box model to predict a "secondary" heavy gas source (Figure 7) which is input to the downwind dispersion model. The box model of the gravity-dominated flow regime incorporates air entrainment at the gravity-spreading front based on the data correlation shown in Figures 4 and 5. The downwind dispersion phase of the calculation assumes a power law concentration distribution in the vertical and a modified Gaussian profile in the horizontal direction with a power law specification for the wind profile (Figure 7). Vertical mixing (entrainment) is modeled using the data correlation shown in Figure 6. Horizontal dispersion in the stably stratified flow regime and the ensuing passive dispersion regime (a smooth transition, based on the vertical mixing data of Figure 6 is effected by the model) is forced to reflect experimental data on horizontal dispersion of passive plumes from point sources, such as the power law correlations of σ_y developed by Pasquill (1983). The model also provides for heat transfer from the underlying surface to the cloud, as well as enhancement of vertical mixing by the unstable temperature gradient which results from heat transfer to the cloud. The convective turbulence is modeled using an approach adapted from Zeman and Tennekes (1977).

The DEGADIS model provides for treatment of transient (including instantaneous) releases as a series of pseudo-steady state releases. It has been used to simulate a large group of field heavy gas experiments, including instantaneous isothermal gas and LNG/LPG spill (evaporative) releases, in a wide range of meteorological conditions. Table 1 summarizes the test conditions reported for two tests each selected from the Burro experiments at China Lake, California, the LNG/LPG releases at Maplin Sands, UK, and the Thorney Island Heavy Gas Trials in the UK. Figures 8 through 13 compare the measured and DEGADIS-predicted maximum gas concentration vs. downwind distance for the same tests. The concentration measurement height in each of the tests is indicated. The predictions are all for ground level but do not differ importantly from predictions at the respective sensor heights. In all cases the measurements reflect the maximum of the time-averaged value reported at that location. The averaging times used in preparing the reported concentration time histories are also indicated. The DEGADIS model has been used to simulate the 39 field experiments listed in Table 2. Overall, the agreement between predicted and measured maximum concentration for all of the experiments is similar to Figures 8 through 13. The predicted and experimental estimates of maximum distance to concentration levels in the LFL range (1-5%) agree for all of these experiments within a factor of about two. Considering the uncertainties in the required input to the model, such as the evaporative fluxes for the cryogenic spills, the results indicate the validity and consistency of the model for such predictions. Sensitivity tests of the model indicate that differences of the same magnitude can result by variation of the input specifications within their expected range of uncertainty.

RECOMMENDATIONS

Further analysis of laboratory density-stratified mixing experiments is warranted to demonstrate the validity of air entrainment models. Experimental data on vertical mixing rates in non-isothermal density-stratified flows should be used to test the applicability of heat transfer and thermal turbulence models currently in use. Three-dimensional hydrodynamic models should be evaluated against laboratory and wind tunnel data as a basis for justification of the fundamental assumptions invoked, particularly the turbulence closure. Judicious use of such laboratory data should allow verification of the consistency of the models with field data. Since field data will always be obtained under less controlled (or controllable) conditions, and since such experiments will inevitably be only one sample from the ensemble which would be anticipated if the experiment could be repeated in the "same" conditions, field experimental results should be used only to verify modeling approaches which have been tested against controlled (laboratory) experiments, whenever possible.

NOMENCLATURE

A_F	cloud side area, m^2
A_T	cloud top area, m^2
B	half-width of gas area source (Figure 7), m
b	half-width of horizontally homogeneous central section of gas plume (Figure 7), m
C_E	constant in Equation 2
C_1	constant in Equation 4
c	concentration, kg/m^3
c_c	centerline maximum concentration (Figure 7), kg/m^3
c_u	concentration designating isocontour (Figure 7)
E	gas source evolution rate, kg/s
H	cloud height, m
h	enthalpy, J/kg
k	von Karman constant, = 0.4
L	source length (Figure 7), m
q_0	surface-to-cloud heat flux, $J/m^2\ s$
Q^*	cloud atmospheric takeup flux (Figure 7), $kg/m^2\ s$
R	cloud radius (Figure 2), m
R^*	nondimensional cloud radius, (Figures 3, 4), $R/V^{1/3}$
S_y, S_z	horizontal and vertical concentration scaling parameters (Figure 7)
Ri_*	bulk Richardson number, (Equation 5), $g \Delta H / u_*^2$
T	characteristic time, $V^{1/6} / \sqrt{g \Delta}$
t	time, s
t_F	characteristic cloud formation time, s
t_T	cloud travel time to maximum distance exposed to the concentration of interest
t^*	nondimensional time, t/T
u_e	horizontal entrainment velocity, m/s
u_f	cloud front gravity spreading velocity, m/s

u_j	velocity component, m/s
u_0	wind velocity measured at $z = z_0$ (Figure 7), m/s
u_*	friction velocity, m/s
V	cloud volume, m^3
$\dot{V}_a$	rate of air entrainment, m^3/s
w_e	vertical entrainment velocity, m/s
x,y,z	cartesian coordinates, m
z_r	surface roughness, m
z_0	reference height in wind profile specification (Figure 7)

α	constant in power law wind profile (Figure 7)
Δ	relative density, $(\rho - \rho_a) / \rho_a$
ϕ_i	similarity function (Equation 1)
λ	Monin-Obukhov length, m
ρ	cloud density, kg/m^3
ρ_a	air density, kg/m^3
τ_0	surface shear stress, N/m^2
τ_δ	shear stress at cloud top, N/m^2
ψ	function describing influence of stable density stratification on vertical entrainment (Equation 5)
ψ_M	function describing influence of stable density stratification on vertical momentum transfer (Equation 6)

Table 1. Selected Field Experiments Simulated with DEGADIS

	Burro 8	Burro 9	Maplin 29	Maplin 46	Thorney 7	Thorney 15
Description*	1	1	2	3	4	4
Volume Released, m^3	28.4	24.2	21.9	22.2	2000	2000
Rate Released, m/sec	16.0	18.4	4.1	2.8	Instant	Instant
Wind Speed @ Height, m/sec, m	2.4 8.0	6.5 8.0	7.4 10.0	8.1 10.0	3.2 10.0	5.4 10.0
Stability	E	C	D	D	E	D
Roughness, m	2.1e-4	2.1e-4	3.4e-4	3.4e-4	1.0e-2	1.0e-2
Temperature Air, C	33	35	16	19	17	10
Temperature Surface, C	37	37	17	18	--	--
Relative Humidity, %	5	12	52	71	81	88

*1 - LNG on water, evaporative release (0.085 kg/m^2s), dispersion on land
2 - LNG on water, evaporative release (0.085 kg/m^2s), dispersion on water
3 - Propane on water, evaporative release (0.12 kg/m^2s), dispersion on water
4 - Freon-air (sp. gr. = 2.0), instantaneous release, isothermal gas, dispersion on land

Table 2. DEGADIS Test Simulations

	No. Tests
Propane releases from diked land areas (Welker, 1982)	10
LNG releases from diked land areas (AGA, 1974)	3
LNG releases on water (ESSO, 1972)	2
Burro/Coyote LNG releases (US DOE, 1980)	6
Maplin Sands LNG-LPG releases (Shell, 1981)	12
Thorney Island Heavy Gas Trials (BHSE, 1983)	6

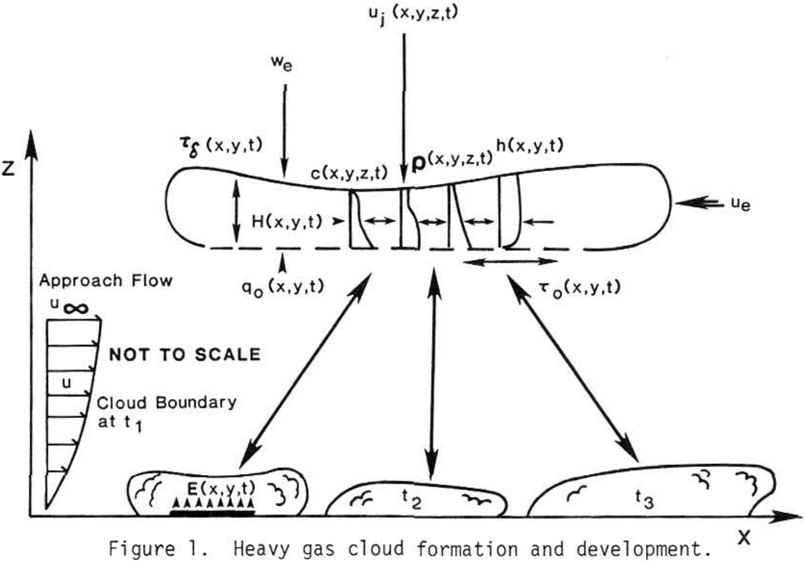
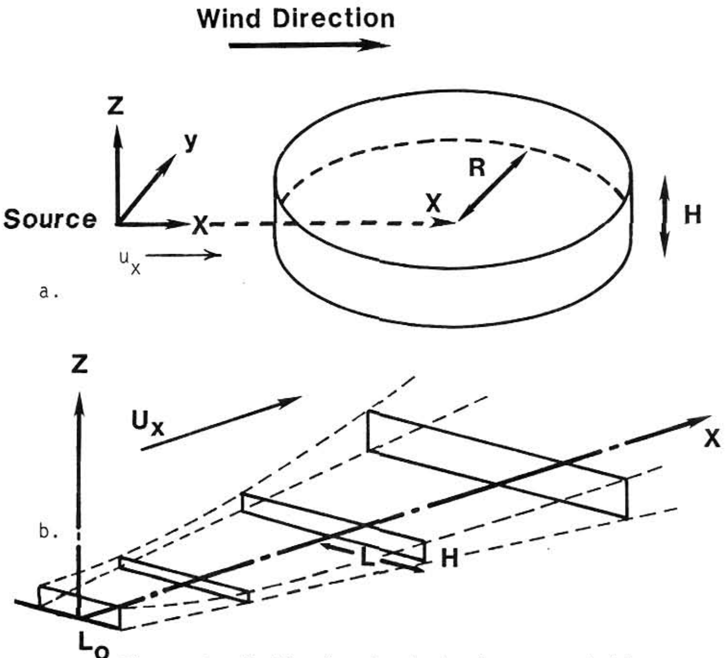


Figure 1. Heavy gas cloud formation and development.



Fiqure 2. Uniformly mixed cloud representation.

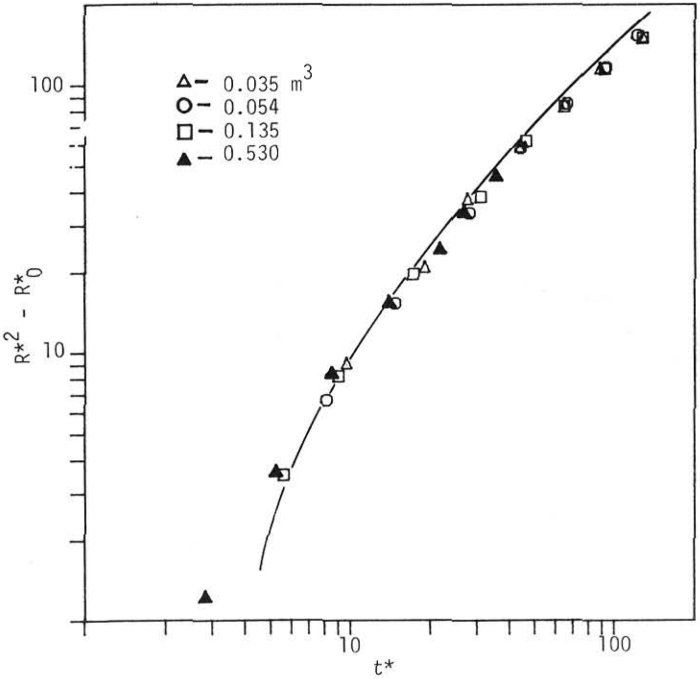


Figure 3. Cloud front position vs. time Freon-12, H/D = 1.0, instantaneous release.

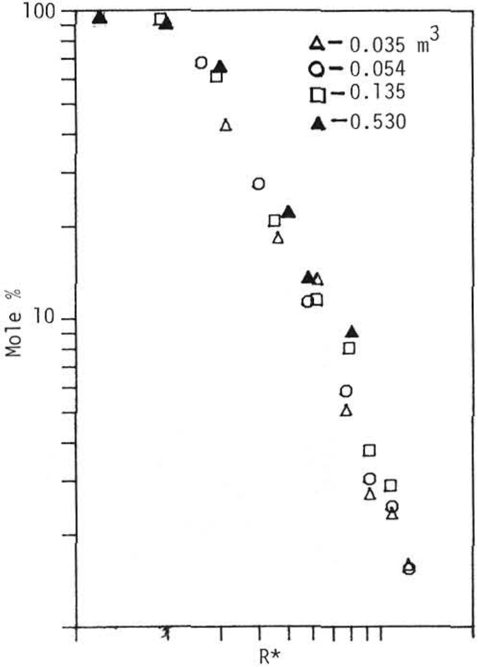


Figure 4. Maximum ground level concentration vs. distance, Freon-12, H/D = 1.0, instantaneous release.

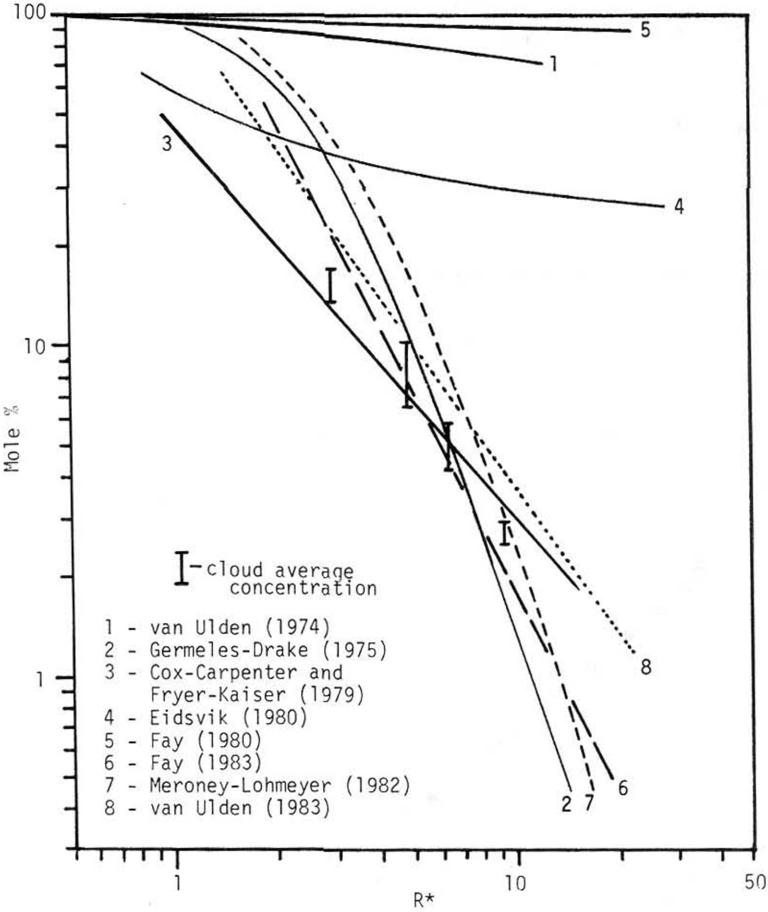


Figure 5. Cloud concentration vs. front position, predictions compared with cloud average concentration data from Spicer (1983), Freon-12, H/D = 1.0, instantaneous release.

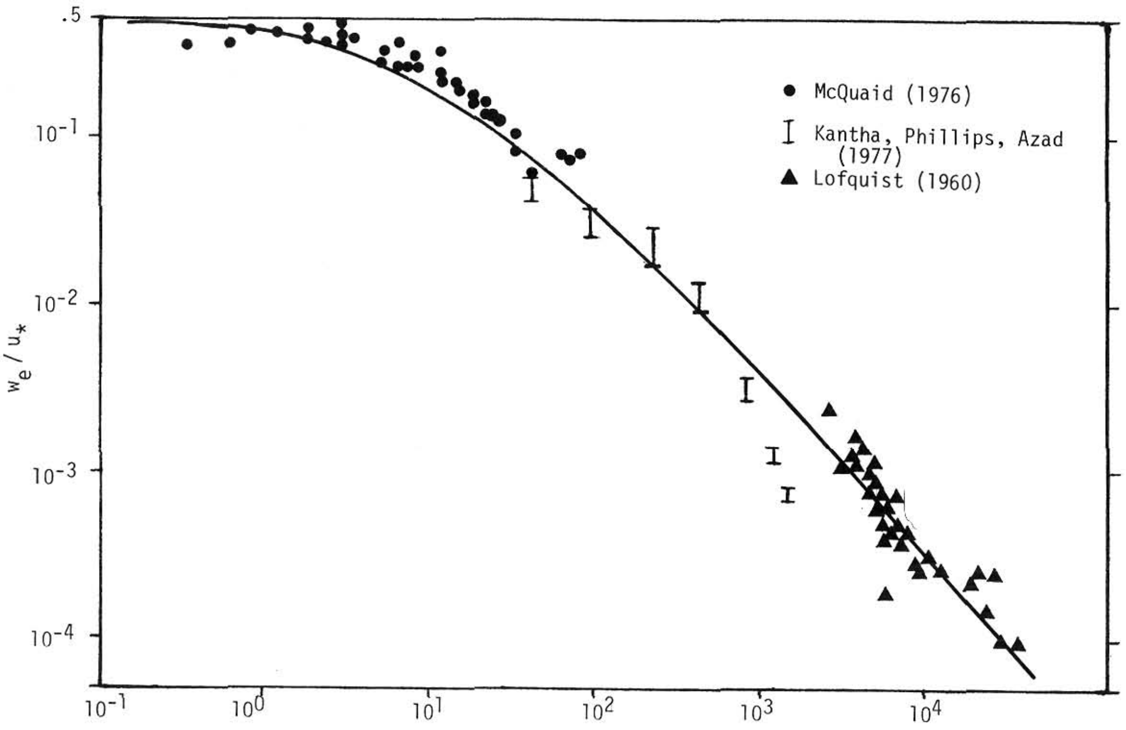
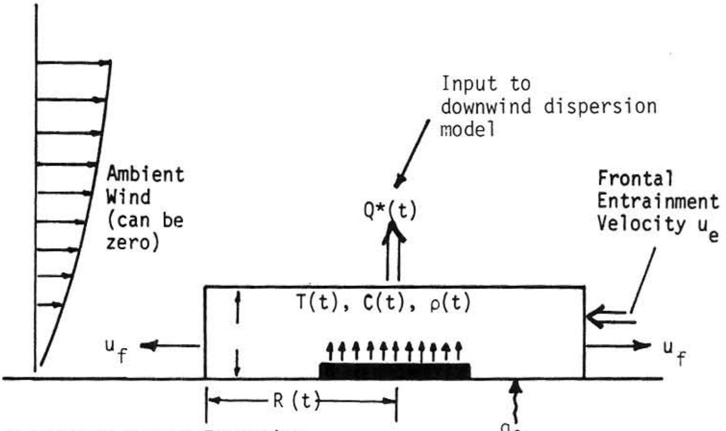
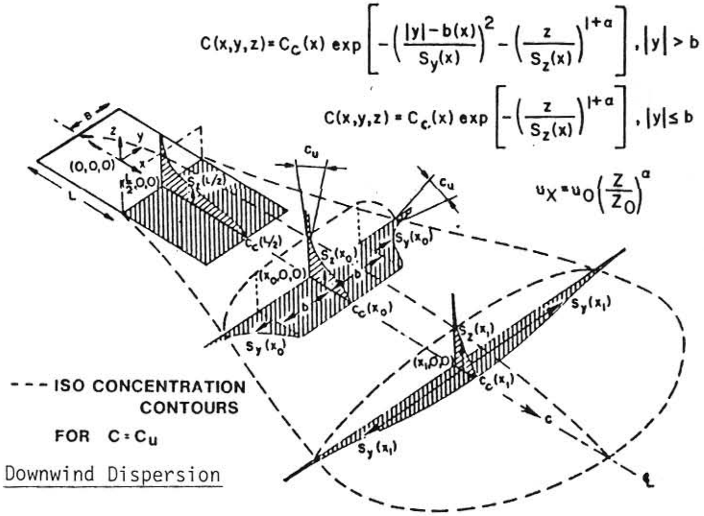


Figure 6. Correlation of vertical entrainment velocity with bulk Richardson number.



Secondary Source Formation



Downwind Dispersion

Figure 7. Schematic diagram of DEGADIS model.

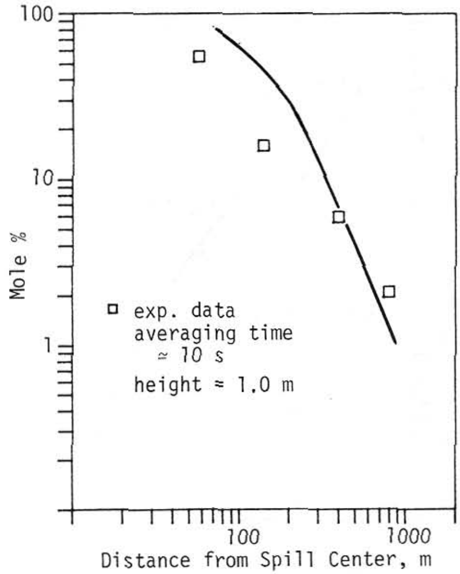


Figure 8. Burro 8 simulation.

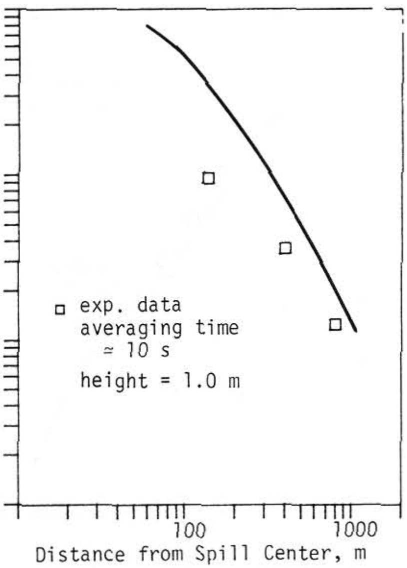


Figure 9. Burro 9 simulation.

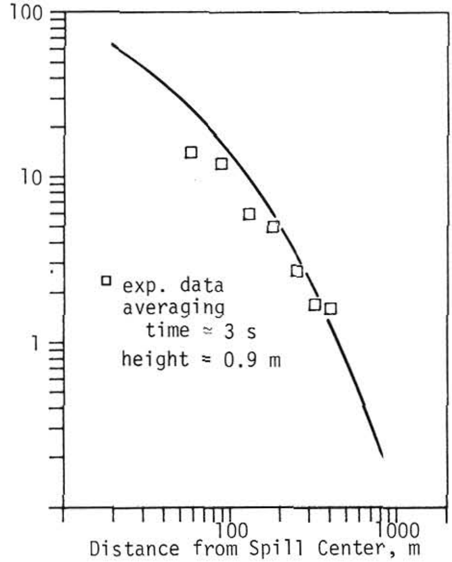


Figure 10. Maplin 29 simulation.

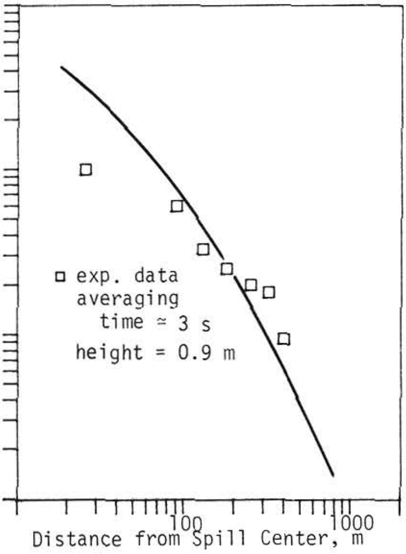


Figure 11. Maplin 46 simulation.

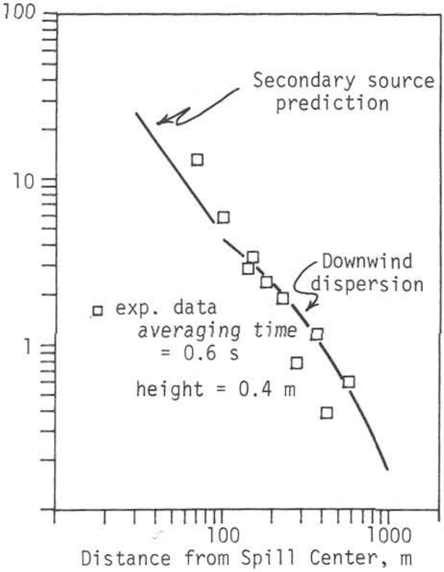


Figure 12. Thorney 7 simulation.

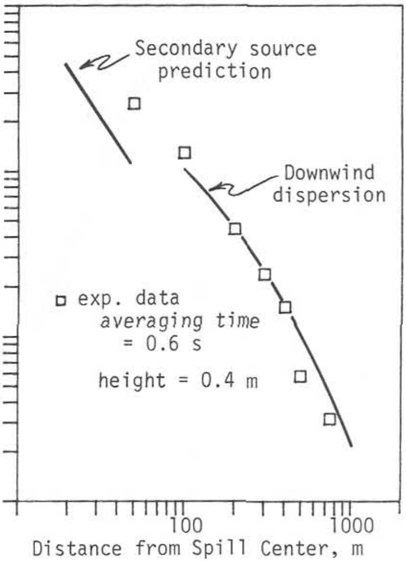


Figure 13. Thorney 15 simulation.

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