# THE ROBERTS, SNYDER, BAUMGARTNER MODEL: RSB

## INTRODUCTION

RSB is based on the experimental studies on multiport diffusers in stratified currents described in Roberts, Snyder, and Baumgartner (1989a,b,c), which should be consulted for detailed explanations. These studies were conducted with an experimental configuration shown in Figure 53. The diffuser is straight and consists of horizontally discharging round nozzles which are uniformly spaced. The ports discharge from both sides of the diffuser, which is similar to most prototype applications. This configuration would include diffusers consisting of pipes with ports which are holes along each side or T-shaped risers each containing two ports as shown in Figure 53.

The receiving water is linearly density-stratified, and flows at a steady speed at an arbitrary angle relative to the diffuser axis. RSB will also predict dilutions for a surfacing wastefield caused either by a weak stratification or by unstratified conditions.
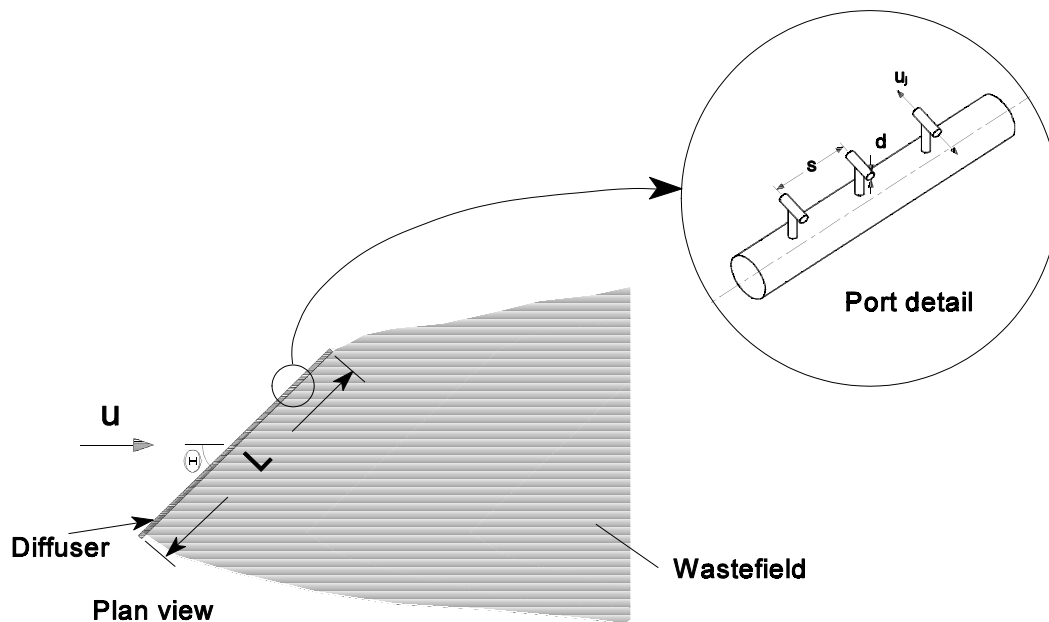


**Figure 53**. Diffuser configuration considered by RSB.

As discussed later, RSB is also a good approximation for diffusers in which the ports are clustered in multiport risers, at least up to 8 ports per riser. The range of the experimental parameters (port spacing, port diameter, jet exit velocity, current speed, current direction, and density stratification) was chosen to be representative of highly buoyant discharges such as

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domestic sewage and some industrial wastes into coastal and estuarine waters. When RSB is used outside the parameter range for which these experiments were conducted, it extrapolates the results to obtain a solution and gives a warning that the answers are extrapolated.

The model can be thought of as a replacement for and a significant update of ULINE (Muellenhoff et al., 1985). Whereas ULINE was based on experiments in unstratified environments, RSB is based on experiments in stratified environments, and so is therefore more reliable in this situation. Also, ULINE applies only to single line plumes whereas RSB is based on experiments with multiport diffusers. It therefore includes the effects of port spacing and source momentum flux, and is more realistic in that it includes discharges from both sides of the diffuser.

## DEFINITIONS

The definitions used in RSB in relation to the geometry of the initial mixing region are shown in Figure 54 and described below. At the end of this region the dilution is called the initial dilution and the wastefield is said to be established. The established wastefield then drifts with the ocean currents and is diffused by oceanic turbulence.
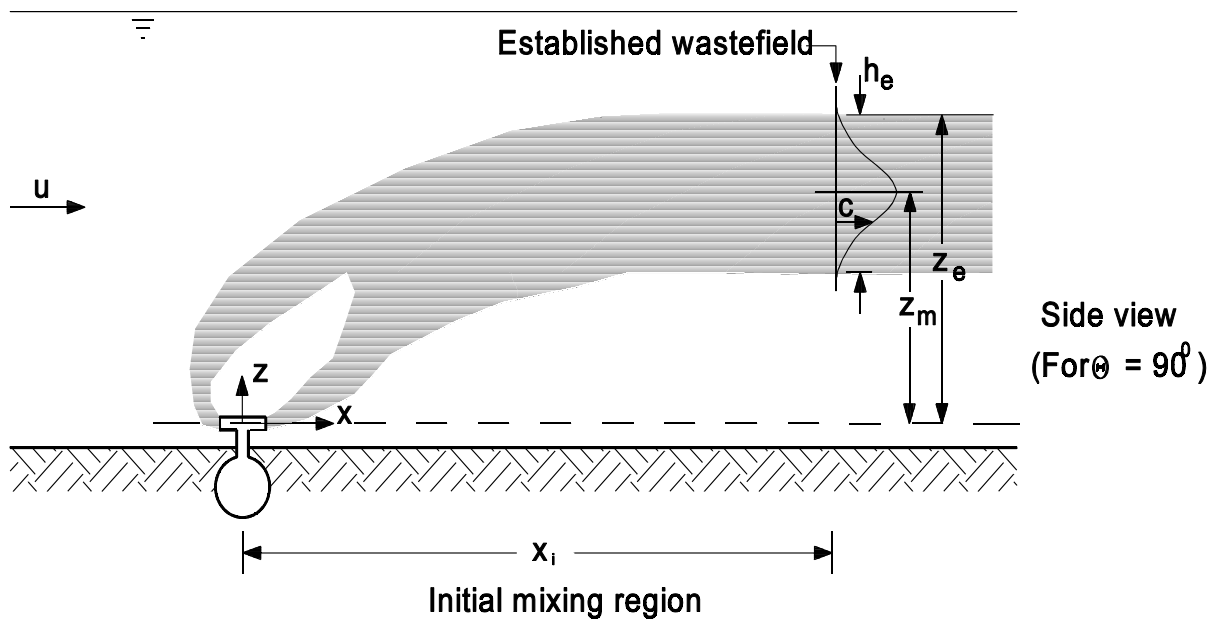


**Figure 54**. Definition of Wastefield Geometry.

In RSB this "initial mixing region" or "hydrodynamic mixing zone" is defined to end where the self-induced turbulence collapses under the influence of the ambient stratification and initial dilution reaches its limiting value. The length of the initial mixing region is denoted by $x_i$. The

geometrical wastefield characteristics (see Figure 53) at this point are thickness $h_e$ height to top $z_e$ and height to level of maximum concentration (or minimum dilution) $z_m$. The minimum initial dilution $S_m$ is defined as the smallest value of dilution (corresponding to maximum concentration) observed in a vertical plane through the wastefield at the end of the initial mixing region.

## MODEL BASIS

The initial mixing of wastewater discharged from a multiport diffuser depends on diffuser design and receiving water characteristics. The diffuser can be characterized by fluxes of volume, momentum, and buoyancy per unit diffuser length:

$$q = \frac{Q}{L} \qquad m = uq \qquad b = g_o' q \qquad (19)$$

where $Q$ is the total discharge, $L$ the diffuser length, $u_j$ the jet exit velocity, and $g_o' = g(Q_a - Q_j)/Q_a$ is the reduced gravitational acceleration due, g is the acceleration due to gravity, $Q_a$ is the ambient density at the level of the ports and $Q_j$ the effluent density. A linear density stratification can be characterized by the buoyancy frequency, $N$, also referred to as the Brunt-Vaisala frequency, usually expressed in units of sec$^{-1}$:

$$N = \left( \frac{g}{\rho_a} \frac{d\rho}{dz} \right)^{1/2} \qquad (20)$$

We define three length scales:

$$l_q = \frac{q^2}{m} \qquad l_b = \frac{b^{1/3}}{N} \qquad l_m = \frac{m}{b^{2/3}} \qquad (21)$$

Note that these length scales are defined based on the *total* fluxes, rather than the flux from each side of the diffuser. The geometrical characteristics defined in Figures 53 and 54 can then be expressed as:

$$z_e, \, h_e, \, z_m = f(q, b, m, s, u, N, \Theta) \qquad (22)$$

Which, by means of dimensional analysis, becomes:

$$\frac{z_e}{l_b}, \frac{h_e}{l_b}, \frac{z_m}{l_b} = f\left( \frac{l_m}{l_b}, \frac{s}{l_b}, F, \Theta \right) \qquad (23)$$

Where $F = u^3/b$ is a dynamic variable which is a type of Froude number. In Equation 5, the effect of the source volume flux $q$ is neglected as an independent variable. This is because $l_q/l_b$ is usually much less than one and therefore has little dynamic effect except very near to the

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ports. The corresponding normalized expression for dilution is:

$$\frac{S_m q N}{b^{2/3}} \cdot f\left(\frac{l_m}{l_b}, \frac{s}{l_b}, F, \Theta\right) \tag{24}$$

where $S_m$ is the minimum initial dilution, as previously defined. An average dilution $S_a$ is computed as $1.15\, S_m$ based on hydraulic model tests by Roberts (1989).

The two length scale ratios $l_m/l_b$ and $s/l_b$ are diffuser parameters which characterize the significance of source momentum flux and port spacing respectively. Note that these length scale ratios encompass the jet exit velocity, port diameter, port spacing, effluent density, and ambient stratification. Based on consideration of actual operating conditions, the range of experiments was chosen to be $0.31 < s/l_b < 1.92$ and $0.078 < l_m/l_b < 0.5$. For $s/l_b < 0.3$ and $l_m/l_b < 0.2$, the discharge approximates a line plume, i.e. the individual plumes rapidly merge and the effect of source momentum flux is negligible, many ocean outfalls operate in the regime in which momentum is negligible (Roberts et al., 1989a). Therefore the range of diffuser parameters can be considered to be $s/l_b < 1.92$ and $l_m/l_b < 0.5$

A more important parameter is $F$, which characterizes the importance of the current speed relative to the buoyancy flux of the source. Small values of $F$ signify little effect of current; according to Roberts et al. (1989a) the current exerts no effect on dilution if $F < 0.1$. Larger values of $F$ denote situations where the plumes are rapidly swept downstream by the current; dilutions are always increased by increased current speeds, although not always at the regulatory (critical) mixing zone boundary, as shown in Figure 5. (See Figures 4 and 6 in Roberts, Snyder, and Baumgartner, 1989a for photographs of plumes at various Froude numbers, $F$). The tests were run at differing current speeds to obtain $F = u^3/b$ in the range 0 (zero current speed) to 100.

The effect of the current also depends on the direction of the current relative to the diffuser $\Theta$. For a line diffuser $0 < \Theta < 90^\circ$. Tests were run with $\Theta = 90^\circ$ (diffuser oriented perpendicular to the current), $45^\circ$, and $0^\circ$ (parallel to the current). In general, diffusers oriented perpendicular to the current result in highest initial dilutions and lowest rise heights.

## MODEL DESCRIPTION

Results for wastefield geometry and initial dilution were presented graphically (Figures 8, 10-12 of Roberts et al. 1989a) in the dimensionless form of Equations 5 and 6 for line plume conditions ($s/l_b < 0.3$ and $l_m/l_b < 0.2$). Results to predict the length of the initial mixing zone $x_i$ are in Figures 4 and 8 of Roberts et al., 1989b. For higher port spacings and higher momentum fluxes the results are given in Figures 5 and 6, and 7 and 8 of Roberts et al., 1989c.

For some of these results, semi-empirical equations are given. These equations are semi-empirical because they are physically based, but the coefficients must be obtained from the

experiments. Examples are the dilution and rise height of line plumes in perpendicular currents (Equations 14 and 17 of Roberts et al., 1989a):

$$\frac{S_m q N}{b^{2/3}} \cdot 2.19 F^{1/6} \& 0.52, \qquad \frac{z_e}{l_b} \cdot 2.5 F^{\&1/6} \tag{25}$$

In other cases, for example, high momentum jets in a parallel current, only graphical solutions are available. In these cases, purely empirical equations are fitted to the curves, and the results interpolated as appropriate. RSB can therefore be thought of as a coding of the graphs and equations in the original papers. For linear stratifications, the model should give exactly the same results as obtaining the solution graphically.

For nonlinear stratifications, RSB assumes that the density profile is linearized over the rise height. In RSB, the solution procedure is iterative, solving automatically for the rise height $z_e$. This method, which is similar to that used by Brooks (1973) is shown in Figure 59. As discussed later, this approximation usually works very well, even for very nonlinear stratifications. In fact, this is a conservative assumption, as linear stratifications lead to less rapid spreading, thinner wastefield, less subsequent mixing, and therefore less dilution than in a wastefield at the same rise height in a nonlinear stratification (Roberts, 1993).

## EXAMPLES

### Introduction

RSB can be run either as a stand alone program or from PLUMES. When run in stand alone mode, RSB uses the same UDF input file format as previous EPA models (Muellenhoff et al., 1985). This file can be created using the ^YU command in PLUMES, with any ASCII text-editor, or interactively by following prompts within RSB. Note, however, that **RSB assumes discharges from both sides of the diffuser**, whereas the original EPA models implicitly assume discharge only from one side of the diffuser, so the data may be different for different models. In UM this requirement is accommodated by running the cross-diffuser merging configuration, i.e. by specifying half spacing between ports. For example, if ports are staggered every two meters with adjacent ports on one side of the diffuser four meters apart, then the appropriate spacing is two meters. Whether the model is run stand alone or from PLUMES, the solution procedure is the same, so the results should be practically identical.

Recommendations on usage are given in Appendix 1. The ambient density must be stable, i.e. density must not decrease downwards, however, under some circumstances RSB will produce valid results if intermediate levels are specified as unstable due to the method used in RSB to calculate a linear gradient. The total number of ports $n$ and spacing $s$ are inputted to determine the diffuser length $L$ which is then used to compute $q$ and the length scales. Half spacing provides the correct solution for RSB.

$$L \, ' \, s\left(\frac{n}{2}\&1\right) \qquad\qquad\qquad\qquad\qquad\qquad \textbf{(26)}$$

**Seattle Example:  Linear Stratification - Zero Current**

The following example follows that given in Roberts et al., 1989a,b,c.  The parameters are taken from the Metropolitan Seattle outfall discharging into Puget Sound (Fischer et al., 1979):

Design average flow,  $Q = 194$ ft$^3$/s (5.49 m$^3$/s)

Number of ports = 202

Port spacing (on each side of the diffuser),  $s = 6$ ft (1.83 m)

Port diameters,  $d$ = 4.5 to 5.75 inches (0.114 to 0.146 m)
Assume  $d = 5.0$ inches (0.127 m)

Effluent density,  $Q_o = 1.000$ g/cm$^3$

The port depth is about 70 m, and density stratifications at nearby Alki Point vary between 0.002 and 0.025 $\sigma_t$-units per meter.  Taking the strongest stratification (0.025 $\sigma_t$-units per meter) yields, for example, a density of 1.02425 g/cm$^3$ at the surface and 1.02600 g/cm$^3$ at 70 m depth.  The pipe diameter is 96 inches (2.44 m) so the port elevation is 1.22 m and the total depth is set at 71.22 m.

The input and output files of the original RSB (Basic language) model for zero current are shown in Figure 55.  The computed length scales ratios are $s/l_b = 0.14$ and $l_m/l_b = 0.13$ which suggests no effect of the source momentum flux and port spacing so we expect the behavior of this discharge to approximate a line plume.  The predicted minimum initial dilution $S_m$ for this case is 80, and rise height $z_e$ is 32.9 m.  No farfield calculation is provided.

The corresponding PLUMES RSB and UM runs are given in Figure 56 without farfield calculations.  Notice the close agreement between Basic RSB and PLUMES RSB; maximum difference are less than one percent.  Also, notice the approximate agreement between the models, e.g. average dilutions of 92 and 82 for RSB and UM respectively.  In the remainder of this chapter only the PLUMES RSB runs will be displayed.  The corresponding UM run is given in Figure 57.

The Basic language RSB program is not bundled with the plume package.

```
Input file:

Seattle Example
     5.490        202     0.127        0.00        70.0
     0.000    90.000     1.830
      2       1.0000        0
     0.00    1.02425        0.0     0.000
    70.00    1.02600        0.0     0.000

Output file:

Input data:

 Seattle Example
  Flowrate =   5.49 m3/s
  Effluent density =   1   g/cm3
  Number of ports =   202
  Port diameter =   .127 m;       Port spacing =   1.83 m
  Discharge depth = 70 m
  Current speed =   0 m/s;     Angle of current to diffuser = 90 degrees
  Computed diffuser length = 183.0 m

    Density profile:
  Depth (m)     Density (g/cm3)
    0.0          1.02425
   70.0          1.02600

Results:

  Length scale ratios are:   s/lb =   0.14,   lm/lb =   0.13
  Froude number, u3/b =    0.00;   Jet Froude number, Fj = 12.1
  Rise height to top of wastefield, ze = 32.9 m
  Wastefield submergence below surface = 37.1 m
  Wastefield thickness, he = 22.7 m
  Height to level of cmax, zm = 21.5 m
  Length of initial mixing region, xi =   25.3 m
  Minimum dilution, Sm =  80;   Flux-average dilution, Sfa =  92 (1.15 x Sm)
```

**Figure 55**. Input and output of the original RSB program (Roberts, 1991).

```
 Mar 15, 1994,  14:58:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of   8
 Title   Seattle Example                                               linear
  tot flow   # ports port flow   spacing  effl sal effl temp  far inc   far dis
      5.49      202               0.9144
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
        70     0.127    0.1270     2.145             0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc    decay  Froude # Roberts F
         1      0.0       1.0         0      100         0     11.92 1/320E-13
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    0.9144   26.000.00001000  0.000453            214500 0.0001221
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0      1e-5     24.25                          0   0.01546    0.2550
        70      1e-5     26.00                          0 buoy flux puff-ther
                                                          0.007571     36.61
                                                        jet-plume jet-cross
                                                            1.425     24150
                                                        plu-cross jet-strat
                                                        6.930E+12     3.952
                                                        plu-strat
                                                            6.581
                                                         CL conc>=

 CORMIX1 flow category algorithm is turned off.
  5.49 m3/s, 125.3 MGD, 193.9 cfs.                       >0.0 to 100 m3/s range
 Help: F1.   Quit: <esc>.  Configuration:ATNO0.  FILE: rsbeg.var;
                                 RSB
                  Written by Philip J. W. Roberts (12/12/89)
                     (Adapted by Walter E. Frick (1/12/92))

  Case:  1: Seattle Example
  Length scale ratios are: s/lb =   0.14 lm/lb =   0.13
  Froude number, u3/b =          0.00
  Jet Froude number, Fj =        12.1

  Rise height to top of wastefield, ze =   32.9
  Wastefield submergence below surface =   37.1
  Wastefield thickness, he =               22.8 m
  Height to level of cmax, zm =            21.5 m
  Length of initial mixing region, xi =   25.3 m
  Minimum dilution,      Sm =     79.8
  Flux-average dilution, Sfa =    91.8 ( 1.15 x Sm)
  Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed
<key> for farfield prediction

... UM Simulation ...

  plume dep plume dia poll conc  dilution   CL conc   hor dis
       m        m                                        m
     70.00    0.1270    100.0     1.000     100.0     0.000
     69.64    0.9207    12.94     7.556     24.10     2.019 -> merging
     59.89    3.047     3.125     31.22     4.529     6.675
     42.82    7.686     1.509     64.62     2.159     9.387 -> trap level
     29.89    27.12     1.192     81.79     1.702    11.98
  -> plume element overlap.
```

**Figure 56**.  PLUMES RSB run for Seattle example.

## Seattle Example: Linear Stratification - Flowing Current

Consider now an ambient flowing current of 0.30 m/s perpendicular to the diffuser.  The new input and output data files are shown in Figure 57.

The minimum dilution is now increased by the current to 181, and the rise height (to the top of the wastefield) reduced from 32.9 m to 26.5 m.  This process can be continued for other current speeds to generate the results shown as Table 2 in Roberts et al., 1989a.  Note that numbers may differ slightly from this table due to slightly differing interpolation procedures.

```
 Mar 15, 1994,  14:59:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   3 of   8
 Title   Seattle Example; with current                                  linear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
      5.49       202  0.02718    0.9144                                        
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
       70     0.127   0.1270     2.145     2.145    0.000      0.10        500
 port elev ver angle cont coef  effl den poll conc    decay  Froude # Roberts F
        1       0.0       1.0        0       100                11.92     3.563
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90    0.9144    26.00    0.3000   0.000453            7.152 0.0001221
    depth    current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0       0.3     24.25                            0    0.01546    0.2550
       70       0.3     26.00                            0 buoy flux puff-ther
                                                            0.007571     1.178
                                                         jet-plume jet-cross
                                                            1.425    0.8049
                                                         plu-cross jet-strat
                                                            0.2567     3.952
                                                         plu-strat
                                                            6.581
                                                          hor dis>=

CORMIX1 flow category algorithm is turned off.
 5.49 m3/s, 125.3 MGD, 193.9 cfs.                          >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: rsbeg.var;

 Case:  3: Seattle Example; with current
 Length scale ratios are: s/lb =   0.14 lm/lb =   0.13
 Froude number, u3/b =          3.62
 Jet Froude number, Fj =        12.1
 Rise height to top of wastefield, ze =  26.5
 Wastefield submergence below surface =  43.5
 Wastefield thickness, he =           21.5 m
 Height to level of cmax, zm =        17.4 m
 Length of initial mixing region, xi =   165 m

 Minimum dilution,       Sm =    180.5
 Flux-average dilution, Sfa =   207.6 ( 1.15 x Sm)
Wastefield width:     183.92m   Avg. flux dilution (width*he*u/Q):     216.3
```

**Figure 57**.  RSB Seattle example, with current.

**Seattle Example:  Model Extrapolation**

This example illustrates the effect of running RSB outside the range of values on which it is based.  The port diameter is reduced to 60 mm (0.06 m);  the new data files are shown in Figure 58.

In this case the decrease in nozzle size causes an increase in nozzle exit velocity and an increase in momentum flux.  The length scale ratio $l_m/l_b$ becomes equal to 0.60, which exceeds the experimental range.  Note that RSB still gives answers in these situations and gives a warning message that the predicted results are extrapolated and therefore may be unreliable;  the interpretation of these results is at the discretion of the model user.  The primary predicted effect of the increased momentum flux is a decrease in rise height;  the dilution is unchanged. The reasons for this type of behavior are discussed in Roberts et al., 1989c.

```
 Mar 15, 1994,  15: 0:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   4 of   8
 Title   Seattle Example; extrapolated                                linear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
     5.49        202   0.02718    0.9144
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
       70       0.06   0.06000     9.612     9.612    0.000      0.10        500
 port elev ver angle cont coef  effl den poll conc    decay  Froude # Roberts F
        1       0.0       1.0         0       100              77.71 1.319E-13
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     0.9144   26.000.00001000  0.000453           9612000.00005769
     depth    current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0       1e-5     24.25                             0   0.01546    0.2550
       70       1e-5     26.00                             0 buoy flux puff-ther
                                                             0.007571     99.49
                                                           jet-plume jet-cross
                                                               4.390     51110
                                                           plu-cross jet-strat
                                                           6.930E+12     5.750
                                                           plu-strat
                                                               6.581
                                                            hor dis>=
... RSB ...
 Case:  4: Seattle Example; extrapolated

 Length scale ratios are: s/lb =   0.14 lm/lb =   0.60
 Froude number, u3/b =           0.00
 Jet Froude number, Fj =        78.7

 Rise height to top of wastefield, ze =  26.5
 Wastefield submergence below surface =  43.5
 Wastefield thickness, he =          19.9 m
 Height to level of cmax, zm =       17.8 m
 Length of initial mixing region, xi =  25.3 m

 Minimum dilution,        Sm =    79.8
 Flux-average dilution, Sfa =    91.8 ( 1.15 x Sm)
 Results extrapolated beyond their experimental values, may be unreliable
 Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed

... UM ...
 plume dep plume dia poll conc  dilution   hor dis
       m        m                             m
    70.00   0.06000    100.0     1.000     0.000
    69.96    0.9254     6.381    15.30     2.160 -> merging
    68.90     2.882     3.125    31.21     7.323
    50.98     9.405     1.269    76.83    23.13 -> trap level
    40.35     21.51     1.031    94.59    31.55 -> plume element overlap.
```

**Figure 58**.  Seattle example, reduced port size, RSB model extrapolation.

**Seattle Example: Nonlinear Stratification**

In this example the nonlinear ambient density profile shown in Figure 59 is used.  The density profile is the one used in the Boston Harbor Diffuser model tests.  It consists of a uniform, well-mixed surface layer about 8 m thick, followed by a sharp change in density through the thermocline, which is about 13 m thick, then a uniform density down to the bottom.  The port depth in this case is 31.3 m below the water surface.  The diffuser of the Seattle example is used and the new data files are given in Figure 60.
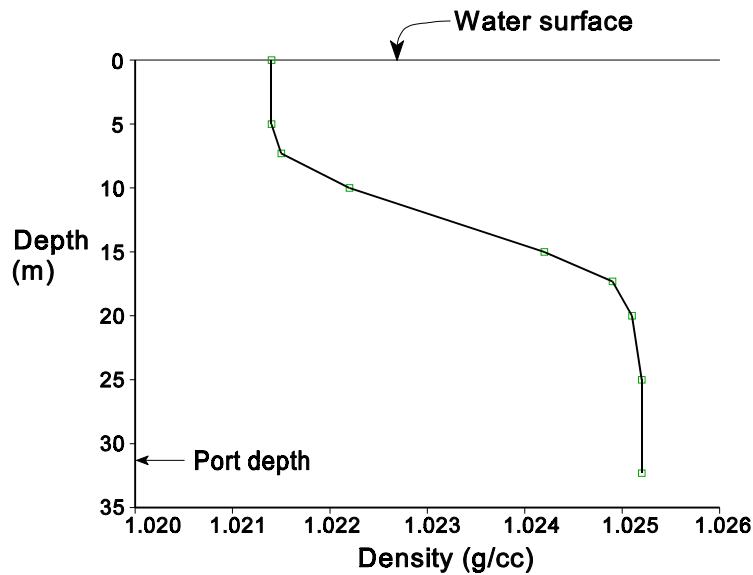


**Figure 59**.  Density Profile used in Non-Linear Example.

RSB predicts a rise height of 17.4 m, which is in the pycnocline.  The solution procedure, which is transparent to the user, is to linearize the density profile over this 17.4 m.  The method can fail, an example is described in Appendix 6.  In that example, which is similar to Figure 58, the solutions oscillate depending on the vertical position of the pycnocline, one solution showing the plume rising into the upper unstratified layer while the other shows it remaining in the bottom layer. Which one is selected depends on the vertical position and extent of the stable layer between the neutral layers.  One way to stabilize the solution is to make the neutral layers slightly stable.  To identify sensitive situations, it may be worthwhile to compare RSB and UM solutions for general agreement.  Also, varying the depth of the stable layer and ambient density inputs can help identify potential problems.

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```
 Mar 15, 1994,  15: 4:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   6 of   8
 Title   Seattle example; Boston density profile                         linear
  tot flow   # ports port flow   spacing effl sal effl temp   far inc   far dis
     5.49       202  0.02718    0.9144
  port dep port dia plume dia total vel horiz vel vertl vel asp coeff print frq
     31.3      0.127    0.1270     2.145     2.145     0.000      0.10        500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
     1.22         0         1         0       100         0     12.11 1.362E-13
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90    0.9144    25.200.00001000  0.000453             214500 0.0006118
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0      1e-5      21.4                            0   0.03408    0.2471
        5      1e-5      21.4                            0 buoy flux puff-ther
      7.3      1e-5      21.5                            0  0.007346     36.99
       10      1e-5      22.2                            0 jet-plume jet-cross
       15      1e-5      24.2                            0     1.448     24150
     17.3      1e-5      24.9                            0 plu-cross jet-strat
       20      1e-5      25.1                            0 6.717E+12     2.662
       25      1e-5      25.2                            0 plu-strat
       35      1e-5      25.2                            0     3.609
                                                           hor dis>=

 CORMIX1 flow category algorithm is turned off.
  5.49 m3/s, 125.3 MGD, 193.9 cfs.                       >0.0 to 100 m3/s range
 Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: rsbeg.var;
...
 Case:  6: Seattle example; Boston density profile

 Length scale ratios are: s/lb =   0.26 lm/lb =   0.25
 Froude number, u3/b =           0.00
 Jet Froude number, Fj =        12.3

 Rise height to top of wastefield, ze =  17.4
 Wastefield submergence below surface = 13.9
 Wastefield thickness, he =             13.1 m
 Height to level of cmax, zm =          11.7 m
 Length of initial mixing region, xi =  13.5 m

 Minimum dilution,      Sm =    42.3
 Flux-average dilution, Sfa =    48.6 ( 1.15 x Sm)
 Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed
```

**Figure 60**.  Seattle example, non-linear density profile.

**Multiport Risers Example**

Many outfalls with multiport risers are now operating (San Francisco and Sydney), under construction (Boston), or proposed (Hong Kong). Except for San Francisco, these are tunneled outfalls for which the cost of the risers is very high, of the order of several million dollars each. It is therefore necessary to minimize the number of risers without unduly impairing dilution. This is different from a pipe diffuser in which, for a given diffuser length, the number of ports in the pipe wall and their spacing is not a significant cost consideration.

The following example is for the Boston outfall. This is a convenient example as experimental results from the hydraulic model tests done for this diffuser are available (Roberts, 1989). The example also illustrates the effects of nonlinear stratifications.

The basic assumption is that the behavior of the wastefield is the same as if the ports were uniformly distributed along both sides of the diffuser, rather than clustered in multiport risers. This was originally demonstrated by Isaacson et al. (1978, 1983) to be a good assumption for certain limited conditions. The caveat to this assumption is that entraining water must be available to the plumes. This implies that not more than 8 ports per riser be used, otherwise the flow collapses to a rising ring with reduced dilution.

The following examples are of the final design, which has 55 risers spaced a distance of 122 ft (37.2 m) apart. Each riser has 8 ports with nominal diameters of 6.2 inches (0.157 m). Tested flowrates were 390 mgd (17.08 m³/s), 620 mgd (27.16 m³/s), and 1270 mgd (55.63 m³/s). If the ports were uniformly distributed along the diffuser, the port spacing $s$ would be 122/4 = 30.5 ft (9.30 m). A typical data file for 390 mgd, zero current speed, with a density profile as shown in Figure 59 (this is referred to as the Late Summer Profile in Roberts, 1989), is given in Figure 61. Table IV gives more comparisons between measured and predicted dilutions.

**Table IV**. Model measurement and predicted wastefield characteristics for Boston Harbor Outfall.

| Current speed (cm/s) | Flowrate Q (mgd) | Minimum initial dilution $S_m$ | | Rise height to top of wastefield, $z_e$ (m) | | Wastefield thickness $h_e$ (m) | |
|---|---|---|---|---|---|---|---|
| | | Measured | Predicted | Measured | Predicted | Measured | Predicted |
| 0 | 390 | 81 | 67 | 16.3 | 17.1 | 7.5 | 12.8 |
| 25 | 390 | 223 | 215 | 16.3 | 15.8 | 14.5 | 14.1 |
| 0 | 620 | 70 | 59 | 17.8 | 16.9 | 10.5 | 12.7 |
| 0 | 1270 | 56 | 46 | 17.8 | 16.9 | 14.5 | 12.7 |

```
 Jun 28, 1992,  11:29:45  ERL-N PROGRAM PLUMES, July 1, 1992   Case:   7 of   8
 Title   Boston, multiport risers                                      linear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    17.08        440  0.03882       4.15
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
    31.3      0.157    0.1570     2.005     2.005     0.000      0.10       500
port elev ver angle cont coef  effl den poll conc      decay  Froude # Roberts F
        1        0         1         0       100         0     10.18 4.327E-13
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     4.150    25.200.00001000  0.000453            200500 0.0007564
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
     0.0      1e-5      21.4                              0    0.03408    0.2471
       5      1e-5      21.4                              0 buoy flux puff-ther
     7.3      1e-5      21.5                              0  0.002311     39.82
      10      1e-5      22.2                              0 jet-plume jet-cross
      15      1e-5      24.2                              0     1.505     27900
    17.3      1e-5      24.9                              0 plu-cross jet-strat
      20      1e-5      25.1                              0 9.593E+12     2.861
      25      1e-5      25.2                              0 plu-strat
      35      1e-5      25.2                              0     3.946
                                                           hor dis>=


... RSB ...

 Case:  7: Boston, multiport risers

 Length scale ratios are: s/lb =   1.70 lm/lb =   0.22
 Froude number, u3/b =          0.00
 Jet Froude number, Fj =        10.3

 Rise height to top of wastefield, ze =  17.2
 Wastefield submergence below surface =  14.1
 Wastefield thickness, he =             12.9 m
 Height to level of cmax, zm =          11.5 m
 Length of initial mixing region, xi =   9.4 m

 Minimum dilution,       Sm =    63.6
 Flux-average dilution, Sfa =    73.2 ( 1.15 x Sm)
 Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed

... UM ...

 plume dep plume dia poll conc  dilution   hor dis
       m         m                             m
    31.30    0.1570    100.0     1.000     0.000
    25.39     2.569    3.125     31.24     5.444
    18.96     4.183    1.408     69.29     6.703 -> merging
    16.92     4.802    1.217     80.15     6.989 -> trap level
    14.16     9.749    1.075     90.80     7.539 -> plume element overlap.
No farfield prediction; cause not known.
```

**Figure 61**.  Boston example, multiport risers; RSB and UM simulations.


It can be seen that, despite the very large difference between the conditions on which RSB is based (paired ports, linear stratification) and the Boston tests (ports clustered 8 per riser, very nonlinear stratification), the predictions are very good. Dilutions are generally underestimated, i.e. the model is conservative.  This is most probably due to the additional mixing which occurs in the horizontally spreading layer in the nonlinear profile compared to that in the linear profile.

## DESIGN APPLICATIONS

RSB is a useful tool for the design of outfall diffusers.  Time can be saved when doing this by keeping in mind the following guidelines:

> The most important parameter for an ocean outfall diffuser for a fairly large flow is the length $L$.  This can be chosen first, and the details, i.e. port spacing and diameter chosen later.

> The flow approximates a line source for $s/l_b < 0.3$.  At this point the dilution is a maximum (for fixed diffuser length) and adding more ports so that the spacing is less will have no effect on dilution or rise height.  Also, there is little point in making the port diameter smaller than the value which results in $l_m/l_b = 0.2$, as this will result in increased head losses.  The only constraints are internal hydraulics (which may be complex for tunneled outfalls) and that the ports flow full, i.e. $F_j > 1$.

> Momentum only affects dilution when $l_m/l_b > 0.2$.  Therefore decreasing the port diameter to increase momentum will only affect dilution if it results in $l_m/l_b > 0.2$.  Even then the primary effect on the wastefield is reduced rise height (in a linear stratification), and dilution is only slightly affected.

# UM MODEL THEORY

## PERSPECTIVE

UM is the latest in a series of models first developed for atmospheric and freshwater applications by Winiarski and Frick (1976) and for marine applications by Teeter and Baumgartner (1979). The marine version, known as OUTPLM, became the basis of the MERGE model (Frick, 1980). Both underwent modifications to become the UOUTPLM and UMERGE models (Muellenhoff et al., 1985). Since 1985 the UMERGE model has been further generalized and enhanced; including treatments of negatively buoyant plumes and background pollution. These improvements are included in UM, one of two resident initial dilution models in PLUMES. Other active research focusing on the generalization to three dimensions and to geothermal applications continues (e.g. Frick, Baumgartner, and Fox, 1994).

Outstanding UM features are the Lagrangian formulation and the projected area entrainment (PAE) hypothesis. The Lagrangian formulation offers comparative simplicity that is useful in developing PAE.

The projected area entrainment hypothesis is a statement of forced entrainment — the rate at which mass is incorporated into the plume in the presence of current. As a general statement it was articulated at least as early as 1960 (Rawn, Bowerman, and Brooks). However, Frick (1984), Lee, Cheung, and Cheung (1987), and Cheung (1991) find that most implementations (e.g. Hoult, Fay, and Forney, 1969) of the hypothesis are incomplete. They typically include only one or two of the PAE terms that have been identified, which are then tuned for best fit. For two-dimensional flow, UM and JETLAG (Lee and Cheung, 1990) use all three terms, thereby eliminating the need for tuning. In addition to PAE, the traditional Taylor entrainment hypothesis (Morton, Taylor, and Turner, 1956) is also used.

It is not in the scope of this work to present extensive verification of the UM model, however, Figures 62 and 63 do give a general indication of the quality of prediction. The superiority of the PAE hypothesis is demonstrated by Lee and Cheung (1990) and Cheung (1991) who adapt the approach to three dimensions in the JETLAG model and show that the Lagrangian plume models using PAE predict observed asymptotic behavior in a number of flow regimes. Frick, Baumgartner, and Fox (1994) show example comparisons between UM and JETLAG.

In Figure 63 the densimetric Froude number of the effluent is given by $F_j$: a measure of the ratio of momentum to buoyancy in the plume, with large Froude numbers (jets) indicating relatively high momentum and small Froude numbers indicating strong buoyancy. The ratio of efflux velocity to current is given by $k$; a high value indicates a relatively strong effluent velocity or low current speed.

The Lagrangian model and its entrainment hypotheses are described below in some detail. To understand the model it is necessary to first have an appreciation of the basic model building

block — the plume element. On that basis, the plume element dynamics, conservation principles, entrainment, and merging are more easily understood. Simultaneously, a detailed mathematical description of the model is given.
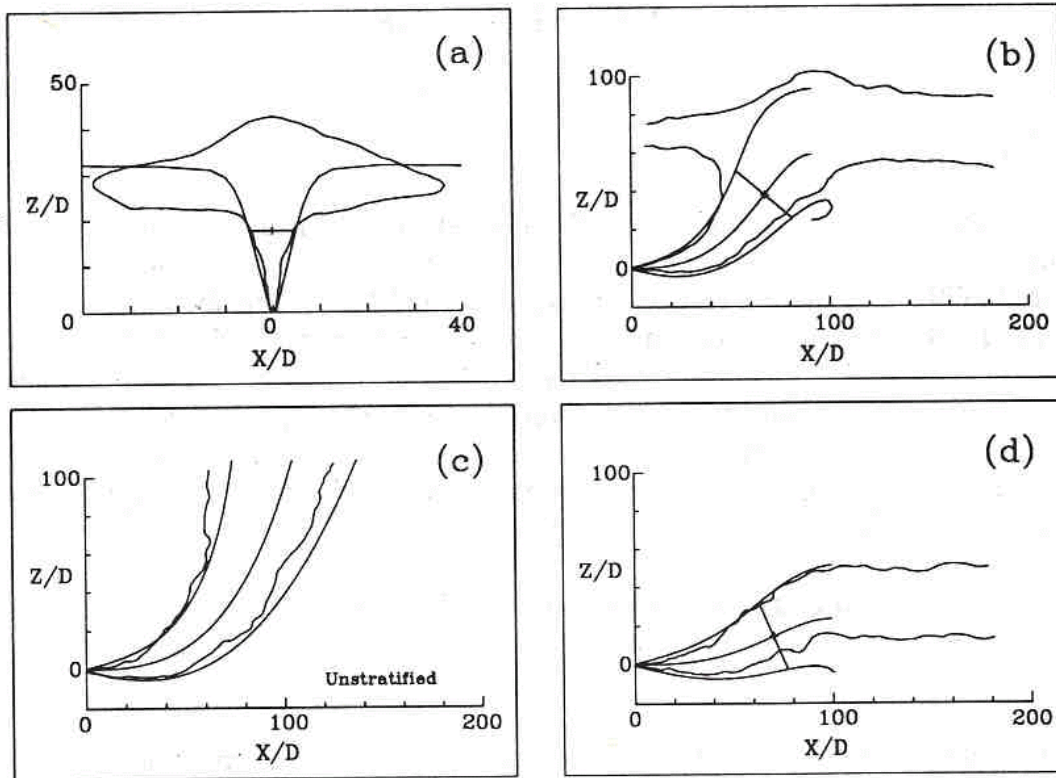


**Figure 62**. UM centerline and boundary predictions in stagnant ambient compared to Fan (1967). (a) Jet No. 10, (b) Jet No. 16, (c) Jet No. 22, unstratified, and (d) Jet No. 32.

## BASIC LAGRANGIAN PLUME PHYSICS

### The Plume Element

The shape of the element is very important to plume modeling because it determines the projected area, to which forced entrainment is directly proportional, at least in the initial dilution region. In UM the constant of proportionality is simply unity — 1. Forced entrainment and Taylor entrainment determine the growth of the element and play a key role in the dynamics of the plume.

In terms of the dynamics of the plume element, shown at three stages of development in Figure 64, simple models like the Lagrangian or Eulerian integral flux models provide only an estimate of the element trajectory, i.e., s, the path of the center-of-mass of the plume element. It is shown as a solid line passing through the centers of the elements as if all the mass of the plume element

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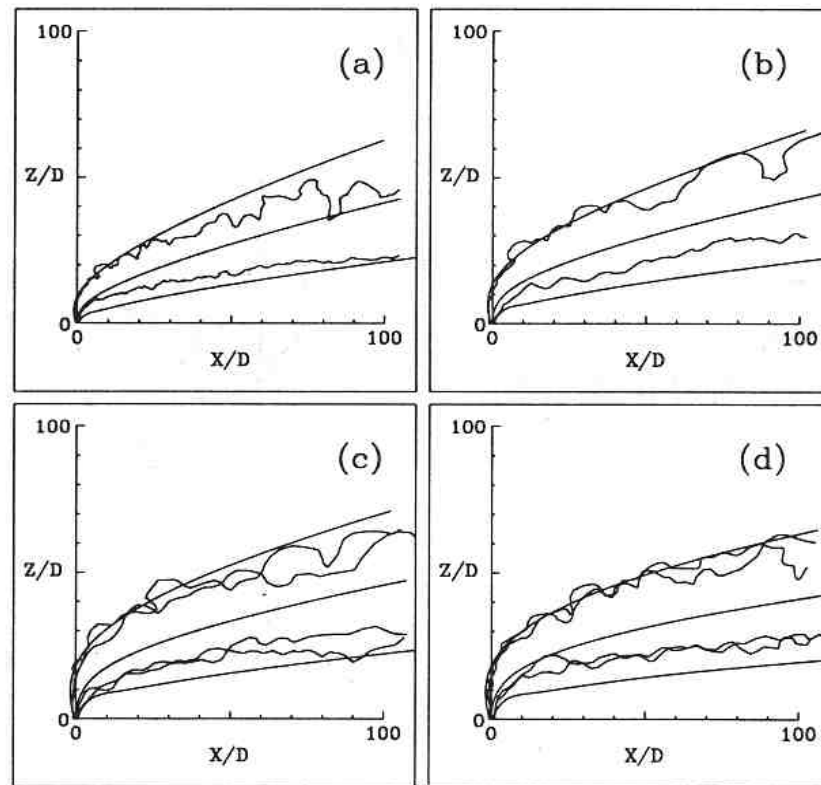
**Figure 63**. Plume trajectory, the element at three stages of development, and selected plume variables.

were concentrated there.

In Lagrangian and comparable integral flux models, that is the only coordinate variable that is predicted by the plume model. Other variables characterizing the distribution of mass are inferred or assumed. The shape of the element is established arbitrarily before the growth of the particle can be determined. In other words, the modeler determines how the shape of the plume is specified. Normally, a particular interpretation of the round plume assumption is used to establish the distribution of mass about the trajectory of the plume element; it holds that the plume element is basically cylindrical in shape.

But, if it is assumed, as it generally is, that the element is defined by a smooth surface on the exterior of the plume and by interior planes, or faces, that are perpendicular to the particle trajectory, and that the plume trajectory is curved, then this definition results in an element that is not cylindrical but has the shape of a section of bent cone. Because the length of the element along the trajectory must be small for mathematical reasons, it is better to conceive of the element as a thin round wedge with a blunt or sharp edge. This is the element form assumed in UM.

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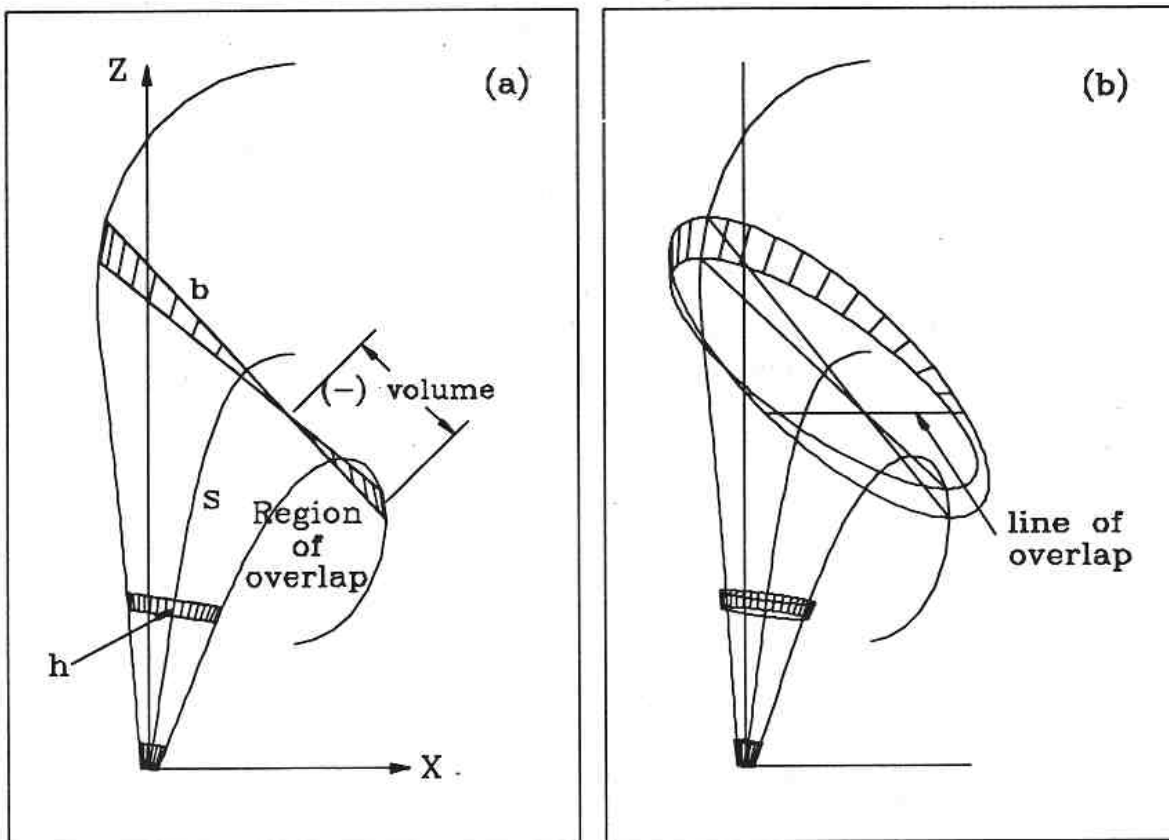
**Figure 64**. UM predictions in flowing ambient compared to Fan (1967). (a) $F_j$=10, $k$=8, (b) $F_j$=20, $k$=12, (d) $F_j$=40, $k$=16, and (d) $F_j$=80, $k$=16.

In special cases of plume trajectory of smaller radius-of-curvature than the plume radius itself, the element faces would intersect, or overlap, a physically impossible situation. This complication is depicted in Figure 64 and is considered further subsequently.

Furthermore, the asymmetry in shape is not consistent with the conventional practice of constructing equal plume element radii symmetrically about the trajectory. The plume trajectory represents the center-of-mass of the plume element which is generally <u>not</u> at the center of the circular cross section and therefore the lengths of the "radii" are directionally dependent.

The rigorous treatment of these complications is beyond the scope of the UM model. However, UM does issue a warning when overlap begins and, in its the default mode, terminates the initial dilution computation. In other models of the same class, both Lagrangian and Eulerian integral flux, the condition is not identified, or even recognized, and results in the over-prediction of plume radius and entrainment unless the increase has been effectively tuned out, a practice that would introduce spurious behavior elsewhere. Empirical models are not subject to the error.

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The plume is assumed to be in steady state. In the Lagrangian formulation that implies that successive elements follow the same trajectory. The plume envelope remains invariant while elements moving through it change their shape and position with time. However, conditions can change as long as they do so over time scales which are long compared to the time in which a discharged element reaches the end of the initial dilution phase, usually at maximum rise. The steady state assumption is used to derive the length of the plume element as a function of the instantaneous average velocity, its initial length, and the initial effluent velocity.

Thus, the length of the element does not in general remain constant but changes with time due to the different velocities of the leading and trailing faces. It follows that the radius of the element must respond to this velocity convergence or divergence, as well as to entrainment, because the fluid is practically incompressible, though incompressibility and the limiting Boussinesq approximations (Spiegel and Veronis, 1960) are not incorporated in UM.

The exterior boundary of the plume element coincides initially with the edge of the orifice from which it issues (or the vena contracta diameter). By integrating from this known initial and boundary condition the plume volume is calculated based on the entrained mass and the assumed element shape. It is assumed that the properties of the plume at the boundary are indistinguishable from those in the adjacent ambient fluid. This has important implications, one being that drag is not an important force in plume dynamics. It also implies that mass crosses the projected area of the element at the speed of the ambient current.

**Conservation Principles**

The model includes statements of conservation of mass (continuity), momenta, and energy. Conservation of mass states that the initial mass of the element and that added, or entrained, over time is conserved. In modeling terms the element mass is incremented by the amount of fluid that flows over the outside boundary of the plume element in a given amount of time. Given that mathematical artifacts like overlap do not occur, the PAE assures that excessive or inadequate amounts of entrainment are not inadvertently incorporated, i.e. entrained, into the plume.

Similarly, horizontal momentum is conserved. The horizontal momentum, the product of the element mass and horizontal velocity, is increased by the horizontal momentum of the entrained fluid in the same time step. Vertical momentum is not generally conserved because it is usually changed by buoyancy, a body force arising from the density difference between the element and the ambient fluid.

Finally, energy is conserved, similarly incremented by adding an amount of energy equal to the product of a constant specific heat, the entrained mass, and the ambient temperature. It provides the means for estimating the average temperature of the element which is used in the equation of state to obtain the densities of fresh and sea water in salinity and temperature ranges that are representative of terrestrial and coastal waters.

**Entrainment and Merging**

   Entrainment is the process by which the plume incorporates ambient material into itself. It may be thought of as a process in which fluid flows into the plume interior through the exterior surface. Alternatively, it may be considered to be a process of accretion followed by the redistribution of material. The former model is used here and is consistent with the projected area entrainment hypothesis.

   Several mechanisms of entrainment are considered: aspirated, forced, and turbulent, or eddy, diffusion. Aspirated entrainment is shear (or Taylor) entrainment which is present even in the absence of current. It is due to the fact that high velocity regions are regions of relative low pressure which causes inflow of material into the plume. Thus the plume induces a flow field in the surrounding ambient fluid. Forced entrainment is due to the presence of current that advects mass into the plume. Diffusion is assumed always to be present but is only important beyond the zone of initial dilution. It becomes dominant after the other two entrainment mechanism die off due to the steady reduction in shear between the plume and the ambient. The transition separates the near-field from the farfield. Strictly speaking, the latter dilution is not a part of the UM theory because UM is still primarily a near-field model. Instead, farfield diffusion is parameterized, for example, by the "4/3 law" (Tetra Tech, 1982).

   Entrainment through the projected area of the plume is composed of three terms. The first term is proportional to the length and radius of the element (the cylinder component), the second to the growth in diameter of the plume, and the third to the curvature of the plume trajectory that opens or closes area on the element surface. All are simply mathematical parts of the overall projected area that contribute to forced entrainment. A fourth term, encompassing the entire peripheral area, accounts for aspiration entrainment.

   When adjacent plumes grow sufficiently they begin to merge and entrain each other. Merging of plumes has the immediate effect of reducing entrainment by reducing the contact area between the plume and its environs. Each of the four entrainment terms is decremented to a different degree as merging proceeds. In essence, merging simply necessitates some geometric corrections. Surface and bottom effects as demonstrated by Wood (1990), or Coanda attachment (Akar and Jirka, 1990), are not modeled.

   Only the merging of adjacent plumes discharging from linear diffusers (pipes) are considered here. This simplification helps to reduce the problem to two dimensions. Diffusers are assumed to be long so that end effects can be ignored and unbalanced internal diffusion is neglected.

   Variations in the angle between the diffuser and the current are accommodated by mathematically reducing the spacing distance between adjacent ports by the appropriate trigonometric factor. Currents between 90 and 45 degrees may be handled in this way and lead to reductions of entrainment in agreement with measurements made by Roberts (1977).

   Typically diffusers are perforated on both sides. In a current the upstream plumes will then frequently bend over and merge with downstream plumes. This cross-diffuser merging is not

simulated explicitly.  In UM there are three ways to estimate the reduction in dilution due to cross-diffuser merging.  The simplest way is to reduce the spacing between ports by a factor of two (i.e. spacing is equal to the diffuser length divided by the total number of ports).  This method is justified by experience but it is not known with certainty how accurate it is.  The effect may also be estimated by specifying the "background" concentration generated by the upstream plume, which results in the prediction of a reduced effective dilution.  A third method involves doubling the flow per port and increasing the diameter of the port to maintain approximately the same densimetric Froude number.  None of the methods account for the changes in density profile that the upstream plume effects on the downstream plume.

## MATHEMATICAL DEVELOPMENT

### Basic Model Theory

With respect to the foregoing discussion, it is emphasized that the element in Figure 64 is **not** a cylinder but is in general a section of a bent cone.  The consequences of this fact cannot be overstated because the shape of the element determines the projected area which in turn determines forced entrainment, frequently the dominant source of entrainment.  In general, a bent cone plume element has a projected area that differs substantially from the projected area of a simple cylinder. Thus, the growth and curvature terms are required to accurately describe the projected area of the plume element (Frick, 1984; Cheung, 1991).

As has been stated, the principle of superposition allows the entrainment terms to be described separately.  The projected area entrainment hypothesis states that

$$\frac{dm}{dt} = \rho_a A_p u \tag{27}$$

where $dm$ is the incremental amount of mass entrained in the time increment $dt$, $A_p$ is the projected area, $u$ is the ambient current speed normal to the projected area, and $\rho_a$ is the local ambient density. This hypothesis, neglecting Taylor entrainment for a moment, makes it possible to explain observed plume behavior in simple terms without tuning.

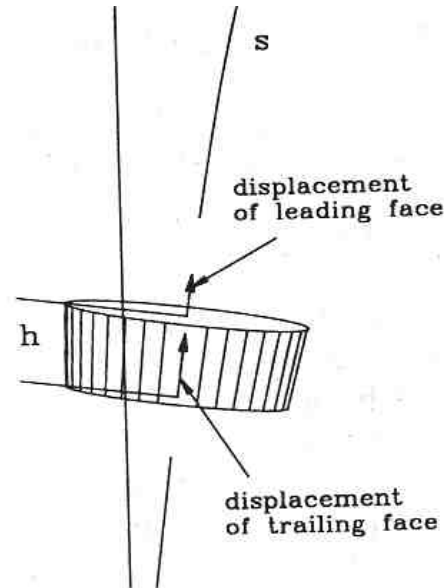Equation 27 can be written in vector terms

$$\frac{dm}{dt} = \&\rho_a \, \underline{A_p}.\underline{U} \tag{28}$$

where the underline notation is used to indicate vectors.  $\underline{A_p}$ lies in a vertical plane containing the current vector and points generally upstream out of the element.  $\underline{U}$ is the average velocity of the ambient flow through the projected area.  $\underline{A_p}$ and $\underline{U}$ point in opposite directions so that their dot product is intrinsically negative.

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To estimate the projected area it is necessary to express mathematically how the length of the element, $h$, changes in response to changes in other plume properties. The reason $h$ changes is due to the difference in velocity of the leading and trailing faces of the element which causes the faces to converge or diverge with time. Just how much their separation changes depends on how much the local current velocity differs from the element velocity. Because mass is conserved, changes in h result in changes to the radius. The effect is substantiated by dilution and radii data tabulated by Fan, 1967.

Referring to Figure 65, $\hat{I}^{*}\underline{V}^{*}$ is seen to be the difference in velocity at two opposing faces of the semi-infinitesimal element. (The velocity vectors are proportional to the displacement vectors shown. Also, in both formulations the element is infinitesimal only along the trajectory, thus it is a hybrid integrating volume which is treated differently from truly infinitesimal volume elements.) Since the Lagrangian formulation deals with material elements and it is assumed the velocity is uniform, the faces separate or converge, proportional to $\hat{I}^{*}\underline{V}^{*}$, i.e.,

$$\Delta h \; ' \; \Delta^{*}\underline{V}^{*} \; \delta t \tag{29}$$



**Figure 65**. Convergence of element faces due to differences in face velocities.

where $\hat{I}t$ is an arbitrary, but constant, time increment. Integrating Equation 29 and noting that the corresponding speed differentials and lengths are $\hat{I}^{*}\underline{V}_{o}^{*}$ and $h_{o}$, and, $\hat{I}^{*}\underline{V}^{*}$ and $h$ yields

$$\int_{h_{o}}^{h} dh \; ' \; \delta t \int_{u_{so}}^{u_{s}} du_{s} \tag{30}$$

where $u_{s} = {}^{*}\underline{V}^{*}$ and $u_{so} = {}^{*}\underline{V}_{o}^{*}$. Equation 30 can be integrated to yield

$$h \; \& \; h_{o} \; ' \; (u_{s} \; \& \; u_{so})\delta t \tag{31}$$

Finally, since $\hat{I}t$ can be chosen to be $h_{o}/u_{so}$

$$\frac{h}{h_{o}} \; , \; \frac{u_{s}}{u_{so}} \tag{32}$$

and ${}^{*}\underline{V}^{*}$, i.e. $u_{s}$ and $h$ change proportionally.

## Plume Dynamics

It is convenient to begin a discussion of the Lagrangian plume equations with the equation of continuity, in other words, the entrainment equation. Equations 27 or 28 is a partial expression for entrainment; it states that the "forced" part of the amount of mass added to the element in time $dt$ is equal to the total mass flux through the element surface. The complete entrainment equation is a sum of the forced and Taylor induced entrainment terms

$$\frac{dm}{dt} \cdot \quad \& \rho \ \underline{A}_p \cdot \underline{U} \ \% \ \rho A_T \ v_t \tag{33}$$

where $A_T$ is the area of the plume element in contact with the ambient fluid and $v_T$ is the Taylor aspiration speed. Since, in the absence of merging, $A_T$ wraps completely around the element it is not expressed as a vector. $v_T$ is often related to an average plume velocity through a proportionality coefficient, $\alpha$:

$$v_T \cdot \quad \alpha *\underline{V}* \tag{34}$$

where $*\underline{V}*$ is the average, or top hat, plume element velocity (but in other formulations it could be the centerline velocity with $\alpha$ scaled accordingly).

For plumes (jets with buoyancy) adequately described by a Gaussian profile (see a subsequent section entitled "Average and Centerline Plume Properties") a value of 0.082 is often attached to $\alpha$. However, this is based on a nominal plume boundary which encompasses only the central portion of the plume. The corresponding value for jets in stagnant ambient is 0.057. However, Frick (1984) makes arguments for a constant $\alpha$. The conversion from nominal Gaussian plumes to a "top hat", or average, description of the plume element yields corresponding values of 0.116 and 0.081. According to Frick (1984), the latter is underestimated so that an average value for $\alpha$ of 0.1 is thought to be slightly conservative in terms of describing aspiration entrainment. A comparison with JETLAG supports this conclusion (Frick, Baumgartner, and Fox, 1994).

Strictly speaking, the areas are infinitesimal areas which might be indicated with the differential d prefix. This is because h is ideally an infinitesimal distance. However, the model equations are approximations in which small algebraic values substitute for infinitesimal ones.

Both entrainment areas need further elaboration. The Taylor aspiration area in the absence of merging, dynamic collapse, and element facial overlap (sharp trajectory curvature) is simply

$$A_T \cdot \quad 2\pi b h \tag{35}$$

where $b$ is the element radius. The reduction in this area due to merging is described in a later section. The effects of dynamic collapse (Frick et al., 1990) are not included in UM.

Deriving the projected area is more difficult than deriving the Taylor entrainment area. An
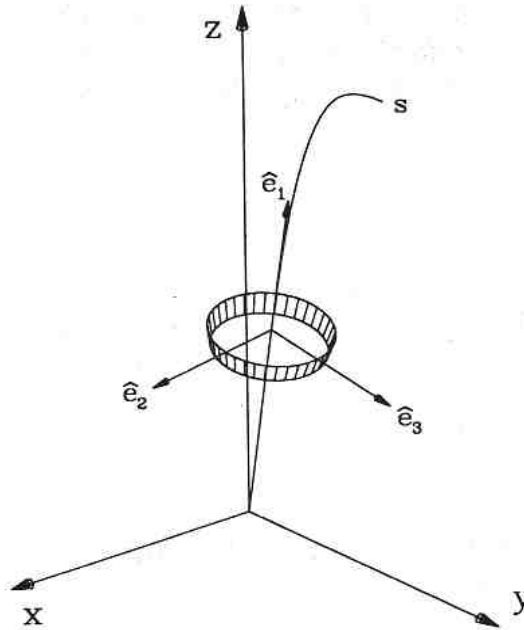


**Figure 66**. The local coordinate system.

approach that applies to three-dimensional plumes is useful. It holds that, since the current, $\underline{U}$, is a vector field it may be transformed into a useful coordinate system by well established rules of vector rotation. A particularly useful coordinate system is the local coordinate system shown in Figure 66. The ambient velocity vector, i.e., the current, can be expressed as the sum of components in each of the local coordinate system directions

$$\underline{U} = u_1 \hat{e}_1 + u_2 \hat{e}_2 + u_3 \hat{e}_3 \tag{36}$$

where $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$ are the unit vectors in the direction of the trajectory, the horizontal normal to the trajectory, and in a vertical plane respectively. The vector $\hat{e}_3$ can be expressed in terms of the cross-product of $\hat{e}_1$ and $\hat{e}_2$:

$$\hat{e}_3 = \hat{e}_1 \times \hat{e}_2 \tag{37}$$

The unit vectors are derived by constructing a rotation matrix that transforms between the coordinate systems.

As far as each velocity component is concerned the corresponding projected areas are particularly simple, see Figure 67. Again ignoring merging, collapse, and overlap, the projected area associated with $u_1$, i.e., $A_1$, is simply an annulus that wraps around the plume

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a.



growth term

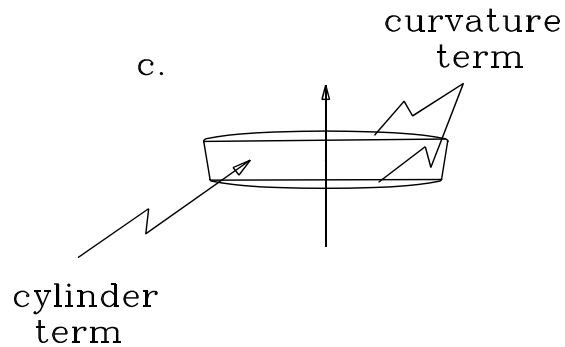curvature
term

b.

c.
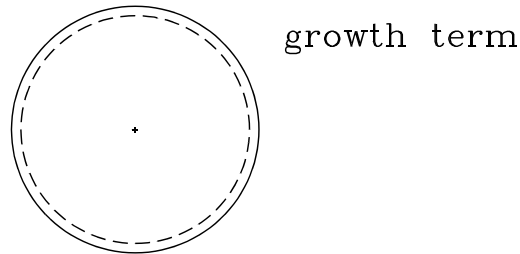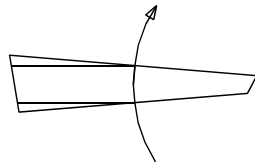
cylinder
term

**Figure 67**. The projected area entrainment components: a) the growth area, b) side view of the element, and c) the cylinder and curvature area.

$$A_1 \quad ' \quad \pi b \, \Delta b \tag{38}$$

where $\hat{l}\,b$ is the difference between the radius of the leading and trailing faces of the plume element. This is the "growth" contribution to the projected area (see Figure 67a). The assumption is made that only the upstream portion of the area, half the circumference, has flow going through it. The flow in the wake is altered and is assumed to flow parallel to the plume surface.

The difference in radius over the length of the element is

$$\Delta b \quad ' \quad \frac{Mb}{Ms} h \tag{39}$$

where $s$ is the distance along the centerline. The derivative is estimated from the difference in radius in successive program steps divided by the distance traversed.

Each one of the velocity components $u_2$ and $u_3$ has two projected area terms associated with it,

one which is due to the curvature of the plume trajectory, the other simply being the projection of a cylinder (see Figure 67b and 67c respectively). Since only the two-dimensional problem is considered the $u_3$ component is ignored; its cylinder and curvature contributions are due to current flowing into the side of the plume element caused by directional changes with depth in the ambient flow.

The cylinder projected area is simply

$$A_{cyl} \ ' \ 2bh \tag{40}$$

The change in direction of the average plume element velocity, $\underline{V}$, which is parallel to $\hat{e}_1$, over the length of the plume element $h$, in other words the curvature of the centerline $s$, produces the "curvature" component to the projected area. Since the faces defining the element are normal to $s$, in regions of strong trajectory curvature the element is deformed into a wedge shape. A depiction
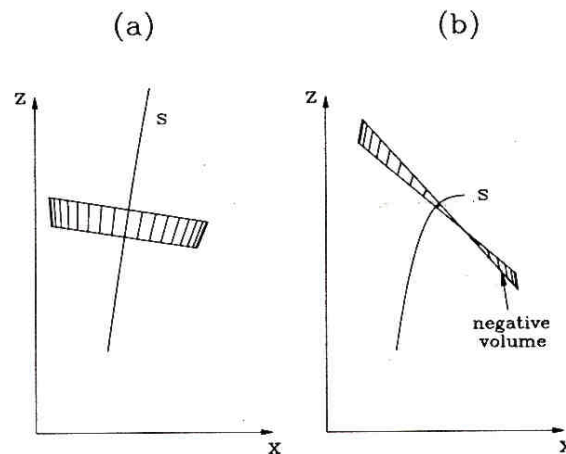


**Figure 68**. a) The plume element in a region of weak trajectory curvature and b) strong trajectory curvature (showing overlap).

is given in Figure 68.

The curvature component of the projected area is

$$A_{cur} = \& \frac{\pi}{2} b^2 \frac{\delta\theta}{\delta s} h \tag{41}$$

where $\theta$ is the elevation angle of $s$. This area can be positive or negative depending of the sign of $\delta\theta/\delta s$ which is determined with reference to successive values of $\underline{U}$. Positive curvature has the effect of reducing the total projected area.

Historically the growth and curvature terms have either not been recognized or have been thought to be small compared to the cylinder term (Schatzmann, 1979). However, in general, it can be shown that all three contributions to the total projected area are important. Any earlier perceived inadequacies in the projected area entrainment hypothesis can be attributed to the omission of the growth and curvature terms. Further details are available in Lee, Cheung, and Cheung (1987), Cheung (1991), and Frick (1984).

Conservation of momentum is given by

$$\frac{dm\underline{V}}{dt} = \underline{U}\frac{dm}{dt} \& m\frac{(\rho_a \& \rho)}{\rho} g \tag{42}$$

where $m$ is the mass of the plume element ($m = \pi b^2 h$), $\rho_a$ and $\rho$ are the ambient and average element densities respectively, and $g$ is the gravity vector. Ideally $\underline{U}$ represents the average ambient velocity over the exposed plume surface. This point is worth emphasizing since the surface area is infinitesimal only along the centerline and can be extensive in the two dimensions orthogonal to the centerline, over which, therefore, the ambient velocity can vary significantly. In UM it is approximated by the ambient velocity at the level of the particle, i.e., the center of the cross-section.

Equation 42 states that the change in momentum in the element is due to the amount of momentum introduced by the entrained mass $dm$ and the change in vertical momentum generated by the buoyant force. The implicit assumption is that drag effects are absent. This is consistent with the conception of the element having the same properties as the ambient on the outside surfaces of the element. Effectively, there are no shears that can generate drag.

While interactions with solid and free surfaces are not modelled, UM gives warning when some of them occur. The warnings, which are not exhaustive, are explained in Appendix 4. The bottom is assumed to be flat. In Muellenhoff et al. (1985) predicted dilutions were reduced by 10% when the sea surface was encountered. Generally, plumes rise in a matter of minutes so that the Coriolis force is safely ignored.

To evaluate the buoyancy term in the conservation of momentum equation, it is necessary to define the conservation of energy equation, approximated by

$$\frac{d\,mc_p(T\&T_{ref})}{dt} \, \cdot \, c_p(T_a\&T_{ref})\frac{dm}{dt} \tag{43}$$

where $c_p$ is the specific heat at constant pressure. $T$, $T_a$, and $T_{ref}$ are the average element temperature, the ambient temperature, and an arbitrary reference temperature, respectively. More correctly, the terms in Equation 43 should be represented by integrals. However, it is assumed that $c_p$ is constant over the range of interest permitting Equation 43 to be simplified,

$$\frac{d\,mT}{dt} \, \cdot \, T_a\frac{dm}{dt} \tag{44}$$

Radiation, conduction, and diffusion are assumed to be small. Like salinity, temperature is assumed to be a conservative property.

Several other relationships are necessary. Conservation of salinity is expressed by

$$\frac{d\,mS}{dt} \, \cdot \, S_a\frac{dm}{dt} \tag{45}$$

where $S$ and $S_a$ are the average element salinity and the ambient salinity respectively. The symbol for ambient salinity should not be confused with average dilution of the plume. Conservative pollutants would be expressed similarly, however, since important pollutants, such as coliform bacteria, are subject to decay, a first order decay term is included.

$$\frac{d\,mX}{dt} \, \cdot \, X_a\frac{dm}{dt} \, \& \, kmX \tag{46}$$

where $X$ and $X_a$ are the concentrations of the species of interest in the element and ambient respectively and $k$ is a first order decay constant, which is zero for conservative pollutants. Non-conservative pollutants are also assumed to be subject to decay in the farfield.

The momentum equation includes the reduced gravity, $((Q_a - Q)/Q)g$, which must be determined. Densities are derived from the equation of state (Sigmat function) used by Teeter and Baumgartner (1979). It is independent of pressure, limiting UM to shallow water, by deep ocean standards. It is also limited to ordinary temperatures. At 150 o/oo the error in density in sigma-t units is about 10 percent.

**Boundary Conditions and Other Pertinent Relationships**

To completely describe the problem, the boundary and initial conditions must also be specified. The main boundary condition is the location of the source from which the subsequent position of the element may be determined by integrating the trivial relationship

$$\frac{dR}{dt} \ ' \ \underline{V} \tag{47}$$

where $\underline{R}$ is the radius vector of the particle, i.e., the center-of-mass of the element. To give an example of how the equations are solved in a finite difference model, the new $\underline{R}$ is

$$\underline{R}_{t\%dt} \ ' \ \underline{R}_t \ \% \ \underline{V} \ dt \tag{48}$$

Another boundary condition is the initial plume radius. Initial conditions include the efflux velocity, the effluent temperature, etc..

Various auxiliary equations are also required. They include linear interpolations that determine ambient conditions at the level of the particle. Also, because the Lagrangian plume equations require a very small time step initially, but not later in the simulation, a method of varying the size of the time step is used to control the relative amount of mass that is entrained during any one single step. This is done in the interest of computational efficiency.

The general computational procedure followed in the model is: 1) a time step is provided (guessed), 2) the entrainment equations are then used to determine the amount of mass that will be added given this time step, 3) this increase is then compared with the target mass increase and the appropriate adjustments are made to the time step and the entrainment components to meet the appropriate doubling criterion, 4) the equations of motion and other model equations are solved, and 5) the new time step is established and the cycle is repeated.

It is important to recognize that some of the above equations are not always solved for the quantity on the left hand side of the equal sign. In other words, the dependent variable may be some other variable besides the one on the left hand side of the equal sign. For example consider Equation 49 which expresses the mass of the element in terms of its dimensions and the density:

$$m \ ' \ \rho\pi b^2 h \tag{49}$$

For modeling purposes the radius, b, is not an independent variable, rather it is a dependent variable. Since mass is computed by integrating from its initial value using the entrainment, or continuity, equation, it is effectively an independent variable in Equation 49. Equation 49 is inverted and used to solve for the radius:

$$b_{t\%dt} \ ' \ \sqrt{\frac{m_{t\%dt}}{\pi\rho_{t\%dt}h_{t\%dt}}} \tag{50}$$

When overlap occurs Equation 50 gives anomalous results (Frick, Baumgartner, and Fox, 1994.) This is the source of the overestimation of radius and entrainment described previously.

**Merging**

The basic approach to handling plume merging is to 1) reduce the entrainment areas, both Taylor and forced, to account for the loss of exposed surface area that occurs when neighboring plumes interfere with each other, and, 2) to confine the plume mass from each plume to the space between them that is known to be available from symmetry considerations. It is assumed that the plumes are identical and any interaction between them is mutual, i.e. gains equal losses.

Considering Taylor entrainment first, the conditions of merging are depicted in Figure 69. It is
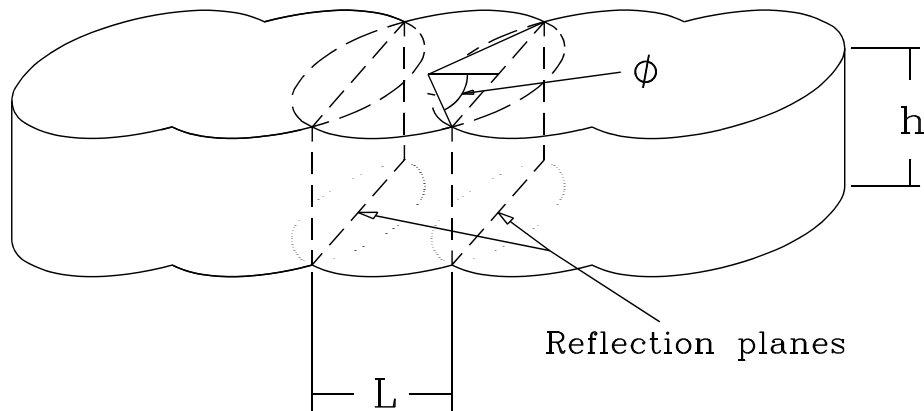


**Figure 69**. Merging geometry and reflection planes.

seen that the uncorrected Taylor entrainment area can be multiplied by a factor equal to the ratio of the exposed circumference to the total circumference to reduce it to the actual exposed area. Assuming no overlap, the side of the plume element that is longer and larger in area due to trajectory curvature compensates for the opposite side that is shorter and smaller.

The appropriate ratio of correction is

$$a_T \cdot \frac{\pi \, \& \, 2\varphi}{\pi} \tag{51}$$

where

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$$\phi \;{}' \; \arctan \sqrt{\frac{4b^2 \& L^2}{L^2}} \tag{52}$$

where $\phi$ is defined in Figure 69 and $L$ is the spacing between adjacent ports. The same correction factor applies to the growth entrainment term.

While it is assumed that the current is perpendicular to the diffuser axis, the method may be used for angles between 45 and 135 degrees (90 degrees being equivalent to a current perpendicular to the diffuser) by multiplying L by the factor $\sin \psi$ where $\psi$ is the angle between $\underline{U}$ and the diffuser axis. This method is justified by measurements of dilution of merging plumes (Roberts, 1977).

The correction factor for the cylinder projected area is simply

$$a_{cyl} \;{}' \; \frac{L}{2b} \tag{53}$$

Finally, the correction term for the curvature projected area entrainment contribution is

$$a_{cur} \;{}' \; 1 \; \& \; \frac{2\phi}{\pi} \; \% \; \frac{\sin 2\phi}{\pi} \tag{54}$$

Equations 49 and 50 must also be modified when merging occurs. As was pointed out in the previous section, the mass of the plume element is obtained by knowing the initial mass and integrating the entrainment equation. Given that the mass, average plume density, and element length are known, the element radius can be determined. Upon merging, the transverse dimension of the plume element (i.e. along $\hat{e}_2$) is assumed to be limited to a maximum length of $L$, the spacing distance. Effectively, a vertical plane half way between the ports acts as a wall or reflecting plane. This technique is common in air pollution modeling (Turner, 1970) where a fictitious mirror source is used to estimated dispersion in the presence of an actual physical barrier. With plume merging the sources are real.

Thus, the volume of the plume element can be thought to be the product of $h$ and the area of a rounded rectangle, see Figure 70. This area is the quotient of the element volume and the length which, after simplification, becomes

$$\pi b_r^2 \;{}' \; \pi b^2 (1 \; \& \; \frac{2\phi}{\pi}) \; \% \; 2b^2 \sin\phi \cos\phi \tag{55}$$

where $b_r$ is the unmerged round element radius and $b$ is now the radius of the element in the vertical plane. In other words, $b$ describes the plume element parallel to $\hat{e}_3$. Solving for $b$
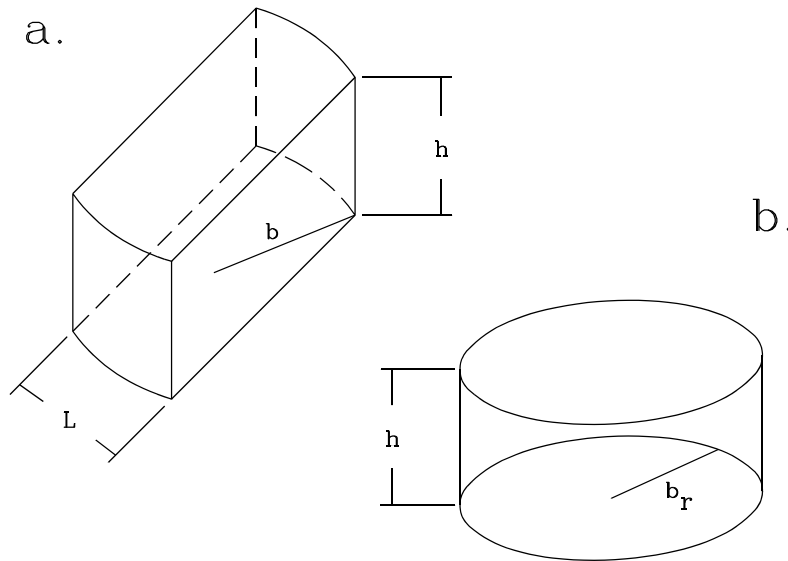
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**Figure 70**. Derivation of dimensions under merging: a) the merged element with volume confined between reflection planes, and b) the corresponding unmerged element of equal volume.

$$b \ ' \ \frac{\pi b_r}{\pi \ \& \ 2\varphi \ \% \ 2\sin\varphi\cos\varphi} \tag{56}$$

the subscript $t+\hat{I}t$ has been left off for simplicity. Since $n$ is larger than $\sin n \cos n$, $b$ is larger than $b_r$.

**Average and Centerline Plume Properties**

The previous discussion is in terms of average plume properties because average plume properties are physically compatible with the average motion of the plume element. We do not expect that centerline buoyancy can accurately describe, via vertical acceleration, the plume trajectory traced by the center-of-mass of the plume element. After all, the element is an entity which stretches from one boundary with the ambient flow to the other, with widely varying properties in between.

On the other hand, centerline concentrations often concern environmentalists because they have the potential for acutely affecting organisms. Fortunately, plumes are often found to possess

predictable patterns of cross-sectional properties. For example, plumes discharged into quiescent fluid tend to display the Gaussian profile, very dilute at the edges and concentrated at the center. However, the Gaussian profile is not very compatible with the plume element described above because it extends to infinity whereas we have described an element with definite boundaries. Consequently, another profile, the 3/2 power profile (Kannberg and Davis, 1976), which closely matches the Gaussian profile over the concentrated portion of its range, is used to determine the centerline concentration as a function of the average concentration, or dilution, that UM predicts.

The 3/2 power profile is expressed by

$$\Phi = \left( 1 - (\frac{r}{b})^{\frac{3}{2}} \right)^2 \tag{57}$$

where $\Phi$ is instantaneous scaling factor relating differences between the plume and the ambient of an appropriate property, such as the concentration of some pollutant or velocity, $b$ is the plume radius, and $r$ is the distance from the center of the plume to the point within the plume at which $\Phi$ is measured.

The peak-to-mean ratio is simply the ratio of the centerline to the average concentration, it is obtained from a flux integral. We start with the relationship for the average concentration

$$C_{avg} = \frac{\int C v \, dA}{\int v \, dA} \tag{58}$$

where $C_{avg}$ is equivalent to the average concentration obtained from UM, $C$ and $v$ are the instantaneous concentration and velocity in the plume element, $A$ is the cross-sectional area, and $dA$ is the corresponding infinitesimal area. The peak-to-mean ratio is defined to be $C_{max}/C_{avg}$

$$\frac{C_{max}}{C_{avg}} = \frac{C_{max} \int v \, dA}{\int C v \, dA} \tag{59}$$

where $C_{max}$ is the centerline concentration. The integrals in this quotient are not easy to solve analytically and, therefore, are estimated numerically in UM.

It is illuminating to define limiting values of the coefficient. When dilutions and currents are large a simplification is possible. In this case the velocity can be considered constant and can be factored from the integrals, giving

$$\frac{C_{max}}{C_{avg}} = \frac{C_{max} \int dA}{\int C \, dA} \tag{60}$$

Using this approximation and assuming the 3/2 power profile a peak-to-mean ratio of 3.89 is found

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for round plumes. The corresponding ratio for a fully merged line plume is 2.22. However, the ratios vary and in much of the plume the peak-to-mean ratios are considerably smaller than these limiting values, in fact, near the source they often approach 1.0, depending on the uniformity of the source. The centerline concentration prediction is approximate and occasionally deviates from the expected trend when vertically varying background pollutant concentrations are present.

## Experimental Justification of the Projected Area Entrainment Hypothesis

In 1989, Roberts, Snyder, and Baumgartner published three papers in ASCE (1989a,b,c) which record the behavior of merging laboratory plumes in flowing, stratified environments. Although they did not set out to do so, their findings directly corroborate PAE, as shown below:

Starting with Equation 13a of Roberts, Snyder, and Baumgartner (1989a) for unstratified conditions

$$\frac{S_m q N}{b^{2/3}} \cdot 1.08 F^{1/6} \tag{61}$$

$$N \cdot (\& \frac{g}{\rho_a} \frac{d\rho}{dz})^{1/2} \tag{62}$$

where $S_m$ is the centerline dilution in the plume, $q$ is the diffuser volume flux per unit length, $b$ is the buoyancy flux per unit length (i.e. the product of the reduced gravitational acceleration and the volume flux per unit length), $F$ is a type of Froude number ($u^3/b$, where $u$ is the current speed), and $N$ is the buoyancy (Brunt-Vaisala) frequency
and $d\rho/dz$ is the ambient density gradient. Their Equation 13b states

$$\frac{z_e}{l_b} \cdot 1.86 F^{\&1/6} \tag{63}$$

where $z_e$ is the rise above the port datum of the top of the fully merged wastefield and $l_b$ is a buoyant length scale defined by Roberts et al., 1989a Equation 4

$$l_b \cdot \frac{b^{1/3}}{N} \tag{64}$$

Combining, noting that $q = Q/L$, where $L$ is the length of the diffuser and $Q$ is the diffuser total volume flux, and making the appropriate substitutions yields

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$$S_m \doteq \frac{1.08}{1.86} \frac{L z_e u}{Q} \tag{65}$$

The quantity $L z_e u$ is, of course, just the flux through the projected area, which is the integrated form of PAE!  The coefficient is within the general range described in the previous section, however, it differs markedly from the factor of 1.15 used in RSB.

In stratified flow a similar derivation is possible.  Neglecting the additive term of -0.52 in Equations 25, justified in moderate to strong current or high $F$, the peak-to-mean ratio of 1.15 (more accurately 2.5/2.19, or 1.142) used in the RSB model is obtained.  However, it is clear that this is the lower limit of the ratio which would be greater if the additive term were not neglected.

Finally, it might be argued that the more appropriate measure of plume wastefield thickness is $h_e$, not $z_e$.  However, in large currents the bottom of the plume is often near the sea bottom. Furthermore, if plume spacing is smaller, then the latter measure is indeed the appropriate one for estimating entrainment flux.

This derivation proves, at least in an overall sense, that, in sufficiently high current, initial dilution is given simply by the quotient of the flux through the projected area of the wastefield divided by the source flux, multiplied by a constant factor.  In lieu of convincing evidence to the contrary, it is eminently reasonable to assume that such an integrated outcome is the result of adding the individual projected area fluxes throughout the plume trajectory.  In other words, it is not reasonable to assume, a priori, that the plume entrains differentially over its projected area, perhaps at twice the rate at one point and half the rate at another.  Any such deviations are thought to be due to the aspiration effect of the Taylor entrainment coefficient which can be treated separately. In other words, the two entrainment mechanisms act independently, are mathematically linear, and may be added.

# FARFIELD ALGORITHM

## PLUMES IMPLEMENTATION

Equation 17, developed by Brooks (1960), may be transformed into Equation 66 for near shore coastal waters, confined channels, and wherever a conservative analysis is desired

$$S' \frac{S_a}{erf\left(\sqrt{\dfrac{b^2}{16\alpha\, b^{4/3} t}}\,\right)} \tag{66}$$

where *erf* is the error function, $S$ is the centerline dilution in the farfield plume, $S_a$ is the initial dilution (at maximum rise, overlap, or other special condition), $\alpha$ is a dispersion coefficient (Fischer, 1979; Okubo, 1962), $b$ is the width of the plume field at the end of initial dilution, and $t$ is the time of travel from the point of the end of initial dilution to the point of interest.

The relationship between $\alpha$ (in Equation 66) and $\varepsilon_o$ (in Equation 17) is simply

$$\alpha' \; \varepsilon_o / b^{4/3} \tag{67}$$

For example, if $\varepsilon_o = 4$ m$^2$/sec and $b = 900$ m, then

$$\alpha' \; 4/900^{4/3} \; ' \; 0.00046 \; m^{2/3}/\sec \tag{68}$$

The value for $\alpha$ is entered into the farfield diffusion [far diff] cell of the interface. To compute the travel time, PLUMES uses the value in the farfield increment [far inc] cell divided by the farfield velocity [far vel] cell to compute the travel time, $t$.

The corresponding equation for open coastal waters, where the dispersion coefficient is continuously increased according to the 4/3 power of the local plume field width, is:

$$S' \frac{S_a}{erf\left(\sqrt{\dfrac{1.5}{(1 \; \% \; 8\alpha b^{4/3}\dfrac{t}{b^2})^3 \; \& \; 1}}\,\right)} \tag{69}$$

For coastal areas of known high energy dissipation features, or in many geographical areas at certain times of the year, $\alpha$ may have a value as high as 0.0005 m$^{2/3}$/sec. In less turbulent situations $\alpha$ may be as low as 0.0001 m$^{2/3}$/sec, thus the user has many options to employ in generating more or less conservative estimates of farfield dilution. Small values of $\alpha$ yield the most conservative estimates of farfield dilution.

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In Equations 66 and 69 the width, $b$, is the horizontal width of the wastefield measured perpendicular to the current. It is estimated by

$$b = (N - 1)s_{eff} + d \tag{70}$$

where $N$ is the number of ports, $s_{eff}$ is the effective spacing (spacing multiplied by $\sin\psi$), and $d$ is the diameter of the plume at the end of initial dilution. Equation 70 is simply the physical projection of the diffuser plus the additional growth of the plumes outside of this region. It is an approximation which does not account for the "attraction" of the plumes to each other or other mechanisms which can affect the width of the wastefield, including upstream intrusion.

Equations 66 and 69 only provide estimates of volume dilution, which is appropriate for conservative pollutants (decay = 0) and unpolluted ambient receiving water. PLUMES uses additional equations to estimate the effect of first order decay and ambient background concentrations. The sequence in each time step is as follows.

First a distance (path), presumed to be along ambient streamlines, is established. It is computed by adding the value in the [far inc] cell to the distance traversed by the element in the present time step. When the sum is greater than the value found in the [far dis] cell then it is set to that value and the program is terminated. The time elapsed in traversing the distance between successive values is found by solving the distance-is-rate-times-time formula. The total time is also incremented and Equations 66 and 69 are solved. The incremental mass gained by the element during the time step is determined by

$$\Delta m = (S_{t+\Delta t} - S_t)m_o \tag{71}$$

where $\Delta m$ is the mass entrained during the time step and $m_o$ is the plume element mass at the port. The total pollutant in the element is given by

$$m_{pt+\Delta t} = m_{pt}e^{-k\Delta t} + \Delta m\,\chi_a e^{-kt} \tag{72}$$

where $m_p$ is the total mass of pollutant in the plume element, $k$ is the first order decay constant, $\chi_a$ is the local ambient pollutant concentration.

If the decay rate, $k$, is equal to zero then the exponentials in the above equation are unity. In this case the ambient concentration may be constant. However, if the pollutant in question is not conservative, but is present in the ambient water, then it is also subject to decay. Equation 72 states that the ambient concentration follows the same decay law as that in the plume. These assumptions could impact the analysis of species such as coliform bacteria.

The final farfield calculation made during each time step determines the local average pollutant concentration in the plume element:

$$\bar{\chi} = \frac{\chi_o m_p}{S m_o} \qquad\qquad (73)$$

where $\chi$ with the bar is the average pollutant concentration in the element and $\chi_o$ is the pollutant concentration in the effluent.

The farfield algorithm is much simpler and rudimentary than the initial dilution part of UM. The quality of the estimates should not, in general, be expected to be as high as the initial dilution model. Consequently, if better methods for estimating the farfield concentration are available they should be considered.

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# REFERENCES

Akar P.J. and G.H. Jirka, July 1990. CORMIX2: An expert system for hydrodynamic mixing zone analysis of conventional and toxic multiport diffuser discharges. EPA/600/3-91/073, ERL, Office of Research and Development, USEPA, Athens, GA 30613.

Albertson, M.L., Y.B. Dai, R.A. Jensen, and H. Rouse, 1948. Diffusion of submerged jets. Transactions of the American Society of Civil Engineers, pp 1571-1596.

Anon., 1982. Code of Federal Regulations. Parts 122 and 125. Modifications of secondary treatment requirements for discharge into marine waters. Federal Register. Vol 47, No. 228. pp 53666-85. (November 26, 1982).

Anon., 1983. Clean water act amendments of 1983. Report of the committee on environment and public works, United States Senate. Report No. 98-233. September 21, 1983. U. S. Government Printing Office. Washington.

Anon., 1987. Water quality act of 1987, Public Law 100-4, February 4, 1987. Congress of the United States. U. S. Government Printing Office. Washington.

APHA, 1975. Standard methods for the examination of water and wastewater. 14th Edition. American Public Health Association. Washington. 1193 pp.

Baker, E.T., J.W. Lavelle, R.A. Feely, G.J. Massoth, and S.L. Walker, 1989. Episodic venting of hydrothermal fluids from the Juan de Fuca Ridge. Journal of Geophysical Research.

Baumgartner, D.J., and D.S. Trent, 1970. Ocean outfall design Part I, literature review and theoretical development. NTIS No. PB
203-749. (April 1970).

Baumgartner, D.J., W.E. Frick, W.P. Muellenhoff, and A.M. Soldate, Jr., 1986. Coastal outfall modeling: status and needs. Proceedings Water Pollution Control Federation 59th Annual Conference. Los Angeles, CA. (October 7, 1986).

Behlke, C.E. and F.J. Burgess, 1964. Comprehensive study on ocean outfall diffusers. Oregon State University, Engineering Experiment Station, Department of Civil Engineering. 26 pp. May 1, 1964.

Bodeen, C.A., T.J. Hendricks, W.E. Frick, D.J. Baumgartner, J.E. Yerxa, and A. Steele, 1989. User's guide for SEDDEP: a program for computing seabed deposition rates of outfall particulates in coastal marine environments. EPA Report 109-ERL-N. Environmental Protection Agency, Newport, OR 97365. 79 pp.

Brater, E.F. and H.W. King, 1976. Handbook of hydraulics for the solutions of hydraulic engineering problems, Sixth Edition. McGraw-Hill, NY.

Brooks, N.H., 1956.  Methods of analysis of the performance of ocean outfall diffusers with application to the proposed Hyperion outfall.  Report to Hyperion Engineers, Los Angeles California (April 5, 1956).

Brooks, N.H., 1960.  Diffusion of sewage effluent in an ocean current.  pp 246-267.  Proceedings of the First Conference on Waste Disposal in the Marine Environment.  Ed. E.A. Pearson. Pergamon Press. New York. 569 pp.

Brooks, N.H., 1973.  Dispersion in hydrologic and coastal environments.  EPA-660/3-73-010. (August 1973).

Carhart, R.A., A.J. Policastro, S. Ziemer, S. Haake, and W. Dunn, 1981.  Studies of mathematical models for characterizing plume and drift behavior from cooling towers, Vol. 2: mathematical model for single-source (single-tower) cooling tower plume dispersion.  Electric Power Research Institute, CS-1683, Vol. 2, Research Project 906-01.

Carhart, R.A., A.J. Policastro and S. Ziemer, 1982.  Evaluation of mathematical models for natural-draft cooling-tower plume dispersion.  Atmospheric Environment, Vol 16, pp. 67-83.

Carr, V.E., W.D. Watkins, and J.F. Musselman, 1985.  Ocean Outfall Study, Morro Bay California. Report to Region IX Shellfish Specialist. Northeast Technical Services Unit. Davisville, R.I. U.S. Department of Health and Human Services. 74 pp.

Callaway, R.J. 1971.  Application of some numerical models to Pacific Northwest estuaries.  pp 29-97.  Proceedings Technical Conference on Estuaries in the Pacific Northwest.  Oregon State University, Engineering Experiment Station Circular 42.  (March 19, 1971).

Cheung, V., 1991.  Mixing of a round buoyant jet in a current.  Ph.D. Thesis, Dept. of Civil and Structural Engineering, University of Hong Kong, Hong Kong.

Davis, L.R. and E. Hsiao, 1991.  An experimental/analytical investigation of buoyant jets in shallow water.  Oregon State University, Corvallis OR.

Doneker, R.L. and G.H. Jirka, 1990.  Expert system for hydrodynamic mixing zone analysis of conventional and toxic submerged single port discharges (CORMIX1).  EPA/600/3-90/012, ERL, Office of Research and Development, USEPA, Athens, GA 30613.

Fan L.N., 1967.  Turbulent buoyant jets into stratified or flowing ambient fluids.  Report No. KH-R-15, W.M. Keck Lab. of Hydraulics and Water Resources, California Institute of Technology, Pasadena, California.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N. H. Brooks, 1979.  Mixing in inland and coastal waters. Academic Press. New York. 483 pp.

Frick, W.E., D.J. Baumgartner, and C.G. Fox, 1994. Improved prediction of bending plumes. Accepted for publication in *Journal of Hydraulic Research*, International Association for Hydraulic Research (IAHR), Delft, The Netherlands.

Frick, W.E., C.G. Fox, and D.J. Baumgartner, 1991. Plume definition in regions of strong bending. Proceedings of the International Symposium of Environmental Hydraulics (December 16-18, 1991).

Frick, W.E., C.A. Bodeen, D.J. Baumgartner, and C.G. Fox, 1990. Empirical energy transfer function for dynamically collapsing plumes. Proceedings of International Conference on Physical Modeling of Transport and Dispersion, MIT, (August 7-10, 1990).

Frick, W.E., 1984. Non-empirical closure of the plume equations. Atmospheric Environment, Vol. 18, No. 4, pp. 653-662.

Frick, W.E., 1981. A theory and users' guide for the plume model MERGE, revised, Tetra Tech Inc., Environmental Research Laboratory, Corvallis, OR.

Frick, W.E. and L.D. Winiarski, 1978. Why Froude number replication does not necessarily ensure modeling similarity. Proceedings of the Second Conference on Waste Heat Management and Utilization. Dept. of Mechanical Engrg., Univ. of Miami (December 4-6, 1978).

Frick, W.E. and L.D. Winiarski, 1975. Comments on "The rise of moist buoyant plumes". J. of Applied Meteorology, Vol. 14, p. 421.

Grace, R.A., 1978. Marine Outfall Systems. Prentice-Hall. Englewood Cliffs. 600 pp.

Gremse, F., 1980. Transmittal of the DPHYDR program. Personal communication.

Hendricks, T.J., 1983. Numerical model of sediment quality near an ocean outfall. NOAA Final Report on Grant # NA8ORAD00041. Seattle, WA.

Hendricks, T., 1982. An advanced sediment quality model. Biennial Report for the years 1981-82. SCCWRP. Long Beach, CA. pp 247-257.

Hoult D.P., J.A. Fay, and L.J. Forney, 1969. A theory of plume rise compared with field observations. J. of Air Pollution Control Association, Vol 19, pp. 585-589.

Hunt, J., 1990. Particle Removal by coagulation and settling from a waste plume. Oceanic Processes in Marine Pollution, Vol. 6. Physical and Chemical Processes: Transport and Transformation. Eds. D.J. Baumgartner and I.W. Duedall. Krieger Publishing Co. Malabar Florida. 248 pp.

Isaacson, M.S., R.C.Y. Koh, and N.H. Brooks, 1978. Sectional hydraulic modeling study of plume behavior: San Francisco Southwest Ocean Outfall Project. W.M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Technical Memorandum 78-2.

Isaacson, M.S., R.C.Y. Koh, and N.H. Brooks, 1983. Plume dilution for diffusers with multiple risers. Journal of Hydraulic Engineering, ASCE, Vol. 109, No. 2, pp 199-220.

Jirka, G., 1992. Review comments of "Dilution models for effluent discharges (draft)."

Jirka, G. and S.W. Hinton, 1992. User's guide for the Cornell mixing zone expert system (CORMIX). National Council of the Paper Industry for Air and Stream Improvement, Inc.. Technical Bulletin No. 624. February, 1992.

Jones, G.R., 1990. "CORMIX3: An expert system for the analysis and prediction of buoyant surface discharges" Masters Thesis, Cornell University.

Kannberg, L.D. and L.R. Davis, 1976. An experimental/analytical investigation of deep submerged multiple buoyant jets. USEPA Ecological Research Series, EPA-600/3-76-101, USEPA, Corvallis, OR.

Koestler, A., 1964. The act of creation. Macmillan Company, New York, NY.

Lee, J.H.W., 1992. Private communication. Letter of 24 Nov 1992.

Lee, J.H.W. and V. Cheung, 1990. Generalized Lagrangian model for buoyant jets in current. ASCE J. of Environmental Engineering, Vol. 116, No. 6, pp. 1085-1106.

Lee, J.H.W., Y.K. Cheung, and V. Cheung, 1987. Mathematical modelling of a round buoyant jet in a current: an assessment. Proceedings of International Symposium on River Pollution Control and Management, Shanghai, China, Oct 1987.

Menzie, C. A. and Associates, 1986. Technical Information and Research needs to Support A National Estuarine Research Strategy. Battelle Contract No. 68-01-6986 Final Report to EPA. Various Paging. (January 1986).

Morton, B.R., G.I. Taylor, and J.S. Turner, 1956. Turbulent gravitational convection from maintained and instantaneous sources. Proceedings of the Royal Society of London. A234: pp 1-23.

Morton, B.R., 1959. Forced plumes. Journal of Fluid Mechanics. 5: pp 151-197.

Muellenhoff, W.P., A.M. Soldate, Jr., D.J. Baumgartner, M.D. Schuldt, L.R. Davis, and W.E. Frick, 1985. Initial mixing characteristics of municipal ocean outfall discharges: Volume 1. Procedures and Applications. EPA/600/3-85/073a. (November 1985).

National Research Council (NRC), 1984. Ocean disposal systems for sewage sludge and effluent. Washington, DC. National Academy Press, 126pp.

Okubo, A., 1962. A review of theoretical models of turbulent diffusion in the sea. Chesapeake Bay Institute, The Johns Hopkins Univ., Tech Report 30, Reference 62-20.

Ozretich, R.J. and D.J. Baumgartner, 1990. The utility of buoyant plume models in predicting the initial dilution of drilling fluids. Oceanic Processes in Marine Pollution, Vol. 6. Physical and Chemical Processes: Transport and Transformation. Eds. D. J. Baumgartner and I.W. Duedall. Krieger Publishing Co. Malabar Florida. 248 pp.

Policastro, A.J., R.A. Carhart, S.E. Ziemer, and K. Haake, 1980. Evaluation of mathematical models for characterizing plume behavior from cooling towers, dispersion from single and multiple source draft cooling towers. U.S. Nuclear Regulatory Commission Report NUREG/CR-1581 (Vol. 1).

Pomeroy, R., 1960. The empirical approach for determining the required length of an ocean outfall. pp 268-278. Proceedings of the First Conference on Waste Disposal in the Marine Environment. Ed. E. A. Pearson. Pergamon Press. New York. 569 pp.

Rawn, A.M., F.R. Bowerman, and N.H. Brooks, 1960. Diffusers for disposal of sewage in sea water. Proceedings of the American Society of Civil Engineers, Journal of the Sanitary Engineering Division. 86: pp 65-105.

Roberts, P.J.W., 1977. Dispersion of buoyant waste water discharged from outfall diffusers of finite length. W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology. Pasadena CA. (Report # KH-R-35).

Roberts, P.J.W., 1989. Dilution Hydraulic Model Study of the Boston Wastewater Outfall. Report Number SCEGIT 89-101, School of Civil Engineering, Georgia Institute of Technology.

Roberts, P.J.W., W.H. Snyder, and D.J. Baumgartner, 1989 a. Ocean outfalls I: submerged wastefield formation. ASCE Journal of Hydraulic Engineering. 115. No. 1. pp 1-25.

Roberts, P.J.W., W.H. Snyder, and D.J. Baumgartner, 1989 b. Ocean outfalls II: spatial evolution of submerged wastefield. ASCE Journal of Hydraulic Engineering. 115. No. 1. pp 26-48.

Roberts, P.J.W., W.H. Snyder, and D.J. Baumgartner, 1989 c. Ocean outfalls III: effect of diffuser design on submerged wastefield. ASCE Journal of the Hydraulic Engineering. 115. No. 1. pp 49-70.

Roberts, P.J.W., 1990. Outfall design considerations. The Sea. Ocean Engineering Science. Vol 9. Eds. B. LeMehaute and D. M. Hanes. Wiley and Sons. New York. pp 661-689.

Roberts, P.J.W., 1991. Basic language RSB program. Personal communication.

Roberts, P.J.W., 1993. "Hydraulic Model Study for the Boston Outfall. I: Riser Configuration," To be published in Journal of Hydraulic Engineering.

Schatzmann M., 1979. An integral model of plume rise. Atmospheric Environment, Vol. 13, pp. 721-731.

Spiegel, E.A. and G. Veronis, 1960. On the Boussinesq approximation for a compressible fluid. Astrophys. J., 131, pp 442-447.

State Water Resources Control Board, 1988. Water Quality Control Plan for Ocean Waters of California, California Ocean Plan, Sacramento. (September 22, 1988).

Teeter, A.M. and D.J. Baumgartner, 1979. Prediction of initial mixing for municipal ocean discharges. CERL Publ. 043, 90 pp. U. S. Environmental Protection Agency Environmental Research Laboratory, Corvallis, Oregon.

Tetra Tech, 1980. Technical evaluation of Sand Island wastewater treatment plant section 301(h) application for modification of secondary treatment requirements for discharge into marine waters. Prepared for U.S. EPA, Washington, D.C..

Tetra Tech, 1982. Revised Section 301(h) Technical Support Document. Prepared for U. S. Environmental Protection Agency. EPA 430/9-82-011. (November 1982).

Tetra Tech, 1984. Technical review of the Sand Island wastewater treatment plant section 301(h) application for modification of secondary treatment requirements for discharge into marine waters. Prepared by Tetra Tech, Inc.

Tetra Tech, 1987. A simplified deposition calculation (DECAL) for organic accumulation near marine outfalls. Prepared for USEPA. Washington, D.C.

Turner D.B., 1970. Workbook of atmospheric dispersion estimates. Office of Air Programs Publication No. AP-26. USEPA, Research Triangle Park, North Carolina.

U. S. Environmental Protection Agency, 1982. Revised Section 301(h) Technical Support Document. EPA 430/9-82-011. (November 1982)

U. S. Environmental Protection Agency, 1985. Technical Support Document for Water Quality-based Toxics Control. EPA-400/4-85-032. (September 1985).

U. S. Environmental Protection Agency, 1986.  Quality Criteria for Water, 1986. EPA 400/ (May, 1986).

Ward, G.H. Jr., and W.H. Espey Jr., Eds., 1971.  Estuarine Modeling: An Assessment. Capabilities and Limitations for Resource Management and Pollution Control.  EPA Water Pollution Control Research Series.  16070 DZV 02/71.  497 pp.  February, 1971.

Weast, R.C., 1978.  CRC Handbook of Chemistry and Physics.  CRC Press, Inc., Cleveland, OH 44128.

Weil J.C., 1974.  The rise of moist buoyant plumes.  Journal of Applied Meteorology, Vol. 13, No. 4.

Winiarski, L.D. and W.E. Frick, 1976.  Cooling tower plume model.  USEPA Ecological Research Series, EPA-600/3-76-100, USEPA, Corvallis, Oregon.

Winiarski, L.D. and W.E. Frick, 1978.  Methods of improving plume models.  Presented at Cooling Tower Environment — 1978.  University of Maryland. (May 2-4 1978).

Wood, I.R. and M.J. Davidson, 1990.  The merging of buoyant jets in a current.  Proceedings of International Conference on Physical Modeling of Transport and Dispersion, MIT, (August 7-10, 1990).

Wright, S.J., 1984. Buoyant jets in density-stratified crossflow. J. of Hydraulic Engineering., ASCE, 110(5), pp 643-656.

# APPENDIX 1:  MODEL RECOMMENDATIONS

## JUSTIFICATION FOR USES OF PLUMES MODELS IN FRESH WATER

The title of this work "Dilution models for effluent discharges" suggests that this report encompasses a broader scope than Muellenhoff et al. (1985) which addressed primarily ocean discharges.  The reasons are many but most importantly, users of Muellenhoff et al. (1985) often applied the plume models to freshwater outfalls because experience showed that some of the models, UMERGE included, worked well in that setting.

However, since 1985 the CORnell MIXing zone models (Hinton and Jirka, 1992), CORMIX, have been developed, supported in part by EPA, for the express purpose of addressing the problem of discharges to shallow and confined water bodies.  CORMIX uses a classification scheme based on length scales to associate a number of formulae and methods appropriate for each sub-category, linking together several discrete plume behaviors into an estimate of overall behavior, much like PLUMES links RSB and UM to a farfield algorithm.  This is done for a broad range of conditions, including single ports, merging plumes, and surface discharges, covering many conditions encountered in practice.

In addition to this practical reason for addressing the fresh water uses of our models, there are valid reasons for occasionally recommending them, even for those categories for which CORMIX was expressly developed.  Speed of analysis is one reason.  Suppose, for example, that it is to be established what percentage of time annually a plume surfaces and that this estimate is to be based on available hourly data collected during a monitoring study.  This may require hundreds of simulations, which might be developed relatively easily with PLUMES.

## MODEL RECOMMENDATION TABLES

### General Considerations

Recommendations for use of the models UM and RSB are based on the experience of the authors who have contributed to the formulation of the models and the interface, PLUMES, and have gained experience with the models in a large number of design and analysis applications.  Our experience with CORMIX is much less extensive and we have not contributed directly to its formulation. Furthermore, CORMIX is only recently available for multiport and surface discharges and we have seen few results of its application to actual cases.

The basic responsibility for choice of a model lies with the user, especially in relation to application for regulatory permits, which may carry important legal implications in addition to professional responsibility.  There are many models and other approaches than can be used to

estimate initial dilution that may be acceptable to regulatory agencies. By presenting the following recommendations we do not claim that any others should not be used. We do not provide recommendations for ULINE, UPLUME, and UOUTPLM because wherever they may have been used appropriately in the past we now believe UM or RSB is used more effectively, even in the case where the regulatory agency requires use of zero ambient current. We do not include UDKHDEN (Muellenhoff et al., 1985) in our recommendations because we have not followed its use since 1985 and we believe Dr. Lorin Davis has made further improvements to his models.

However, the recommendations are supported by extensive verification of the Projected Area Entrainment (PAE) hypothesis given by Lee and Cheung (1990) and Cheung (1991) supports our recommendations. As has been shown, UM uses the PAE hypothesis which is further supported by the experimental data on which RSB is based. Thus the RSB and UM models support each other, though they are certainly not identical.

In general we believe RSB (indicated in Table VI by "R," when well suited, or "r," when less suitable) is applicable to any case that matches closely the experimental conditions used in its development, which were limited to multiple port discharges. Figure 2 of Roberts, Snyder, and Baumgartner (1989a) may be used as a guide -- a complete list of experimental parameters is included as Appendix 1 (Table 5) of Roberts, Snyder, and Baumgartner (1989c). Other cases in which the density gradient over the height of rise can be represented by a linear gradient may be effectively modeled by RSB. However, the model also accept nonlinear density gradients. Submerged diffusers with fairly closely spaced multiport risers may be modeled (Roberts, 1989).

The model UM (indicated in Tables V and VI by "U" or "u") is useful for a similar range of conditions for both single port and multiple port discharges. Again, a lower case "u" is used to indicate where UM is less useful, such as in the case of parallel currents and in shallow water discharges. In addition to coastal applications, UM may be used for freshwater discharges and provides exceptional capability in nascent density cases, where discharge is to cold, fresh water (less than 4 C), owing to a robust and rigorously defined equation of state. Vertical nonuniformities in current speed and direction (primarily merging plumes), as well as nonuniform density and ambient contaminant concentrations are handled directly by UM (however, approximate corrections can be made to RSB dilution predictions for vertically uniform ambient concentrations of contaminants too). UM is well suited for dense seawater brines because the model is not constrained by the Boussinesq approximations and in addition can handle negatively buoyant flows. For very high density discharges the error in the calculated density increases and the linear equation of state may be more appropriate. While not frequently encountered, UM is appropriate for analysis of diffusers with ports along only one side.

**Caveats**

The recommendations given in the following tables are intended for general guidance purposes and to emphasize the complementary capabilities of the RSB and UM models and the CORMIX expert system. No attempt is made to define a rigorous classification system as defined in CORMIX, which, between CORMIX 1, 2, and 3, classifies perhaps 90% of common plume problems. The CORMIX classification system is made possible by adopting assumptions which, while making it possible to analyze a majority of freshwater and seawater outfall problems objectively, does not define the remainder. Some of the latter are important in certain regions of the country and/or under special circumstances. Hence, a different, somewhat complementary system is presented, albeit one which must appeal to the user for help in assuring that the models are appropriately implemented. However, cases may arise which even this generalized system does not include. The user must be the ultimate judge of the applicability of any given model under the circumstances at hand.

**Description and Usage**

Table V specifies the applicability of the CORMIX1 (single port CORMIX) and UM models to single port submerged discharge problems. Similarly, Table VI addresses multiport submerged diffusers. General applicability is indicated by the placement, in alphabetical order, of either a *C* for CORMIX1 or R, r, U, or u, for RSB or UM. Because we are more knowledgeable with our own models than with CORMIX, we indicate a general quality of our models with an upper case letter, e.g. U, signifying that we think the model generally performs well in this category, or lower case letter, e.g. u, suggesting that the user may wish, depending on the sensitivity of the project and other considerations, to seek other models, like CORMIX, if they apply.

An italicized C, i.e. *C*, for CORMIX conveys the fact that we are not experts in CORMIX usage and do not feel justified in assigning a measure of quality it. We simply include it to indicate the general domain of applicability of the CORMIX models, bearing in mind that the importance of a particular category is not necessarily represented by the relative size of the box. In its domain CORMIX can be used in analysis and generally be accepted by the authors and regulators in regulatory situations, providing that some special circumstances, some of which are identified below, do not invalidate such usage.

Each table classifies conditions and effluent types in an array in which the categories are not exclusive, but rather assimilative. Guidance is derived from the tables by identifying the appropriate effluent type (row) and then examining the applicability ratings in that row. The row can be likened to a chain in which each condition relevant to the problem is a link. The weakest link determines the strength of the chain.

For example, with respect to Table V, if there exists a deeply submerged outfall (i.e. boundary conditions, BCs, are unimportant), discharging effluent which is moderately buoyant, into a lake

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which is stratified into two layers, with co-flowing current (directed in the same general direction as the effluent), and no background pollution, decay, or upstream intrusion (the presence of which would be indicated by UM with an overlap message), then both CORMIX and UM would be applicable. In this case, the chain would consist of the "1,2 Stratification" and "2-D Current" categories (columns) which show U's in both instances, i.e. strong links.

If the current were not co-flowing but directionally stratified, implying need for a 3-D current modeling capability (link), then the UM link would be relatively weak, and, given that all CORMIX simulation modules use formulae and coefficients that are uniformly appropriate, CORMIX would be the model of choice. On the other hand, going back to the original case, if background pollution is present then the CORMIX chain would contain a weak link.

It should be noted that CORMIX does not explicitly include background in its simulations, but a *C* followed by the word decay is entered in that column to indicate that decay has been added since the first edition of this manual was published. Calculations could be made separately to estimate the consequences of background concentrations on predictions.

The meaning of the table columns and rows and other comments are given in the following sections.

**Single Port Diffuser Model Recommendations: Table V**

Table V: Columns

Table V sub-divides the Stratification column into three sub-columns, one each for unstratified, singly or doubly stratified, or multiply stratified water bodies. Length scale analysis may be used, as it is in CORMIX, to define these categories more precisely. Whether stratification is important depends on the strength of stratification as well as the buoyancy flux of the source, however, an unstratified system is one in which truly buoyant discharges (possessing no nascent density) reach the surface, which, if there is doubt, can be established quickly simply by running UM. In stratified systems the density varies with depth and the plume will trap (come to equilibrium) at some intermediate depth.

For cases with current, the 2-D sub-column is restricted to effluents and conditions where the current is either substantially co-flowing or counter-flowing, or, the current is sufficiently weak and does not affect trajectory plume direction significantly in the initial dilution region, i.e. before attaining maximum rise, overlap, or trapping. The latter condition, i.e. weak current, justifies the use of UM in the example given in the CORMIX1 Comparison Chapter even though the problem is three-dimensional (the fact that the analysis was conservative further justifying its use). Three dimensional current (3-D) means there is a significant component of current

**Table V**. Single port discharge model recommendations. $C$ = CORMIX, U, u = UM.

| Conditions | Stratification | | | Current | | Other sources, decay | BCs | Intrusion | VSW |
|---|---|---|---|---|---|---|---|---|---|
| Effluent Types | none | 1,2 | 3+ | 2-D | 3-D | | | | |
| Buoyant discharges: sewage, industrial waste especially to saline waters | $C$<br>U | $C$<br>U | U | $C$<br>U | $C$<br>u | $C$ (decay)<br>U | $C$<br>u | $C$<br>u | u |
| Slightly buoyant discharges, signif. momentum: thermal discharges | $C$<br>U | $C$<br>U | U | $C$<br>U | $C$<br>u | $C$ (decay)<br>U | $C$<br>u | $C$<br>u | u |
| Dense discharges: light brine, R.O. discharge, industrial waste | $C$<br>U | $C$<br>U | U | $C$<br>U | $C$<br>u | $C$ (decay)<br>U | $C$<br>u | $C$<br>u | u |
| Discharges with nascent or non-linear density effects: thermal discharge to cold water | U | U | U | U | u | U | u | u | u |

perpendicular to the flow of the effluent or the current direction varies with depth and significantly affects the trajectory.

The Other sources, decay column indicates that there are significant levels of uniform horizontally distributed background pollution (ambient pollution concentration) in the water body, or that there is a nearby source which creates a localized background pollution field in the vicinity of the outfall, and/or the pollutant in the effluent is subject to first order decay. Note, while the effect of uniform horizontally distributed background is well simulated by UM, nearby sources may create fields with large horizontal gradients which may make farfield estimates questionable. For example, can the user establish that spatially separated plumes actually interact? Also note, that UM assumes background fluid is entrained at the level of the center-of-mass of the plume element so that pollution profiles may need to be adjusted to compensate for the effect of this assumption. For example, given a body of water stratified with high pollution near the surface and low pollution near the bottom, the plume pollutant concentration would tend to be underestimated.

The boundary conditions (BCs) column indicates that boundaries, bottom, surface, and/or sides, play an important role in the plume problem. The concern here is whether the models appropriately limit entrainment due to the interference of the boundary. If side boundaries are important then CORMIX should be used exclusively, given there are no missing or weak links. However, if only surface boundaries are important, then UM can generally be used up to the point where it indicates

the surface is hit.  In general, the UM message indicating that the bottom is contacted is less important because the interaction is along the weakly entraining side of the plume.  However, for negatively buoyant plumes, the bottom boundary condition is as important as the surface boundary condition is to truly buoyant plumes.

The Intrusion column indicates that portions of the plume will flow upstream and form either stable or unstable upstream protrusions.  If an estimate of the length of the effect is wanted, it is usually appropriate to use CORMIX.  However, for estimating the dilution in the wastefield UM will provide estimates which are consistent with the amount of dilution water available for entrainment due to current or aspiration and can be considered to be reliable.  As in Muellenhoff et al. (1985), the dilution could be reduced by ten percent to assure the analysis is conservative.

The final column, VSW, or very shallow water, defined to be water less than three plume diameters deep, was built into UM to take advantage of its merging algorithm (reflection technique) to estimate initial dilution in cases in which CORMIX provides no estimates, an excluded category brought to our attention by one of our reviewers.  While such outfalls are not recommended, where they exist they sometimes need to be analyzed.  UM can be applied using the <shallow/surface Z> command. (Run the READ1st.exe file for the latest developments on this topic.)  In such cases the surface or bottom are encountered almost immediately and no criterion is known to establish an appropriate beginning of the farfield.  As a result, widely varying estimates of plume spreading are given, depending on where the farfield zone is initiated using the Pause Cell capability in the Configuration menu for the farfield start.  Our recommendation is that the VSW capability be used only for screening purposes.  If it needs to be established that a migration path exists for various fish, then the solution giving the greatest spread might be used as a conservative indicator of wastefield width.  If maximum concentration at a mixing zone are of concern, the solution giving the highest concentration might be used.

Table V: Rows

The first three rows in Table V are self-explanatory.  Additional information is available in other parts of this manual, especially the introductory chapter.  The CORMIX manuals (Doneker and Jirka, 1990; Jirka and Hinton, 1992) may also be consulted.  The term "R.O. discharge" refers to brine plumes created by a reverse osmosis desalination process.

The nascent density row is important, even though the effect is not widely recognized.  At low ambient temperatures the nonlinearities in the equation of state for fresh or low salinity water, particularly in the 0 to approximately 4 C range, cause initially buoyant thermal plumes to become negatively buoyant as they cool by mixing.  The effect, described in the first chapter, is important in cold climate regions.  As explained in the CORMIX example chapter, existing versions of CORMIX do not address the problem.

As was pointed out, the problem causes some models to fail completely (one could say catastrophically), by predicting that the effluent will rise to the surface instead of sinking to the

bottom. The ramifications could be serious, causing, for example, a monitoring program to be designed to study healthy surface biota while the benthic community is actually at risk.

## Multiport Outfall Model Recommendations: Table VI

**Table VI**. Model recommendations for multiport diffusers.

| Conditions / Effluent Types | Stratification | | | Current | | Merging | | Other sources & decay | BCs | Intrusion | Stage |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | no | 1,2 | 3+ | cross | par'l | part | full | | | | |
| Buoyant discharges: sewage, industrial waste especially to saline waters | C R U | C R U | R U | C R U | C R | R U | C R U | C (decay) U | C u | C R u | C |
| Slightly buoyant discharges, signif. momentum: thermal discharges | C r U | C r U | r U | C R U | C R | C R U | C R U | C (decay) U | C u | C R u | C |
| Dense discharges: light brine, R.O. discharge, industrial waste | C R U | C R U | r U | C r U | C r | C R U | C R U | C (decay) U | C u | C R U | C |
| Discharges with nascent or non-linear density effects: thermal discharge to cold water | U | U | U | U | u | U | U | U | u | u | |

## Table VI: Columns and Rows

The multiport discharge model recommendations are given in Table VI. In general, the same comments that apply to Table V apply to Table VI as well. Notable differences are the addition of the models RSB (denoted by R or r) and columns for degree of merging and staged diffusers.

The Current category sub-columns have been changed to indicate the importance of diffuser alignment on plume behavior. Generally, cross-diffuser flow is from perpendicular to 45 degrees off perpendicular, other cases falling in the parallel sub-column.

The Merging column indicates the degree of merging, either partial or full. It is worth noting that RSB is considered to be particularly appropriate to tunneled outfalls with multiport risers.

With respect to the Intrusion column, only CORMIX provides an estimate of the length of penetration upstream. However, RSB and UM do provide estimates of the dilution in the wastefield. RSB is considered to be especially applicable for making dilution estimates and provides other information lacking with CORMIX. If the surface is hit, UM predictions should be interpreted at that point, that dilution being consistent with the amount of dilution water available for entrainment due to current or aspiration. Again, the dilution could be reduced by ten percent to assure the analysis is conservative.

The Stage column refers to staged diffusers, diffuser pipes with ports not perpendicular to the diffuser axis. Such diffusers are staged to use the momentum in the effluent to carry effluent farther from shore. Of the models under consideration, only CORMIX applies to this diffuser configuration.

**SURFACE DISCHARGES**

CORMIX (CORMIX3) is recommended for modeling surface discharges.

**OTHER VIEWPOINTS AND RECOMMENDATIONS**

As described previously, the plume classification scheme presented in this appendix differs from the CORMIX classification scheme. Within the CORMIX classification scheme UM is thought apply to the near-field of the following classes (Jirka, 1992).

Single ports: S1, S2, S3, S4, S5, V1, V2, V3, V5, H1, H2, H3, H4, NV1, NV2, NH1, NH2, and NH4, provided they are not associated with an attachment suffix (A..).

Multiport diffusers: MS1, MS2, MS3, MS4, MS5, MS6, MS7, MS8, MU1V, MU1H, and MNU2.

These recommendations do not necessarily correspond to the ones described in Appendix 4. Also, no attempt has been made to define the applicability of the RSB model in the above context.

# APPENDIX 2:  THE DIFFUSER HYDRAULICS MODEL PLUMEHYD

## MODEL DESCRIPTION

The model PLUMEHYD is based on the hydraulics model DPHYDR used by Tetra Tech in the early 1980's to help assess 301(h) applications (Gremse, 1980), and, based on a limited number of trials, gives approximately identical results.  It is appropriate for use with multiport diffusers with bell shaped or sharp-edged ports.  It also considers multi-segmented diffusers of varying diameter.  The program uses metric (SI) units and works in batch mode.  A discussion of diffuser hydraulics is available in Grace (1978).

## MODEL USAGE

At this time PLUMEHYD.exe works only in the batch mode, which means you must construct the input file in an ASCII editor, like the built-in Turbo Pascal editor.  Sample input is shown in Figure 71.

The first line of input is a title.  It is followed by a line containing the number of ports, number of diffuser sections, and the ratio of the density difference between the ambient and effluent fluids to the effluent density, $(\rho_a - \rho_e)/\rho_e$.  The individual values must be separated by blanks.

```
Honouliuli diffuser hydraulics
74 4 0.0267
bell
 1  1 1.22  7.315 0.0 0.215
 2 22 1.22  7.315 0.0 0.134
23 47 1.677 7.325 0.0 0.129
48 74 1.982 7.315 0.0 0.123
0.014 0.1818
```

**Figure 71**.  PLUMEHYD batch input file.

The third line should contain the words "bell" or "sharp", for bell shaped or sharp edged ports.  Sharp edged ports cause a dynamic constriction in the plume diameter within a short distance of the port and increase the effective densimetric Froude number of the discharge.

There follow a variable number of lines defined by the number of diffuser sections on the second line of input, in this case, 4.  Each line, starting from the end of the diffuser, specifies the number of the first port in the section, the last port, the pipe diameter, the port spacing, the rise between ports, and finally the port diameter.  The spacing is the distance between adjacent ports on opposite sides (staggered ports).  If there are two ports at the same point but on opposite sides of the pipe, half the spacing between pairs of ports should be used.  Note that in this case the diffuser has a large port at the end of the diffuser described in the line immediately below the word "bell".  Its purpose may be to maintain a high flow velocity in the end of the diffuser to prevent sedimentation within the line.

The last line of input specifies the Mannings number and the total flow rate.  The units are SI (MKS).  Estimates of the Mannings number may be obtained from Brater and King (1976) or other engineering texts.

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**PLUMEHYD COMPUTER LISTINGS**

**Pascal Version of PLUMEHYD**

```
{$r+}
{
  Program PLUMEHYD.pas
  Metric system (SI) units assumed
}
const
  g = 9.807;
  criterion = 1e-6;
type
  porttype = (bell,sharp);
  st80 = string[80];
var
  piped,dxpipe,dzpipe,ff,portd: array[1..20] of real;
  fin,fxn,title: st80;
  nf,nl: array[1..20] of integer;
  qq,ee: array[1..50] of real;
  e,cd,pipev,portfn,portv,q: array[1..400] of real;
    ab,al,a1,cdc,dr,dx,dz,error,eorg,e0,f,fnf,gprime,hlf,hlz,
    mann,pd,pid4,pod,qc,qorg,qsum,qt,q0,v,vnew,vorg,zman: real;
  i,iter,np,ns,ans: integer;
  ptype: porttype;
  fi,fx: text;
{
  dr = drho/rho
  dxpipe = horizontal length of the section
  dzpipe = vertical rise of the section
  mann = Manning's n
  nf = number of the first port in a given section
  nl = number of the last port in a given section
  np = number of ports
  ns = number of diffuser sections
  piped = pipe diameter of the section
  portd = port diameter
  ptype = port type, bell or sharp
  qt = total discharge
}
```

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```
function pwr(a,b: real):real; var sign: integer;
{ an exponentiation function }
begin
if a < 0 then begin sign:=-1; a:=-a; end else sign:=1;
a:=exp(b*ln(a)); if sign = -1 then pwr:=-a else pwr:=a; end;

function strip(s:st80): st80;
{ strips blanks out of a string of characters }
begin while s[1] = ' ' do delete(s,1,1); strip:=s; end;

procedure cvnew(var enew,vold,cd,vnew: real);
{ sets up PLUMEHYD for analyzing diffusers with bell or sharp-edged ports }
var dv,f1,f2,v,v2: real;
begin
v:=0;
f1:=0.5/g/enew;
f2:=al/ab*sqrt(2*g*enew);
  if ptype = bell then begin
  v:=vold;
    repeat
    v:=vnew;
    v2:=sqr(v);
    cd:=0.975*pwr((1-v2*f1),0.375);
    vnew:=vold+cd*f2;
    dv:=v-vnew;
    v:=vnew;
    until abs(dv) - criterion < 0;
  end
  else
  begin { sharp }
  v:=vold;
    repeat
    v2:=sqr(v);
    cd:=0.63-0.58*v2*f1;
    vnew:=vold+cd*f2;
    dv:=v-vnew;
    v:=vnew;
    until abs(dv) - criterion < 0;
  end;
end;
```

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```
procedure loop; var j,k,n1,n2: integer;
{ main program element }
begin
vorg:=0; eorg:=e0; k:=0; qsum:=0;
  for j:=1 to ns do begin
  pd:=piped[j];
  ab:=pid4*sqr(pd);
  dx:=dxpipe[j];
  dz:=dzpipe[j];
  f:=ff[j];
  pod:=portd[j];
  al:=pid4*sqr(pod);
  fnf:=1/al/sqrt(gprime*pod);
  n1:=nf[j];
  n2:=nl[j];
  hlz:=dz*dr;
  hlf:=f*dx/pd/2/g;
    for i:=n1 to n2 do begin
    cvnew(eorg,vorg,cdc,vnew);
    k:=k+1;
    e[k]:=eorg;
    qc:=(vnew-vorg)*ab;
    q[k]:=qc;
    cd[k]:=cdc;
    pipev[k]:=vnew;
    portv[k]:=qc/al;
    portfn[k]:=qc*fnf;
    eorg:=hlz+eorg+vnew*vnew*hlf;
    qorg:=qc;
    qsum:=qsum+qc;
    vorg:=vnew;
    end;
  {}if j-ns < 0 then begin
   v:=vorg*sqr(piped[j]/piped[j+1]);
   eorg:=eorg+0.7*sqr(v-vorg)/2/g;
   vorg:=v;
   end;
  end;
iter:=iter+1; ee[iter]:=e0; qq[iter]:=qt-qsum; end;

procedure input; var portst: st80;
begin
write('Input  file (CR for default name of "HYD.IN": '); readln(fin);
```

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```
if fin = '' then fin:='hyd.in';
assign(fi,fin); reset(fi);
write('Output file (CR for default name of "HYD.EX": '); readln(fxn);
if fxn = '' then fxn:='hyd.ex';
assign(fx,fxn); rewrite(fx);
readln(fi,title); readln(fi,np,ns,dr);
readln(fi,portst); portst:=strip(portst);
if upcase(portst[1]) = 'B' then ptype:=bell else ptype:=sharp;
  for i:= 1 to ns do
  readln(fi,nf[i],nl[i],piped[i],dxpipe[i],dzpipe[i],portd[i]);
{ write('Input Mannings n, q (m^3/sec)'); } readln(fi,mann,qt);
end;


procedure initialize;
{ initializes program variables }
begin
error:=0.001; pid4:=pi/4;
zman:=124.58*mann*mann;
for i:=1 to ns do ff[i]:=zman/pwr(piped[i],0.33333);
q0:=qt/np;
a1:=pid4*sqr(portd[1]);
eorg:=sqr(q0/a1)/2/g;
ee[1]:=eorg; e0:=eorg;
iter:=0; gprime:=dr*g; end;


procedure outputit; var j,k: integer; begin
writeln(fx,title); writeln(fx);
writeln(fx,'Number of ports     = ',np:4);
writeln(fx,'drho/rho            = ',dr:9:4);
writeln(fx,'Number of sections   = ',ns:4);
  if ptype = bell then writeln(fx,'bell')
  else
  writeln(fx,'sharp');
writeln(fx);
writeln(fx,'Mannings N          = ',mann:9:4);
writeln(fx,'Desired Q          = ',qt:9:4);
writeln(fx,'Calculated Q        = ',qc:9:4); writeln(fx);
  for k:= 1 to ns do begin
    writeln(fx,
    'Friction factor F    = ',ff[k]:9:4,' ':9,
    'Pipe diameter     =',piped[k]:9:4);
    writeln(fx,
```

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```
  'Length between ports = ',dxpipe[k]:9:4,' ':9,
   'dz between ports  =',dzpipe[k]:9:4);
   writeln(fx,'Port diameter      = ',portd[k]:9:4);
 writeln(fx);
   writeln(fx,
   ' Port  Specific  Coeff   Pipe    Port    Port');
   writeln(fx,
   'number  energy     cd   velocity  velocity discharge  Froude #');
   writeln(fx,
   '          (m)            (m/sec)  (m/sec) (m^3/sec)');
 writeln(fx);
   for j:=nf[k] to nl[k] do
   writeln(fx,j:6,e[j]:10:4,cd[j]:10:4,pipev[j]:10:4,
   portv[j]:10:4,q[j]:10:4,portfn[j]:10:4);
 writeln(fx); end;
end;


{ main program element }
begin
input; initialize;
 repeat
 loop;
   if iter = 1 then
   e0:=ee[1]*sqr(qt/qsum)
   else
   e0:=(ee[iter-1]*qq[iter]-ee[iter]*qq[iter-1])/(qq[iter]-qq[iter-1]);
 until abs(qq[iter]) < error;
qc:=qsum; outputit; close(fi); close(fx); end.
```

**Sample Input File**

```
Honouliuli diffuser hydraulics
74 4 0.0267
bell
 1  1 1.22   7.315 0.0 0.215
 2 22 1.22   7.315 0.0 0.134
23 47 1.677 7.325 0.0 0.129
48 74 1.982 7.315 0.0 0.123
0.014 0.1818
```

**Sample Output File**

Honouliuli diffuser hydraulics

```
Number of ports      =    74
drho/rho             =     0.0267
Number of sections   =     4
bell

Mannings N           =     0.0140
Desired Q            =     0.1818
Calculated Q         =     0.1818

Friction factor F    =     0.0229        Pipe diameter      =    1.2200
Length between ports =     7.3150        dz between ports   =    0.0000
Port diameter        =     0.2150
```

| Port number | Specific energy (m) | Coeff cd | Pipe velocity (m/sec) | Port velocity (m/sec) | Port discharge (m^3/sec) | Port Froude # |
|---|---|---|---|---|---|---|
| 1 | 0.0017 | 0.9747 | 0.0055 | 0.1763 | 0.0064 | 0.7429 |

```
Friction factor F    =     0.0229        Pipe diameter      =    1.2200
Length between ports =     7.3150        dz between ports   =    0.0000
Port diameter        =     0.1340
```

| Port number | Specific energy (m) | Coeff cd | Pipe velocity (m/sec) | Port velocity (m/sec) | Port discharge (m^3/sec) | Port Froude # |
|---|---|---|---|---|---|---|
| 2 | 0.0017 | 0.9744 | 0.0076 | 0.1762 | 0.0025 | 0.9408 |
| 3 | 0.0017 | 0.9739 | 0.0097 | 0.1762 | 0.0025 | 0.9405 |
| 4 | 0.0017 | 0.9734 | 0.0119 | 0.1761 | 0.0025 | 0.9402 |
| 5 | 0.0017 | 0.9728 | 0.0140 | 0.1761 | 0.0025 | 0.9399 |
| 6 | 0.0017 | 0.9721 | 0.0161 | 0.1760 | 0.0025 | 0.9396 |
| 7 | 0.0017 | 0.9713 | 0.0182 | 0.1759 | 0.0025 | 0.9393 |
| 8 | 0.0017 | 0.9704 | 0.0203 | 0.1759 | 0.0025 | 0.9391 |
| 9 | 0.0017 | 0.9694 | 0.0225 | 0.1759 | 0.0025 | 0.9389 |
| 10 | 0.0017 | 0.9683 | 0.0246 | 0.1759 | 0.0025 | 0.9388 |
| 11 | 0.0017 | 0.9671 | 0.0267 | 0.1759 | 0.0025 | 0.9388 |
| 12 | 0.0017 | 0.9658 | 0.0288 | 0.1759 | 0.0025 | 0.9389 |
| 13 | 0.0017 | 0.9644 | 0.0310 | 0.1759 | 0.0025 | 0.9392 |
| 14 | 0.0017 | 0.9629 | 0.0331 | 0.1760 | 0.0025 | 0.9396 |
| 15 | 0.0017 | 0.9613 | 0.0352 | 0.1761 | 0.0025 | 0.9402 |
| 16 | 0.0017 | 0.9597 | 0.0373 | 0.1763 | 0.0025 | 0.9410 |
| 17 | 0.0017 | 0.9580 | 0.0395 | 0.1764 | 0.0025 | 0.9419 |
| 18 | 0.0017 | 0.9562 | 0.0416 | 0.1767 | 0.0025 | 0.9431 |
| 19 | 0.0018 | 0.9543 | 0.0437 | 0.1769 | 0.0025 | 0.9445 |
| 20 | 0.0018 | 0.9524 | 0.0459 | 0.1772 | 0.0025 | 0.9462 |
| 21 | 0.0018 | 0.9504 | 0.0480 | 0.1776 | 0.0025 | 0.9481 |
| 22 | 0.0018 | 0.9483 | 0.0501 | 0.1780 | 0.0025 | 0.9503 |

```
Friction factor F    =     0.0206        Pipe diameter      =    1.6770
Length between ports =     7.3250        dz between ports   =    0.0000
Port diameter        =     0.1290
```

| Port number | Specific energy (m) | Coeff cd | Pipe velocity (m/sec) | Port velocity (m/sec) | Port discharge (m^3/sec) | Port Froude # |
|---|---|---|---|---|---|---|
| 23 | 0.0018 | 0.9672 | 0.0276 | 0.1834 | 0.0024 | 0.9981 |
| 24 | 0.0018 | 0.9666 | 0.0287 | 0.1835 | 0.0024 | 0.9984 |
| 25 | 0.0018 | 0.9659 | 0.0298 | 0.1836 | 0.0024 | 0.9988 |
| 26 | 0.0018 | 0.9653 | 0.0309 | 0.1836 | 0.0024 | 0.9992 |
| 27 | 0.0018 | 0.9646 | 0.0320 | 0.1837 | 0.0024 | 0.9997 |
| 28 | 0.0019 | 0.9639 | 0.0331 | 0.1838 | 0.0024 | 1.0002 |
| 29 | 0.0019 | 0.9632 | 0.0341 | 0.1839 | 0.0024 | 1.0008 |
| 30 | 0.0019 | 0.9625 | 0.0352 | 0.1841 | 0.0024 | 1.0015 |
| 31 | 0.0019 | 0.9617 | 0.0363 | 0.1842 | 0.0024 | 1.0022 |
| 32 | 0.0019 | 0.9609 | 0.0374 | 0.1843 | 0.0024 | 1.0030 |
| 33 | 0.0019 | 0.9601 | 0.0385 | 0.1845 | 0.0024 | 1.0039 |
| 34 | 0.0019 | 0.9593 | 0.0396 | 0.1847 | 0.0024 | 1.0049 |
| 35 | 0.0019 | 0.9585 | 0.0407 | 0.1849 | 0.0024 | 1.0059 |
| 36 | 0.0019 | 0.9576 | 0.0418 | 0.1851 | 0.0024 | 1.0070 |
| 37 | 0.0019 | 0.9568 | 0.0429 | 0.1853 | 0.0024 | 1.0082 |
| 38 | 0.0019 | 0.9559 | 0.0440 | 0.1855 | 0.0024 | 1.0095 |
| 39 | 0.0019 | 0.9550 | 0.0451 | 0.1858 | 0.0024 | 1.0109 |
| 40 | 0.0019 | 0.9541 | 0.0462 | 0.1861 | 0.0024 | 1.0124 |
| 41 | 0.0019 | 0.9532 | 0.0473 | 0.1864 | 0.0024 | 1.0140 |
| 42 | 0.0020 | 0.9523 | 0.0484 | 0.1867 | 0.0024 | 1.0156 |
| 43 | 0.0020 | 0.9513 | 0.0495 | 0.1870 | 0.0024 | 1.0174 |
| 44 | 0.0020 | 0.9504 | 0.0506 | 0.1873 | 0.0024 | 1.0193 |
| 45 | 0.0020 | 0.9494 | 0.0517 | 0.1877 | 0.0025 | 1.0213 |
| 46 | 0.0020 | 0.9484 | 0.0528 | 0.1881 | 0.0025 | 1.0233 |
| 47 | 0.0020 | 0.9475 | 0.0539 | 0.1885 | 0.0025 | 1.0255 |

| | | | | | |
|---|---|---|---|---|---|
| Friction factor F | = | 0.0194 | Pipe diameter | = | 1.9820 |
| Length between ports | = | 7.3150 | dz between ports | = | 0.0000 |
| Port diameter | = | 0.1230 | | | |

| Port number | Specific energy (m) | Coeff cd | Pipe velocity (m/sec) | Port velocity (m/sec) | Port discharge (m^3/sec) | Port Froude # |
|---|---|---|---|---|---|---|
| 48 | 0.0020 | 0.9607 | 0.0394 | 0.1921 | 0.0023 | 1.0706 |
| 49 | 0.0020 | 0.9602 | 0.0401 | 0.1923 | 0.0023 | 1.0715 |
| 50 | 0.0021 | 0.9596 | 0.0408 | 0.1925 | 0.0023 | 1.0725 |
| ... | | | | | | |
| 63 | 0.0021 | 0.9524 | 0.0506 | 0.1955 | 0.0023 | 1.0895 |
| 64 | 0.0022 | 0.9518 | 0.0513 | 0.1958 | 0.0023 | 1.0912 |
| 65 | 0.0022 | 0.9512 | 0.0521 | 0.1961 | 0.0023 | 1.0929 |
| 66 | 0.0022 | 0.9506 | 0.0528 | 0.1965 | 0.0023 | 1.0948 |
| 67 | 0.0022 | 0.9500 | 0.0536 | 0.1968 | 0.0023 | 1.0966 |
| 68 | 0.0022 | 0.9494 | 0.0543 | 0.1972 | 0.0023 | 1.0986 |
| 69 | 0.0022 | 0.9488 | 0.0551 | 0.1975 | 0.0023 | 1.1005 |
| 70 | 0.0022 | 0.9482 | 0.0559 | 0.1979 | 0.0024 | 1.1026 |
| 71 | 0.0022 | 0.9476 | 0.0566 | 0.1983 | 0.0024 | 1.1047 |
| 72 | 0.0022 | 0.9470 | 0.0574 | 0.1986 | 0.0024 | 1.1069 |
| 73 | 0.0023 | 0.9464 | 0.0582 | 0.1991 | 0.0024 | 1.1091 |
| 74 | 0.0023 | 0.9457 | 0.0589 | 0.1995 | 0.0024 | 1.1115 |

# APPENDIX 3: SUPPORT FOR TABLE I (CHAPTER 1)

## Input and Output for Case 1

Two examples given in Table I corresponding to flows of 4.65 and 46.5 MGD are presented below:

```
Mar 27, 1994,   6:15:28  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of  11
Title   Output corresponding to Table 1, 4.65 MGD                    non-linear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
   0.2038       100  0.002038          3         0       25
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      30      0.075   0.07500    0.4613    0.3262    0.3262      0.10       500
 port elev ver angle cont coef  effl den poll conc    decay  Froude # Roberts F
       1        45         1  -2.89273       100         0     3.160    0.1000
 hor angle red space p amb den p current   far dif  far vel K:vel/cur Stratif #
      90      3.000   26.0000   0.02683    0.0003           17.19  0.001000
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0   0.02683     14.44     21.35        20         0   0.06069    0.2842
      30   0.02683        26     33.75        10         0 buoy flux puff-ther
                                                          0.0001930    0.3846
                                                          jet-plume jet-cross
                                                             0.2231     1.143
                                                          plu-cross jet-strat
                                                             29.99     0.7108
                                                          plu-strat
                                                             1.269
                                                           hor dis>=

CORMIX1 flow category algorithm is turned off.
 0.2038 m3/s, 4.652 MGD, 7.197 cfs.                       >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: TABLE1E3.VAR;
UM INITIAL DILUTION CALCULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
      m         m                             m
     30.00    0.07500     100.0     1.000     0.000
     27.64    0.8083      3.125    31.14     0.9318
     26.63     1.289      1.746    55.74     1.279 -> trap level
     25.91     2.202      1.090    89.30     1.662 -> begin overlap
```

```
Mar 27, 1994,   6:15:58  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   4 of  11
Title    Output corresponding to Table 1, 46.5 MGD                   non-linear
 tot flow   # ports port flow    spacing  effl sal effl temp   far inc   far dis
    2.038       100  0.02038            3         0        25
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
       30     0.075  0.07500       4.613     3.262     3.262      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
        1        45         1  -2.89273       100         0     31.60   0.01000
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     3.000   26.0000   0.02683    0.0003            171.9  0.001000
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
        0   0.02683     14.44     21.35        20             0.06069    0.2842
       30   0.02683        26     33.75        10            buoy flux puff-ther
                                                             0.001930     3.846
                                                             jet-plume jet-cross
                                                                 2.231     11.43
                                                             plu-cross jet-strat
                                                                 299.9     2.248
                                                             plu-strat
                                                                 2.256
                                                              hor dis>=


 CORMIX1 flow category algorithm is turned off.
                                                                 to     range
 Help: F1.  Quit: <esc>.  Configuration:ATCM0.  FILE: TABLE1E3.VAR;
 UM INITIAL DILUTION CALCULATION (nonlinear mode)
  plume dep plume dia poll conc  dilution   hor dis
        m         m                            m
    30.00   0.07500     100.0     1.000     0.000
    26.06     1.926     3.125     31.15     3.372
    25.70     2.095     2.856     34.08     3.638 -> trap level
    24.30     3.048     2.062     47.21     4.798 -> merging
    23.81     4.100     1.807     53.86     5.463 -> begin overlap
  -> dilution overestimated
    23.67     5.204     1.652     58.95     6.112
  -> local maximum rise or fall
```

# APPENDIX 4:  MESSAGES AND INTERPRETATIONS

**CORMIX WINDOW RECOMMENDATIONS**

Historically, work culminating in this manuscript and corresponding software and the EPA sponsored work on CORMIX proceeded independently.  Since about 1990, efforts have been made to integrate the two approaches to take advantage of their complementary capabilities, as explained in Appendix 1.  For example, a CORMIX work element exists to in some way include the traditional EPA models within its framework.  The CORMIX window of the PLUMES interface, implemented for CORMIX1, integrates the CORMIX categorization schemes into PLUMES.  See Hinton and Jirka (1992) for a graphic description of the flow categories.

Providing there are no limitations to its use as described in Table V of Appendix 1, CORMIX1 is considered to be an appropriate solution to the plume problem under consideration in the PLUMES interface.  It is assumed that the Configuration menu has been used to turn the CORMIX1 algorithm on.

Note, since RSB is exclusively designed for merging plumes, only CORMIX1 and UM are applicable to this discussion.  However, in some cases the CORMIX1 categories have a clear relationship to CORMIX2 categories.  Also, in questionable cases, a few runs using both CORMIX1 and UM may be helpful, either corroborating each other or suggesting caution.

**Single: use CORMIX1; merging: UM ok**
> Displayed in cases in which PLUMES predicts flow categories v4 and v6:  The use of CORMIX is definitely recommended for single plumes, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.  Excluded cases must be handled on a case-by-case basis.
>
> To the extent that some CORMIX1 flow categories have obvious CORMIX2 counterparts, the appropriate use of the models for merging plumes may be apparent. Mutual validation and the use of the more conservative analysis are recommended in questionable cases.

**Use CORMIX**
> Displayed in cases in which PLUMES predicts flow categories h4-90, h5-90, nv5, nh3: The use of CORMIX1 is definitely recommended, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.  Excluded cases must be handled on a case-by-case basis.

**Use CORMIX or UM to surface hit**
> Displayed in cases in which PLUMES predicts flow categories nv3, nv4, and nh5:  It is appropriate to continue the analysis with UM until the surface is hit.  The use of

CORMIX is appropriate and possibly preferred, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist. Mutual validation with CORMIX and the use of the more conservative analysis is recommended in questionable cases.

## Use UM

Displayed in cases in which PLUMES predicts no CORMIX1 category or flow categories s1, s3, s4: It is appropriate to continue the analysis with UM. The use of CORMIX is appropriate too, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.

## Use UM to bottom hit

Displayed in cases in which PLUMES predicts flow categories nv1, nv2, nh1, nh2, and nh4: It is appropriate to continue the analysis with UM until the bottom is hit. The use of CORMIX is also appropriate, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.

## Use UM to overlap point

Displayed in cases in which PLUMES predicts flow categories s2, s5, h4-180, h5-180: UM is considered appropriate to the point of overlap, with the farfield model being initiated at that point. The use of CORMIX is appropriate, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.

## Use UM until near surface

Displayed in cases in which PLUMES predicts flow categories v3, v5, h3, h40: UM is weaker and CORMIX is correspondingly stronger in these categories. The ten percent prohibition suggested by Muellenhoff et al. (1985) may be appropriate and can be implemented using the Pause criterion in the Farfield configuration of PLUMES. The use of CORMIX is appropriate, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.

## Use UM until surface hit

Displayed in cases in which PLUMES predicts flow categories v1, v2, h1, h2, and h5-0: UM is considered appropriate to the point of the surface being hit, with the farfield model being initiated at that point. The use of CORMIX is appropriate, but only in cases in which nascent density effects are absent and other weak links in the CORMIX chain (see Appendix 1) do not exist.

**DIALOGUE WINDOW MESSAGES**

The following messages appearing in alphabetical order are more or less frequently displayed by the PLUMES interface.  Here they are explained in more detail.  Some have subsidiary messages, shown here below the main message.  Content that depends on context is contained in brackets [].  Some of the notes may be revealed only briefly, the ^YN command may be used to examine them at your leisure.

**Absolute value of decay too large, reduce value.  <key>**
> Warns of a value for decay that does not convert into the correct units and can cause program crashes.

**A descriptive title.**
> Used to describe the title cell, it is issued by the <List equations> command.

**At [variable] Change sign or <key> to accept [default]**
> This message usually indicates that PLUMES is trying to define the identified cell from an equation involving a square root for which both positive and negative roots are valid. You have to make the appropriate choice.

**Back, Inequalities, Output, Variables (space), or <esc> to quit**
> Used to manipulate data in the Pause (or stop) cell.  Typing "V" or the spacebar brings the various available cells into the window, "B" doing so in the reverse manner.  "I" selects the appropriate pause inequality.  The "O" option installs the hidden variables, e.g. the centerline concentration, on the output table.  The cell is filled with a numeric value in the usual manner, after by using the ^J command to enter the cell.

**Bad file name, old or default file restored**
> Indicates a non-existent case file, normally one with a .VAR extension, was specified for opening.  Usually this happens when you have forgotten the name of the case files and inadvertently specify a nonexistent file name.  The <9> may be used in the <get Work file> command to refresh yourself on existing case files.  You may need to exit to DOS and use the DIR command to refresh yourself on the appropriate names.

**Note: [message] [equation number] of [variable]**
> Appears when a potential data inconsistency is detected.  This can be automatic or happen when the <cHeck consistency> command is used.  The ^YN <Notes> command may be used to check for their occurrence.  The [equation number] refers to the cardinal number of the equations listed for the cell [variable] when the ^L <List equations> command is used.  While efforts should be made to resolve inconsistencies, they do not always indicate incompatible input data.

**Default table, or New table?**
>   Asks you whether to include the default output variables when running UM or to clear the table (New) for the addition of variables of your choosing using the <add to Output> command.

**Discharge in Middle or Surface/bottom of water column?**
>   Appears when the <shallow/surface Z> command is used. You must choose <M> or <S> (or <esc>) to specify your choice, which establishes the proper spacing for the reflection surfaces and other parameters.

**Error detected in case range <key>**
>   Appears after invoking the <Beget new cases> (Miscellany Menu) to indicate that an error in specifying the number of cases to which to copy the current cell has been made.

**Farfield result will not reflect decay in the near field**
>   This is a reminder that RSB, as an initial dilution model, does not include decay. Consequently, if decay is fast or rise times are long, the pollutant concentration can be significantly over-predicted.

**File access denied, directory name? <key>**
>   The inputted file name is not valid because it already specifies a sub-directory.

**File [filename] exists or name illegal, must be new <key>**
>   Issued while using the <fill New file> ^N command when an existing file name or an illegal name, such as a sub-directory name, is specified. You are asked to provide unique case file name.

**Go to case (<space> for default): [default case number]**
>   Used to specify how many cases to run or translate into Universal Data File (UDF) format or to which case to move using the ^C command. For the first two functions all cases between the present and the indicated case, including the present case, will be processed.

**Hit bold letters or arrow keys and <enter>; use control sequences for speed**
>   Issued when accessing the main menu to remind you that the control key sequence for issuing commands is faster than using the menus. (See the User's Guide Chapter.)

**Inconsistency at [variable name 1]: [value 1] vs. [variable name 2]: [value 2]**
>   These messages may appear when using the <cHeck consistency> command if tolerances are not met. In other words, if two different equations of the same dependent variable yield values which differ by more than 1 part per thousand, then this message is issued.

**Inputted case # invalid, reset**

  The case number input is invalid. For example, when running UM, specifying a negative case number will cause this message to be issued. In this case the input is changed to the present case number and a single case is run.

**Input file name (or <9> to select .VAR file):**

  Requests you to enter the name of the case file, i.e. the non-ASCII file used to store the input screen data, such as PLMSTUFF.VAR, or to select the appropriate file with <9> followed by <enter>. These files cannot be edited by an ASCII editor.

**Input starting longitudinal coordinate:**

  When the Brooks-equation-width-input-toggle in the Configuration String is set to "user", PLUMES prompts for the initial width of the wastefield and the initial starting distance, thus allowing for the override of these two parameters. This allows runs of the Brooks equation which are essentially independent of the initial dilution estimates.

**Input wastefield width:**

  See related message, "Input starting longitudinal coordinate:", above.

**Invalid file name <key>**

  An illegal file name was specified while using the ^W command.

**<key> for far field prediction**

  RSB output is displayed on two screens, the near field output and the far field output.

**<key> once again to start PLUMES**

  While using the <shallow/surface Z> command, some condition needing your attention in the initialization phase has been identified. Make tot flow, spacing, plume dep, port dia, port eleve cells independent, and, a non-surface independent ambient depth cell must be defined, which must satisfy: ambient depth >= plume dep. A message appears on three separate dialogue windows when some or all cell values needed to complete the <shallow/surface Z> command are missing.

**New file name (or <esc> to cancel command>**
**An empty line will appear to use to enter the string of case numbers <key>**
**Enter the record numbers of the records to keep (followed by <enter>) <key>**
**Use spaces as separator, .. to indicate a range, e.g. 12 3..9 14 <key>**

  A short explanation for using the <fill New file> command. The command is used to fill a previously nonexistent file with cases from the file in the interface. Cases may be specified in any order and repetition is allowed.

**No changes made**

Appears if a choice other than Middle or Surface/bottom, i.e. no choice, is made after issuing the <shallow/surface Z> command.

**No direct independents to hilite for [variable], remove others.**

Issued when the problem is overspecified and a conflict arises. This happens when a dependent (white) value is replaced by an independent (yellow) value but no immediate independent values for the cell can be identified, i.e. the cell is totally defined by other dependent (white) values. YOU SHOULD IMMEDIATELY REMOVE THE LAST VALUE YOU INPUT OR FIND OTHER INDEPENDENT VALUES TO REMOVE. USE THE <cHeck consistency> COMMAND TO ASSURE CONSISTENCY.

**NO GO, incomplete effluent/ambient blocs.**

Advises you that the data necessary for running UM are not complete. Return to the input screen and check for missing cells.

**Not a number: [string], correction attempted.**

You tried to input non-numerical information in a numerical cell. PLUMES removes the non-numeric characters from the input data and tries to convert the remaining string to numeric data. Other conditions, such as multiple decimal points, will also cause this message to be issued. The value should be checked and corrected if necessary.

**Only for adding hidden variables to the table. <key>**

Variables explicitly displayed on the interface screen are put on or removed from the output table with the <add to Output> ^O command.

**Overwrite existing cases or Append (default)?**

Issued by the <construct Udf file> ^YU command when the read option is chosen. The overwrite option erases the case in which the cursor is located and all subsequent cases.

**Plumes not merged, Brooks method may be invalid.**

The Brooks equations are based on a continuous wastefield, an assumption which is not valid when the plumes are not merged. However, the equations are probably valid if the unmerged distance is small.

**Probable corrupted data file, check SETUP, and files.**
**SETUP should be deleted; program to terminate!**

An error has been identified in the case file. Possibly you asked for a file that is not in the binary case file format, you have moved your files to some new directory and PLUMES is unable to find the files, or some other terminal condition exists. Check the SETUP file for clues, delete it, and start over (or shift attention to other case files).

**Probably not a .VAR file <key>**

A file was specified while using the ^W command which does not contain the correct number of bytes to be a .VAR file.

**Quit (or <esc>), all others to continue**

Message appears when execution of UM has been interrupted. <Q> or <esc> will cause the current run to be abandoned.

**Replicate this cell to case (<space> to accept default):**

Issued by the <Beget new cases> ^YB command. A value in a particular cell in the present case may be copied to the corresponding cell in a specified number of additional cases starting with the next case.

**Save (also <spacebar>), Discard work, <esc> to return to PLUMES**

Message appears when existing PLUMES. <S> or <spacebar> causes the old case file to be updated. <D> restores the previously existing file i.e. all the work done in the current session is discarded. <esc> and other keystrokes cancel the command.

**See guidance material for explanation**

Appears when the Miscellany Menu is accessed. Guidance may be found in the section entitled "User's guide to the model interface, PLUMES" in the manual.

**See users' guide for details**

Appears when the Configuration Menu is accessed.

**Specify max reversals; 0: PLUMES chooses (see manual: configuration):**

You are asked how many vertical velocity reversals UM should use before giving control over to the far field model. Reversals occur in stable ambient at the top of rise or when the plume sinks to a maximum depth (fall). If the trajectory is plotted out, these points are the crests and troughs of the resulting waveform.

**Start farfield at Max-rise, Overlap, or Pause criterion?**

Issued when invoking <Farfield start> on the Configuration Menu for control of the UM model. You are to specify at which point the initial dilution model should end and the farfield model begin. The overlap condition is recommended.

**Sure you want to zap variables? (y/n):**

Reminder after issuing the <Zap most variables> command on the Miscellany Menu, that all variables except the aspiration coefficient, output frequency, decay, farfield dispersion coefficient, and surface ambient depth cell will be blanked out.

**Temperature A) [temperature 1] or <key> [temperature 2]?**
> This message appears when temperature is the dependent variable (defined by density and salinity). In this case an approximation technique is used to solve the density function for temperature. This choice is presented when, starting at different initial guesses, two solutions to the problem converge on separate values.

**To use command, number of ports must = 1**
> Reminder that the <shallow/surface Z> command can only be used for single port outfalls.

**To use put cursor in the filled cell below cells to be interpolated**
> Instructs you how to fill embedded empty cells in the ambient block. You must move the cursor to a filled cell below the embedded empty cells. The corresponding top bounding cell must also exist. The cells in between will be interpolated on the values of the depths in the depth column.

**UM running, <key> to interrupt**
> A "Please wait" message. UM can be interrupted and stopped at any time.

**Use RSB for multiple port diffusers**
> This is a reminder that RSB is a multiport, not a single port, model.

**Use control key sequences or see the Guide for better movement and control**
> Appears when the Movement menu is accessed, reminds you that better movement controls are available by consulting the manual.

**With regard to [variable name] resolve conflicts:**
> Issued when the problem is overspecified and a conflict arises. This happens when a dependent variable is replaced by an independent variable, i.e. one you input. You are forced to move between the highlighted cells until you delete one of them, by pressing <D> or the <delete> on the flashing (chosen) cell.

**Work will be lost with <key>, <esc> to keep work**
> Issued when the Discard option is chosen when quitting PLUMES. It provides additional protection from accidentally discarding changes made in the current work session.

**Write to ("prn" for printer, "console", or disk file name): [default name]**
> Appears after specifying the number of cases to run after issuing the ^B or ^U commands (see "From this case on..."). You are asked to specify the output device which can be the printer (type in the letters prn), monitor (type in console), or disk file (any legal DOS file name). The spacebar may be used to accept the default value.

**xx = current variable, x2 = 1st argument in PRECEDING ns.**
> Provides definitions of xx and x2. Used for programming purposes. Please report such occurrences.

### UM RUN TIME MESSAGES

UM issues various standard text and messages which are useful for interpreting numerical output. They are given here in alphabetical order and explained in detail.

Before running, UM saves the case in which the cursor is located and copies the input to the output file. Thus, even if a run time error were to cause a crash, the input is safely stored away. Next, it copies the screen exactly the way it appears, except for the color, to the output file, which may be a disk file, the printer, or, the console itself.

Immediately below the screen output, on three separate lines, UM prints the message "UM INITIAL DILUTION SIMULATION" and either "linear mode" or "nonlinear mode", followed by a numerical tabulation of variables on the output table (the results of the simulation) headed by the cell names and their corresponding units.

Pertinent output messages are issued when certain criteria are met. They are displayed after the numerical data to which they apply, the association being indicated by an arrow that points to the message. If there is sufficient space it appears on the same line, otherwise it appears on succeeding lines. UM also prints output at the beginning of the simulation and at intervals specified by the [print frq] (print frequency) cell, which specifies the number of program steps between output. Such output is not followed by any message. Messages include:

**absolute value Froude # < 1, potential diffuser intrusion**
> When the absolute value of port Froude number is less than one (1) the plume is so buoyant (or negatively buoyant) that it separates from the bottom (or top) of the port orifice allowing ambient water to flow into the diffuser.

**bank(s) reached**
> Message used only when the <shallow/surface Z> ^Z command, for very shallow water, has been used and the ^Z flag has been placed by UM at the beginning of the title cell. It indicates that the width of the plume equals or exceeds the implied distance to the bank.

**begin overlap**
> Indicates that the definition of the UM plume element is not geometrically and physically self-consistent, viz. part of the element is composed of physically unreal negative volume and negative mass (Frick, Baumgartner, and Fox, 1994). **Note**: this condition

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is an artifact of the uncorrected round plume assumption which is commonly used in Lagrangian and Eulerian integral flux plume models.  The problem occurs when trajectory curvature is great and will produce errors unless the model is specifically modified to correctly handle the problem.  Its significance derives from the fact that the radius is over-estimated when overlap occurs.  Since entrainment is proportional to the radius, it is also over-estimated.  For further details, see the UM Model Theory Chapter, "The Plume Element."

The "end overlap" message, described below, indicates the cessation of the condition causing the error.  If the dilution changes relatively little in this region the message may be safely ignored.  Otherwise, the dilution given at the beginning of overlap may be used to give a conservative estimate of dilution or another model may be used.

**bottom geometry consistent?  Try increasing port elev and/or ambient depth**
Issued only if the bottom is encountered in the first two program steps, i.e. at the source. This advisory frequently has minor significance because it usually relates to the non or weakly entraining side of the plume.  In such cases the port elevation or ambient depth cells may be increased, as appropriate, to prevent this condition from terminating the run. However, negatively buoyant plumes are likely to be significantly affected.  See the related message "bottom hit".

**bottom hit**
This message is issued when the extremities of the plume element intersect the bottom, which is assumed to be at a distance of [port elev] below the port depth or the deepest ambient layer, whichever is greater.  Because the bottom is often hit by the downstream portion of the plume, which is not the primary entraining surface, the condition can sometimes be ignored, at least as long as it is not violated excessively.  However, it should be recognized that the presence of the condition implies considerations of mass continuity and, indirectly, the dimensions of the plume which affect entrainment.

**dilution overestimated**
Associated with the message "begin overlap" explained above.

**end overlap**
The overlap condition ceases.  See the "begin overlap" message above.

**leaving defined depth range**
Occurs if the extremities of the plume penetrate to a depth below the tenth ambient line allowed, if defined.  See the "bottom hit" message.

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**local maximum rise or fall**

When moving through the trap level, see below, the plume element reverses its buoyancy, becoming negatively buoyant if initially positively buoyant and vice versa. The vertical accelerating force then opposes the direction of motion and the plume element ultimately reaches maximum rise or fall, unless some other condition, such as surface interaction intervenes.  This message indicates the reversal in vertical motion occurred during the previous time step.

In many applications, the first maximum rise or fall is the appropriate point for determining the initial dilution achieved and for initiating the farfield diffusion algorithm.  However, when effluent buoyancy and momentum are initially in opposite directions, PAE and Taylor entrainment often continue to be dominant dispersion processes and act after the first maximum rise or fall.  See Appendix 6 for further details.

**merging**

Indicates that neighboring plume elements, assumed to be uniformly spaced and identical, have grown sufficiently to merge.  Merging occurs when the plume diameter is equal to the reduced spacing which is a function of the physical spacing and the horizontal angle of discharge.  The effect of the condition is to reduce the surface area of the plume element and the entrainment.

End effects are not modelled by UM, in other words, it is assumed that the diffuser is infinitely long, the fewer the number of ports, the more important end effects become.  Also, the ports are assumed to be on one side.  Cross-diffuser merging can be simulated by using half the port spacing or by specifying background pollutant concentration in the ambient pollutant concentration [amb conc] cells.

**Quit (or <esc>), all others to continue**

Issued when UM has been interrupted while running.  Execution may be continued with any keystrokes except <Q> and <esc> which terminate the run and return to the interface.

**surface hit**

The extremities of the plume element have intersected the surface.  Since the intersection generally occurs at the upstream, i.e. entraining, portion of the plume, this is an important criterion.  Generally, the dilution process should be assumed to stop here and the PLUMES configuration string and the Pause Cell should be manipulated accordingly if the farfield algorithm is used.  The details of mass continuity are not properly estimated by models of the UM class beyond this point.

In certain special cases the criterion is unreasonably conservative.  This is generally true in shallow water where the surface is intersected by the plume element soon after discharge but in fact it retains substantial kinetic energy to drive the entrainment process.

**surface reflection begins**

Message used only when the <shallow/surface Z> ^Z command, for very shallow water, has been used and the ^Z flag has been placed by UM at the beginning of the title cell. It indicates that the plume has reached the surface implied, in this case, by the port spacing.

**trap level**

This message indicates that the plume element has acquired, if only momentarily, an average density that is equal to that of the surrounding ambient fluid at the same depth. If the plume element where at rest it would remain at rest at this level. However, normally the plume element has a vertical velocity when this level is reached and will traverse the level. If the ambient is density stratified, and normally it will be, multiple trap levels are possible. Thus, in a current, the plume element will trace a wavy path which is sometimes observed in nature.

Historically, the initial trap level has been used as a cut-off point for the initial dilution process. This cut-off is often applied rather arbitrarily. In many cases, the newer models, such as UM, provide reasonable estimates of dilution beyond this point. Generally, unless there is significant overlap, UM is believed to provide good estimates through the level of maximum rise. In negatively buoyant cases UM is sometimes run past the second trap level because such plumes are frequently discharged upward and the plume often has considerable potential energy when reaching maximum rise. See Appendix 6 for further details.

**UM running, <key> to interrupt**

A "Please wait" message. UM is running but may be interrupted at any time.

**RSB RUN TIME MESSAGES**

**Avg. flux dilution (width\*he\*u/Q): [value]**
Estimated volume flux through a cross section in the ambient flow comparable to the wastefield cross section at the end of initial dilution.

**<key> for farfield prediction**
Strike any key to continue the simulation.

**No farfield prediction when far vel = 0.**
Gives the reason for no farfield simulation when using RSB; the far field velocity cannot be equal to zero. This condition also holds for UM.

**No farfield prediction; far dif, far inc, far dis, or far vel defined?**
No farfield simulation is attempted because the farfield diffusion coefficient, increment, maximum distance, or farfield velocity are not defined.

**Results extrapolated beyond their experimental values, may be unreliable**
$s/l_b > 1.92$, $l_m/l_b > 0.5$, or $f > 100$. These parameters define experimental ranges beyond which the quality of the empirical model is increasingly unknown. See the RSB chapter for further details.

**Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed**
An average flux dilution is not calculated because forced entrainment is small or zero. Entrainment flow is primarily induced by the plume, not by the current.

**RSB not compatible with input conditions: [reason]**
This advisory states that RSB be cannot be run for one of the following ([reason]): 1) **stratification not defined**, information to complete the stratification is missing from the ambient block; 2) **effluent density or current not defined**, these cells or cells that are needed to define them are undefined; and 3) **negative buoyancy**, RSB is restricted to cases with positive buoyancy.

**Wastefield plume surfaces**
Warns that a basic assumption of the model, i.e. that the water is infinitely deep, is not met. If rise above the surface is significant the dilution will be substantially over-estimated.

In addition to these messages, RSB always displays the following text:

**Written by Philip J. W. Roberts (12/12/89, 4/22/93)**
　　　　Credit
**Adapted by Walter E. Frick (1/12/92, 5/6/93)**
　　　　Credit
**Case: [case number]:  [title]**
　　　　Case identification
**CAUTION:  convergence criterion not met after [value] steps.  Process truncated.**
　　　　The approximate solution to an equation is not within the tolerance criterion.  Dilution
　　　　and other predicted values may be in error.
**Lengthscale ratios are: s/lb = [value] lm/lb = [value]**
　　　　See the RSB Chapter for these variables and the "Results extrapolated..." message above.
**Froude number, u3/b = [value]**
　　　　A measure of current strength.  When this value is large ( > 0.1) forced entrainment
　　　　dominates.  When it is much smaller, aspiration entrainment dominates.
**Jet Froude number, Fj = [value]**
　　　　A small value indicates a buoyancy dominated plume, a large value a momentum
　　　　dominated one.  A value of 1.0 is a cut-off value for intrusion of ambient fluid into the
　　　　diffuser.
**Rise height to top of wastefield, ze = [value]**
　　　　See Figure 54.
**Wastefield thickness, he = [value]**
　　　　See Figure 54.
**Height to level of cmax, zm = [value]**
　　　　See Figure 54.
**Length of initial mixing region, xi = [value]**
　　　　See Figure 54.
**Minimum dilution, Sm = [value]**
　　　　The minimum, i.e. centerline, dilution at $x_i$.
**Flux-average dilution, Sfa = [average dilution value]  ([ratio value] x Sm)**
　　　　The average dilution value equals the minimum dilution value times the peak-to-mean
　　　　ratio; also defined at $x_i$.
**Wastefield width [value]**
　　　　Width of the wastefield in meters; measured at $x_i$.

**FARFIELD MODULE RUN TIME MESSAGES**

**TEMPORARY NOTE**  The farfield algorithm is under review.  The purpose of the review is to ascertain its consistency with the proper relationship between average and centerline concentrations.

**dilution overestimated**
> Issued when overlap occurs in the initial dilution region and the maximum rise or the Pause Cell criterion override the overlap criterion as the initial dilution stopping criterion.  Dilution is likely to be overestimated.

**Input starting longitudinal coordinate: [default value]**
> This message appears if the PLUMES configuration string <Brooks eqn input> ^RB command has been toggled to 'R' (or reset).  The user may accept the default width by pressing <return> or <spacebar> or type in a new value.  This capability allows the farfield algorithm to be run essentially independently of the initial dilution model.

**Input wastefield width: [default value]**
> This message appears if the PLUMES configuration string <Brooks eqn input> ^RB command has been toggled to 'R' (or reset).  The user may accept the default width by by pressing <return> or <spacebar> or type in a new value.  This capability allows the farfield algorithm to be run essentially independently of the initial dilution model.

**No farfield prediction, check input**
> No farfield simulation is attempted because the farfield diffusion coefficient, increment, or maximum distance are not defined.

**No farfield prediction when far vel = 0.**
> Gives the reason for no farfield simulation when using RSB; the far field velocity cannot be equal to zero.

In addition to these messages, RSB always displays the following text:

**FARFIELD CALCULATION (based on Brooks, 1960, see guide)**
> Indicates the farfield algorithm follows.

**Farfield dispersion based on wastefield width of [width]**
> Indicates the initial width (an initial condition) used by the farfield algorithm.

**--4/3 Power Law--   -Const Eddy Diff-**
> Headers for the farfield concentration columns that follow.  The 4/3 Power Law results are appropriate for open water while the Const Eddy Diff results are appropriate for channels.

**conc dilution     conc dilution distance     Time**

Column headers followed by units. The peak-to-mean ratio established at the end of the initial dilution region may be used to estimate corresponding average dilutions in the farfield region.

# APPENDIX 5:  UNIVERSAL DATA FILE FORMAT (Muellenhoff et al, 1985)

## INTRODUCTION

The Universal Data File (UDF) was introduced by Muellenhoff et al. (1985) to serve as a common data file for the five 1985 EPA plume models: UPLUME, UOUTPLM, UKHDEN, UMERGE, and ULINE.  ULINE and UPLUME are bundled with the PLUMES software, although we believe they are completely superseded by the new models.  UMERGE has also been completely updated in the PLUMES UM model.  UOUTPLM is largely obsolete.  Experience shows that UMERGE (and also UM) and UDKHDEN have similar capabilities and give similar results, although UMERGE is found to be slightly more conservative than UDKHDEN (Baumgartner et al., 1986).

## THE UNIVERSAL DATA FILE

```
UNIVERSAL DATA FILE (UDF) "CARD" DECK

      THE DATA ENTERED ON CARDS 2 THROUGH 7 MAY BE EITHER IN THE FORMAT REQUIRED BY
      EACH CARD OR EACH VALUE ON THE CARD MAY BE SEPARATED BY A COMMA (SHORT FIELD
      TERMINATION).
      AN EXPLICIT DECIMAL POINT OVERRIDES THE FIELD DESCRIPTOR.

CARD 1  FORMAT(10A8)
      IDENTIFICATION OF A DATA SET WITHIN THE UDF.

CARD 2  FORMAT(8I2)
      INTER =1 INTERACTIVE CONTROL OF CARDS 3 AND 4 PARAMETERS.
            =0 "SINGLE" RUN USING PARAMETERS IN DATA SET ONLY.
      IDFP  =1 PRINT "CARD IMAGE" OF DATA SET.
             =0 DO NOT PRINT CARD IMAGE OF DATA SET
      ICUTOP=1 USE OPTIONAL CARD 5 TO CHANGE CONTROL PARAMETERS FROM
               THE DEFAULT VALUES
            = DO NOT READ A CARD 5 (THUS CARD 5 MUST BE OMITTED).
      IPI       INPUT PRINTOUT CONTROL FOR  UPLUME
      IOI                     "             UOUTPLM
      IDI                     "             UDKHDEN (SEE NOTE 1)
      IMI                     "             UMERGE
      ILI                     "             ULINE
      IP0=IPI   OUTPUT PRINTOUT CONTROL FOR UPLUME
      IO0=IOI                 "             UOUTPLM
      ID0=IDI                 "             UDKHDEN (SEE NOTE 1)
      IM0=IMI                 "             UMERGE
      IL0=ILI                 "             ULINE

      FOR EACH OF THE PARAMETERS IPI TO ILI
            =0 USE NEW (8.5 X 11) FORMAT
            =1 USE ORIGINAL FORMAT.
            =2 USE CONDENSED FORMAT (USEFUL IN INTERACTIVE MODE).
         NOTE! 1)  IDI AND ID0 ALLOWED FOR BUT PRESENTLY NOT USED
                   IN UDKHDEN, ENTER THE SAME VALUE AS THE OTHERS.

CARD 3  FORMAT(F10.0,I10,3F10.0)
      QT        TOTAL EFFLUENT FLOW (CUBIC METERS PER SEC).
      NP        NUMBER OF PORTS (SEE NOTE 2).
```

```
          PDIA       PORT DIAMETER (M), EFFECTIVE DIAMETER IF KNOWN.
          VANG       VERTICAL ANGLE (DEG) OF PORT RELATIVE TO THE
                     HORIZONTAL (90 DEGREES FOR A VERTICAL PORT).
                     ULINE ASSUMES VANG=90 DEG.
          PDEP       PORT DEPTH (M) MUST BE GREATER THAN 0.0 AND
                     LESS THAN OR EQUAL TO THE DEEPEST DEPTH OF THE
                     AMBIENT DENSITY PROFILE.

            NOTE!  2)  ULINE REQUIRES TWO OR MORE PORTS, FOR THE
                       OTHERS, IF NP=1 SPACE=1000.0 (DEFAULT) MAKING
                       THE MERGING FLAGS INACTIVE.
  CARD 4  FORMAT(3F10.0)
          UW         HORIZONTAL CURRENT SPEED (M/S) (USED IN UOUTPLM ONLY).
          HANG       ANGLE (DEG) OF CURRENT DIRECTION WITH RESPECT TO DIFFUSER
                     AXIS (90 DEGREES CORRESPONDS TO A CURRENT DIRECTION
                     PERPENDICULAR TO THE DIFFUSER AXIS AND IF VANG=0, BOTH
                     THE CURRENT AND THE DISCHARGE ARE IN THE SAME DIRECTION)
                     (SEE NOTE 3).
          SPACE      DISTANCE (M) BETWEEN ADJACENT PORTS (SEE NOTE 2).

            NOTE!  3)  HANG NOT USED IN UPLUME.  UOUTPLM AND UMERGE
                       ASSUME 90 DEG.  UDKHDEN RANGE 45 - 135 DEG FOR
                       MORE THAN ONE PORT AND 0 - 180 DEG FOR A SINGLE
                       PORT (NOTE, SINGLE PORT ONLY: FOR VALUES GREATER
                       THAN 90 DEG BUT LESS THAN OR EQUAL TO 180 DEG, THE
                       PROGRAM SETS HANG EQUAL TO THE SUPPLEMENTARY ANGLE).
                       ULINE RANGE 0 - 180 DEG.


  CARD 5  OPTIONAL (INCLUDE THIS CARD ONLY IF ICUTOP =1)
          FORMAT(F5.0,2I5,3I2,6F5.0,2I5)


          USED IN UMERGE
          A          ASPIRATION COEFFICIENT                   0.1  BY DEFAULT
          ITER       MAXIMUM NUMBER OF ITERATIONS       5000       BY DEFAULT
          IFRQ       ITERATION PRINTOUT FREQUENCY        150       BY DEFAULT
          NAA        PRINT ARRAY AA IF =1, DO NOT IF =0    0       BY DEFAULT
          NAB        PRINT ARRAY AB IF =1, DO NOT IF =0    0       BY DEFAULT
          NAC        PRINT ARRAY AC IF =1, DO NOT IF =0    0       BY DEFAULT

                     (SEE LISTING OF PROGRAM UMERGE FOR CONTENTS OF ARRAYS
                     AA, AB, AC WHICH ARE MAINLY DEBUGGING AIDS.)


          USED IN UPLUME
          PS         PRINTOUT "INTERVAL"                      3   BY DEFAULT


          USED IN ULINE
          RK         RATIO OF SA/SM IN ROBERTS' EXPERIMENTS  1.41 BY DEFAULT
          DH         INTEGRATION STEP SIZE(M)                0.1  BY DEFAULT


          USED IN UOUTPLM
          H          INITIAL THICKNESS OF PLUME ELEMENT    .5*PDIA BY DEFAULT
          E          IMPINGEMENT ENTRAINMENT COEFFICIENT     1.0  BY DEFAULT
          A          ASPIRATION ENTRAINMENT COEFFICIENT      0.1  BY DEFAULT
          ITERB      NUMBER OF INTEGRATION STEPS ALLOWED   5000   BY DEFAULT
          IR         PRINTOUT INTERVAL                       50   BY DEFAULT

            NOTE!  WHEN CARD IS USED, ALL OF THE PARAMETERS NEED NOT BE
                   GIVEN A NEW VALUE, ONLY THE ONES TO BE CHANGED.  ENTER ZERO
                   FOR THE OTHERS AND THEIR DEFAULT VALUES WILL BE USED.

                   ITER, IFRQ, ITERB AND IR NOT TO EXCEED FOUR DIGITS.

                   NO OPTIONS AVAILABLE FOR UDKHDEN.
```

```
CARD 6   FORMAT(I10,2F10.0)
         NPTS      NUMBER OF DEPTHS WHERE AMBIENT TEMPERATURE, SALINITY, AND
                   HORIZONTAL CURRENT SPEED ARE KNOWN (NPTS MUST BE A LEAST
                   EQUAL TO 2 AND NOT MORE THAN 30).
         S         EFFLUENT SALINITY (PPT) IF T NOT EQUAL TO ZERO
                   EFFLUENT DENSITY (G/CM3) IF T=0
         T         EFFLUENT TEMPERATURE (DEGREES CELSIUS).
                   IF T=0 PROGRAMS ASSUME S IS EFFLUENT DENSITY IN
                   G/CM3, SEE NOTE 4.

CARD 7   FORMAT(4F10.0)
         DP( )     DEPTH IN METERS, MUST HAVE DATA FOR DP( )=0.0
         SA( )     AMBIENT SALINITY (PPT) IF TA( ) NOT EQUAL TO ZERO
                   AMBIENT DENSITY (G/CM3) IF TA( )=0
         TA( )     AMBIENT TEMPERATURE (DEGREES CELSIUS)
                   IF TA( )=0 PROGRAMS ASSUME SA( ) IS AMBIENT DENSITY
                   IN G/CM3, SEE NOTE 4.
         UA( )     HORIZONTAL AMBIENT CURRENT SPEED (M/S) (USED IN UMERGE,
                   UDKHDEN, AND ULINE).

            NOTE!  4)  THERE MUST BE NPTS IMAGES OF CARD 7.  ALSO, EITHER
                       ALL TA(I) MUST BE ZERO OR ALL NOT ZERO, OR ERRORS
                       IN THE INTERPRETATION OF SA( ) AND TA( ) WILL OCCUR.
                       IF, FOR SOME I, SA(I) IS DESIRED TO REPRESENT
                       AMBIENT SALINITY AND TA(I) SHOULD BE EXACTLY 0, SET
                       TA(I) EQUAL TO A SMALL NUMBER INSTEAD (0.000001) FOR
                       INSTANCE).  THIS APPLIES TO S AND T AS WELL.
                       AMBIENT DENSITY (G/CM3) IF TA( )=0
```

Appendix 5:  Universal Data File Format (Muellenhoff et al, 1985)

# APPENDIX 6:  THIRD EDITION CHANGES

## INTRODUCTION

The Second Edition was first received from the publisher in October, 1993.  Of the 500 copies printed, approximately 250 were sent to holders of the "First Edition," a xeroxed draft version made available to trial users in July 1992.  The remaining copies were sent to the authors, a few libraries, selected individuals, and new users. Permission was granted for a third printing of 500 copies by the Narragansett Lab in March, 1994.  At that time about 25 copies of the manual still remained in the hands of the authors for dissemination.

In the period April 1993 through March 1994 342 calls for plume modeling technical assistance were recorded at the Newport Lab, including requests for the manual.  Approximately 10 percent of users spontaneously express reactions to PLUMES that are favorable while perhaps one percent express unfavorable ones.  In addition to their opinions, some users discovered errors and bugs, which motivated some of the changes described here.

## THE PLUME SHIELDING CORRECTION

As is discussed in the UM Model Theory Chapter, the Projected Area Entrainment (PAE) hypothesis is known to work well for conditions for which it was originally developed: plumes discharged to open, unbounded environments free from interference, except for specific merging geometries.

When interference exists, entrainment is affected to some degree or other and some interpretation of the output is necessary.  This interference includes the bottom, the surface, obstructions, and other plumes.  The former are often treated by terminating execution at the point of impact.  However, the effect of other plumes can often be estimated.  Merging plumes is a good example.  This change is an attempt to account for the effect of upstream portions of the plume on its downstream portion.

In the Second Edition an approach was adopted which was thought to be very conservative for plumes reversing their vertical movement.  This included buoyant plumes discharged downward, nascent density plumes discharged upward, and negatively buoyant plumes discharged upward.  In this approach the curvature and cylinder contributions to entrainment were terminated upon reversal of vertical momentum, the beginning of shielding, thereby potentially reducing overall entrainment significantly.

The problem with this approach is that the upstream portion of the plume is generally thinner that the downstream portion, thus only a portion of the terms should be reduced. Secondly, the terms should be re-established when the plume rises, or sinks, out of the depth at which it is

shielded.  In the absence of these modifying factors, a positively buoyant plume discharged downward into a stratified environment could reverse its vertical motion to eventually penetrate the stable layer and reach the surface.  In reality, in many such cases plumes will trap, made apparent by the fact that equivalent plumes discharged upward would trap.  This problem was noticed by some users.

   In this edition the entrainment terms are only partially reduced, in proportion to the projected area that is estimated to actually be blocked by the upstream plume.  Secondly, the vertical extent of shielding is established by maximum upward and downward oscillations of the plume.  Outside of that depth zone no shielding occurs.  The corrections are still believed to give generally conservative results while solving the problem of artificial penetration described above.


## RSB CONVERGENCE

   As explained in the RSB model chapter, RSB linearizes the ambient density stratification over the depth of the plume's rise.  It also uses iterative approximation techniques to solve a couple of its equations.  In some cases the speed of convergence to the correct solution is sensitive to slight variations in the depth of the pycnocline.  Unlike the original Basic language RSB, the PLUMES version limits the number of iterations to prevent infinite loops, but, as a result, the reported solution can be significantly in error when the approximation method is terminated before the convergence criterion is reached.

   The case given in Figure 72 illustrates the problem.  It presents a Second Edition simulation of a plume discharged to receiving water divided in three layers.  The dilutions are anomalously high.  This can be seen by comparing to a UM simulation and by moving the one meter deep pycnocline a small distance up or down in the water column.  For example, placing the pycnocline at a depth of 10 to 11 meters results in a dilution of 222.2.  In both cases UM predicts 821.9 indicating that the solutions are identical within the resolution of a single time step (about one half of one percent).

   In the Third Edition the approximation technique has been improved to converge faster and more regularly.  It also issues a warning if convergence is not attained.  Using the new version, a corrected centerline dilution corresponding to Figure 72 of 262.9 is found, compared to 2028.5. The corresponding corrected flux average dilutions for RSB are 302.3 (Sfa) and 465.9 ("Avg. flux dilution" calculation).  The choice between the latter and UM's 821.9 could be a matter of regulatory priorities.

   RSB is an empirical model.  The experiments on which it is based were conducted under stable ambient stratification.  It is recommended that the sensitivity of RSB predictions to stratification be tested when specifying neutral, unstratified ambient layers.  This can be

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achieved by introducing values representing weakly stratified ambient density and comparing the

```
Mar 27, 1994,  7:28:25  ERL-N PROGRAM PLUMES, Jun 10, 1992  Case:   3 of   5
Title    Joy Paulsen runs                                            linear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
   14.46        440  0.03286      4.64       0.0    15.67       500      2000
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
     30      0.157    0.1570     1.698     1.698     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc    decay  Froude # Roberts F
     0.5       0.0       1.0     -0.94       100        0      8.474     4.419
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
     90      4.640   25.1000    0.2000  0.000453            8.488 0.0002010
   depth    current   density  salinity      temp   amb conc  N (freq) red grav.
     0        0.2       24.1                                   0.01786    0.2556
    11        0.2       24.1                                  buoy flux puff-ther
    12        0.2       25.1                                   0.001810    1.228
    30        0.2       25.1                                  jet-plume jet-cross
                                                               1.252      1.181
                                                              plu-cross jet-strat
                                                               1.050      3.637
                                                              plu-strat
                                                               6.197
                                                                hor dis>=

 CORMIX1 flow category algorithm is turned off.
      6.197 m, 20.33 ft                                         to  m range
 Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: PLMSTUFF.VAR;

                              RSB
           Written by Philip J. W. Roberts (12/12/89, 4/22/93)
             (Adapted by Walter E. Frick (1/12/92, 5/6/93))

 Case:  3: Joy Paulsen runs

 Lengthscale ratios are: s/lb =   0.18 lm/lb =   0.02
 Froude number, u3/b =         4.51
 Jet Froude number, Fj =       8.6

 Rise height to top of wastefield, ze =  61.4 m
 Wastefield submergence below surface =   0.0 m    PLUME SURFACES
 Wastefield thickness, he =              86.1 m
 Height to level of cmax, zm =           67.7 m
 Length of initial mixing region, xi =  729.8 m

 Minimum dilution,        Sm = 2028.5
 Flux-average dilution, Sfa = 2332.8 ( 1.15 x Sm)
 Wastefield width:   2037.12m  Avg. flux dilution (width*he*u/Q):    2425.2


 UM INITIAL DILUTION CALCULATION (linear mode)
  plume dep plume dia poll conc  dilution   hor dis
      m        m                              m
    30.00    0.1570     100.0     1.000     0.000
    28.35    2.194      3.125     31.21     5.343
    26.23    4.674     0.8258     118.0    10.54 -> merging
    12.89    27.28     0.1186     821.9    49.92 -> surface hit
```

**Figure 72**. Example of input to which RSB is susceptible, giving substantially different solutions depending on vertical placement of the stable layer.

predictions to the unmodified ones.

Text and figures in the tutorial and RSB chapters have been updated to reflect the relatively minor changes introduced by this change.

## ESTIMATING DILUTIONS IN PARALLEL CURRENTS USING UM

One thing we have learned in producing this manual is that there are simply too many possibilities in such a complex field to anticipate them all. While it would be nice to give unequivocal advice, hard and fast recommendations are often made to seem foolish for some unexpected reason or other. We have found that the resourcefulness of our users can help overcome deficiencies in the guidance we provide.

One area in which we would like to provide further advice is in cases of currents parallel to diffusers. Generally speaking, the RSB model is recommended for diffusers oriented parallel to prevailing currents. However, some users have had reasons to try to use UM in similar situations.

In previous editions of PLUMES the work of Roberts (1977) was used to justify the use of UM in currents from perpendicular to 45 degrees off perpendicular. The question is, could this approach be extended to smaller angles? If it can be, the approach suggests that diffuser plumes issued from long diffusers oriented parallel to the current might behave approximately like the same diffuser oriented at an angle of 14 degrees to the current. In other words, there is no further reduction in dilution for angles less than 14 degrees.

Attempts to verify this procedure leads to ambiguous results. While the RSB model found in the manual tends to support the procedure (the average dilutions tending to be greater than the ones predicted by RSB and centerline dilutions tending to be smaller), data from the original work on which the method is based are less supportive. Consequently, RSB continues to be recommended for use in parallel currents in general. UM should be reserved for cases in which nascent density effects, nonlinear density effects (which can be significant in cases of ambient water considerably warmer than 4 C), and other special conditions better treated by UM than other models are significant.

## IMPORTANT CHANGES IN THE THIRD EDITION

The Third Edition includes numerous changes to the Second Edition. Most of them are editorial and do not substantively change the meaning of the text. There are a few important exceptions, in addition to those described above, which are listed here.

The program header has been updated with the text: "Ed 3, 3/11/94".

The meaning of Roberts' Froude number and the buoyancy flux has been changed from the port concept to a diffuser concept.  This was done to be faithful to the use of the number as a discriminator between aspiration and forced entrainment dominated multiple plumes, $F <$ and $> 0.1$ respectively.  (For diffusers with ports on both sides, this criterion is appropriate when cross-diffuser merging is considered, i.e. half spacing is used.)  The PLUMES software has been changed accordingly.  Various linkages to other variables were adjusted or deleted to conform to the change, as is reflected in the updated EQNS file.

The Roberts's Froude number criterion for differentiating between dominant aspiration and forced entrainment has been corrected, having been changed from 0.01 to 0.1.

The <get Work file>, ^W, and <fill New file>, ^N, commands have been changed to prevent the inadvertent replacement of the first case by higher numbered cases in the case file.  The credit for identifying this bug has been lost.

The <Beget new cases>, ^YB, command has been changed to allow the replacement of cells in subsequent cases by an empty cell.

Overlap is not reported during the first five UM program steps.  During this time dilution is insignificant.  This helps to assure that only significant instances of overlap are reported.

When running multiple cases with UM, the Quit option to an interrupt now stops subsequent cases from running, not just the case in which the interrupt was detected.

The dialogue window now reports the estimated length of the diffuser when the cursor is located in the number of ports, spacing, and effective spacing cells.  This change was made to help eliminate confusion between side-by-side and cross-diffuser merging.  The value given is: *L = (number of ports - 1) (spacing)*.  It is the physical length of the diffuser, not generally the effective width of the wastefield, which also depends on the plume diameter and the angle of the current to the diffuser.

The disclaimer in the Second Edition was inadvertently left unchanged from prototype earlier versions of the manual.  The less restrictive disclaimer is found in the Third Edition.

We have added Bill Ford, Maynard Brandsma, Robyn Stuber, and Joy Paulsen to the acknowledgements.  We are grateful to the many other users, too numerous to list, who have provided us with comments.

Figure 1 has been changed to better identify the initial trap level and subsequent ones.  Figures 8, 10, and 15 have been updated or improved.

A sentence was added to the discussion relating to Figure 11 to indicate that the computed values were found by dividing Equation 11 by 2.4 x $10^4$.

Instructions for accessing the EPA CEAM Bulletin Board Service were added to the first chapter. The number to call is (706) 546-3402. The communication parameters are 14400/1200 baud, no parity, 8 data bits, and 1 stop bit.

The Home and End keys on standard keyboards have been added to allow movement Case 1 and the highest numbered case in the case file respectively.

A <bEget configuration>, ^RE, command has been added to permit the wholesale change of the configuration string throughout the data set. Also, the change in the configuration string between Figures 50 and 51 is emphasized.

On the first page of the RSB chapter, the sentence "RSB is intended for stratified conditions producing a fully submerged wastefield; other..." has been replaced by one reading: "RSB will also predict dilutions for a surfacing wastefield caused either by a weak stratification or by unstratified conditions."

The sentence "Half spacing provides the correct solution for RSB." has been added to the bottom of page 99.

The ambiguity of two Figures 58 and subsequent numbering has been resolved.

The derivation on pages 130 and 131 justifying the Projected Area Entrainment Hypothesis has been extended to stably stratified ambient fluids. Before the last paragraph on page 131 the following text has been added:

"In stratified flow a similar derivation is possible. Neglecting the additive term of -0.52 in Equations 25, justified in moderate to strong current or high $F$, the peak-to-mean ratio of 1.15 (more accurately 2.5/2.19, or 1.142) used in the RSB model is obtained. However, it is clear that this is the lower limit of the ratio which would be greater if the additive term were not neglected.

"Finally, it might be argued that the more appropriate measure of plume wastefield thickness is $h_e$, not $z_e$. However, in large currents the bottom of the plume is often near the sea bottom. Furthermore, if plume spacing is smaller, then the latter measure is indeed the appropriate one for estimating entrainment flux."

A reference relating to the use of UM in very shallow water has been added:

Davis, L.R. and E. Hsiao, 1991. An experimental/analytical investigation of buoyant jets in shallow water. Oregon State University, Corvallis OR.

and the reference to Frick, Baumgartner, and Fox, 1993, in prep, has been changed to reflect its acceptance for publication in the *Journal of Hydraulic Research*:

> Frick, W.E., D.J. Baumgartner, and C.G. Fox, 1994. Improved prediction of bending plumes.  Accepted for publication in *Journal of Hydraulic Research*, International Association for Hydraulic Research (IAHR), Delft, The Netherlands.

Appendix 3 has been updated with new UM runs corresponding to Table 1.

Consistent with the discussion on plume shielding given above, the message "end curvature, cylinder entrainment" has been deleted from page 172.  This is followed by an appropriate change to the "local maximum rise or fall" message which amends the paragraph beginning with "In many applications" to:

> "In many applications, the first maximum rise or fall is the appropriate point for determining the initial dilution achieved and for initiating the farfield diffusion algorithm.  However, when effluent buoyancy and momentum are initially in opposite directions, PAE and Taylor entrainment often continue to be dominant dispersion processes and act after the first maximum rise or fall.  See Appendix 6 for further details."

The message "Wastefield submergence below surface..." has been deleted from page 176.