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Dilution Models for Effluent Discharges

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DILUTION MODELS FOR EFFLUENT DISCHARGES
(Third Edition)

by

D.J. Baumgartner[1], W.E. Frick[2], and P.J.W. Roberts[3]

[1] Environmental Research Laboratory
University of Arizona, Tucson, AZ 98706
[2] Pacific Ecosystems Branch, ERL-N
Newport, OR 97365-5260
[3] Georgia Institute of Technology
Atlanta, GA 30332

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Standards and Applied Science Division
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Oceans and Coastal Protection Division
Office of Wetlands, Oceans, and Watersheds

Pacific Ecosystems Branch, ERL-N
2111 S.E. Marine Science Drive
Newport, Oregon 97365-5260
U.S. Environmental Protection Agency

ABSTRACT

This report describes two initial dilution plume models, RSB and UM, and a model interface and manager, PLUMES, for preparing common model input and running the models. Two farfield algorithms are automatically initiated beyond the zone of initial dilution. In addition, PLUMES incorporates the flow classification scheme of the Cornell Mixing Zone Models (CORMIX), with recommendations for model usage, thereby providing a linkage between two existing EPA systems.

The PLUMES models are intended for use with plumes discharged to marine and fresh water. Both buoyant and dense plumes, single sources and many diffuser outfall configurations may be modeled.

The PLUMES software accompanies this manuscript. The program, intended for an IBM compatible PC, requires approximately 200K of memory and a color monitor. The use of the model interface is explained in detail, including a user's guide and a detailed tutorial. Other examples of RSB and UM usage are also provided.

This edition contains numerous changes, most of them minor. The most substantive change, described in Appendix 6, involves the calculation of entrainment in UM.

This is Document No. N268 of the Environmental Research Laboratory, Narragansett. The accompanying software also carries No. N268.

DISCLAIMER

The information in this document has been subjected to Agency peer and administrative review, and it has been approved for publication as an EPA Document. Mention of trade names or commercial products does not constitute endorsement or recommendations for use.

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GENERAL ASPECTS OF DILUTION MODELING

INTRODUCTION

Pollution control authorities frequently employ buoyant plume models to simulate expected concentrations of effluent contaminants in ambient receiving waters. During the decade of the 1980s a great deal of attention was given to the subject because of the U.S. Environmental Protection Agency's (EPA) regulation of publicly owned municipal wastewater discharges to marine waters (USEPA, 1982). The central feature of this regulation was a modified permit based on an applicant demonstrating the environmental acceptability of less than secondary treatment, consistent with criteria listed in section 301(h) of the federal Clean Water Act.

A number of models and other methods, e.g., field data, were used in this context, primarily to demonstrate compliance with a variety of applicable regulatory requirements of local, regional, state, and federal agencies. In addition, models were used to aid in the design of marine monitoring programs and in the design of new or modified ocean outfall pipelines and diffuser systems. In 1985 EPA published a user's guide to five models used in these activities (Muellenhoff et al., 1985) although three of the models had been distributed previously (e.g. Teeter and Baumgartner, 1979) and used for years in many applications.

Possibly because of the popularity and the endorsement associated with the EPA user's guide, the models were applied by regulatory agencies, designers, and dischargers to problems beyond those for which they were originally intended. Some applications involved industrial wastes, drilling fluids from offshore oil exploration and development projects, and effluent discharge into freshwater systems, both lakes and rivers. Staff in the EPA offices were asked frequently to assist with these applications, and many users requested EPA to develop a more general model, or specific models for each situation. As a result of these requests, this user's guide and revised computer programs are provided. With respect to the 1985 models (Muellenhoff et al., 1985), UOUTPLM and UDKHDEN are neither reissued nor addressed herein, UPLUME is provided as a separate file but neither recommended nor addressed, ULINE is provided as a separate file also and was recommended in the first edition as an extension of RSB while RSB was not applicable to unstratified conditions, which is no longer true, and UMERGE is modified, extended, and replaced by the resident model UM. To the extent that PLUMES, described immediately below, facilitates UDF file generation, all earlier models are supported by PLUMES.

Both RSB and UM are contained in and managed by the interface program PLUMES. In addition, PLUMES contains two farfield algorithms and the CORMIX1 flow categorization scheme (Jirka and Hinton, 1992). General recommendations for the use of RSB, UM, and CORMIX are issued by PLUMES and explained further in Appendix 1.

The model UM is described subsequently in the manuscript, as is RSB, a model based on

hydraulic model studies by Roberts (1977) and Roberts, Snyder, and Baumgartner (1989 a,b,c).

The new UM model provides essentially equivalent results as UMERGE, in fact, UM may be interpreted to mean "Updated Merge". However, UM possesses considerably more capabilities than its predecessor.

New subjects treated in this report include effluent material discharged at an arbitrary vertical angle to address the cases of positively buoyant material discharged downward, and negatively buoyant material discharged upward. These situations are handled by PLUMES. Discussion is provided on the problem of particulates in the waste stream, as this is becoming recognized as one of the more insidious problems of water pollution control, and on the possible use of the models in freshwater systems. Verification based on field and laboratory data is addressed as is information on uncertainty of predictions.

Subjects such as mixing zones and initial dilution concepts discussed in the 1985 report are repeated, sometimes verbatim, and updated with current interpretations. Discussion of the physical basis of models is expanded.

Readers of the earlier report (Muellenhoff et al., 1985) will also notice some deletions and changes. The computer codes for the programs are not included in the manuscript nor in the diskettes generally provided. (However, the RSB and UM model kernels are available on request.) Another is that the executable models are to be provided on diskette by the EPA marine research laboratory in Newport, Oregon, rather than by NTIS. (They will also be made available on the CEAM, Athens Bulletin Board Service.) These procedural changes are related. Due to user experiences as well as work conducted by EPA it is at times necessary to correct or improve the computer codes. It now appears that changes will occur sufficiently frequently so that it will be more effective to provide current models to users directly from EPA rather than from NTIS. New diskettes distributed by EPA will be accompanied by brief narratives describing the improvements in the physics or the computational routines that take place following publication of this report. These adjustments are judged to be too difficult to arrange on a timely basis through NTIS.

The authors assume readers will have some familiarity with terminology of buoyant plume mechanics, either as applied in regulatory practice or in fluid mechanics generally. Terms used in equations are defined in the text, frequently using different symbols than in original works cited. In different parts of the document, a symbol may represent different quantities, however, the meaning should be clear from the context. Terms and relationships are also explained in the "Help" screens of the interface program PLUMES. General definition sketches are shown in Figure 1.

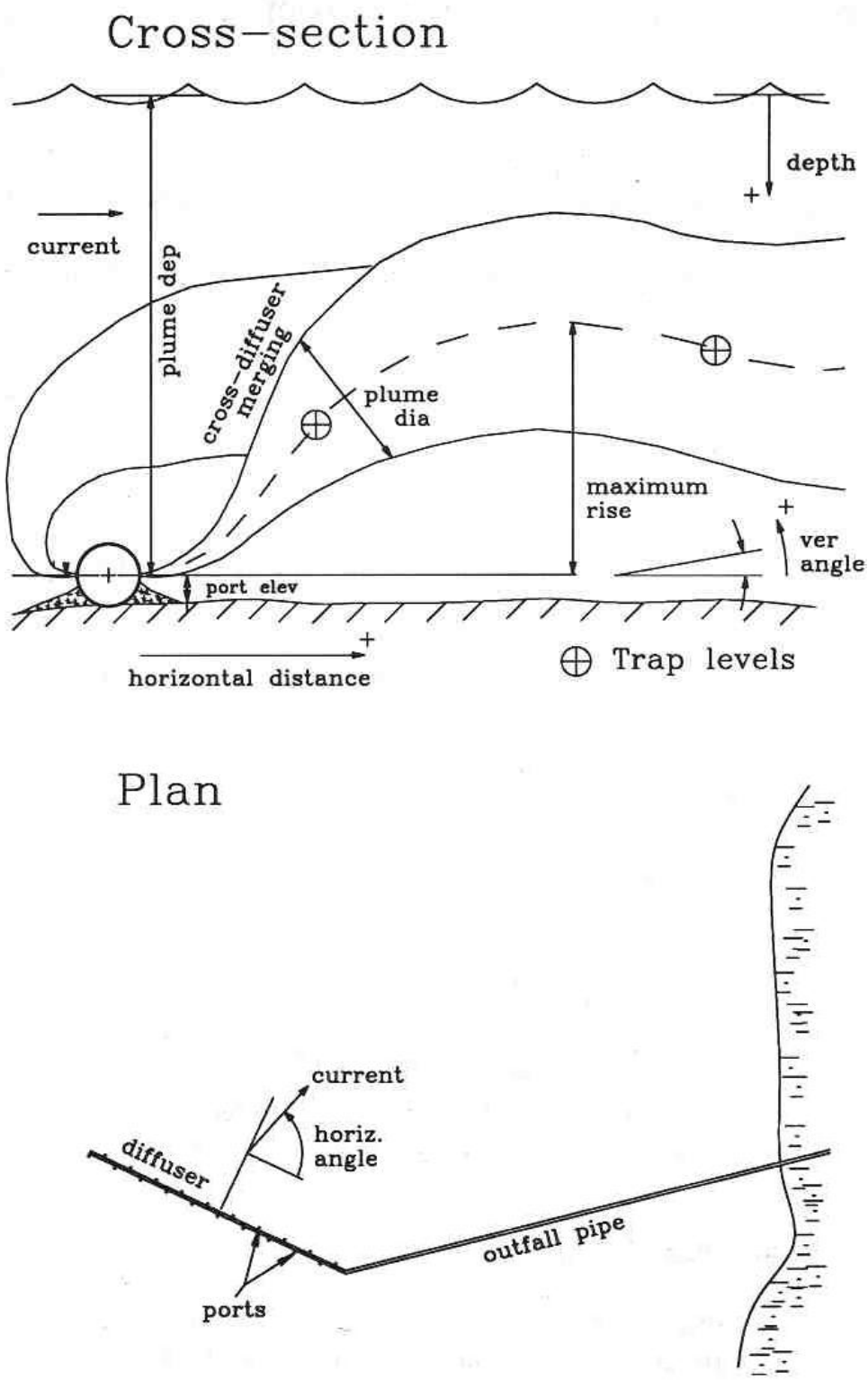

Figure 1. Definition sketch.

REGULATORY ADAPTATION OF PHYSICAL PROPERTIES OF PLUME BEHAVIOR

Initial Dilution

Initial dilution is the dilution achieved in a plume due to the combined effects of momentum and buoyancy of the fluid discharged from an orifice, and due to ambient turbulent mixing in the vicinity of the plume. The rate of dilution is quite rapid in the first few minutes after exiting the orifice and decreases markedly after the momentum and buoyancy are dissipated. Figure 2

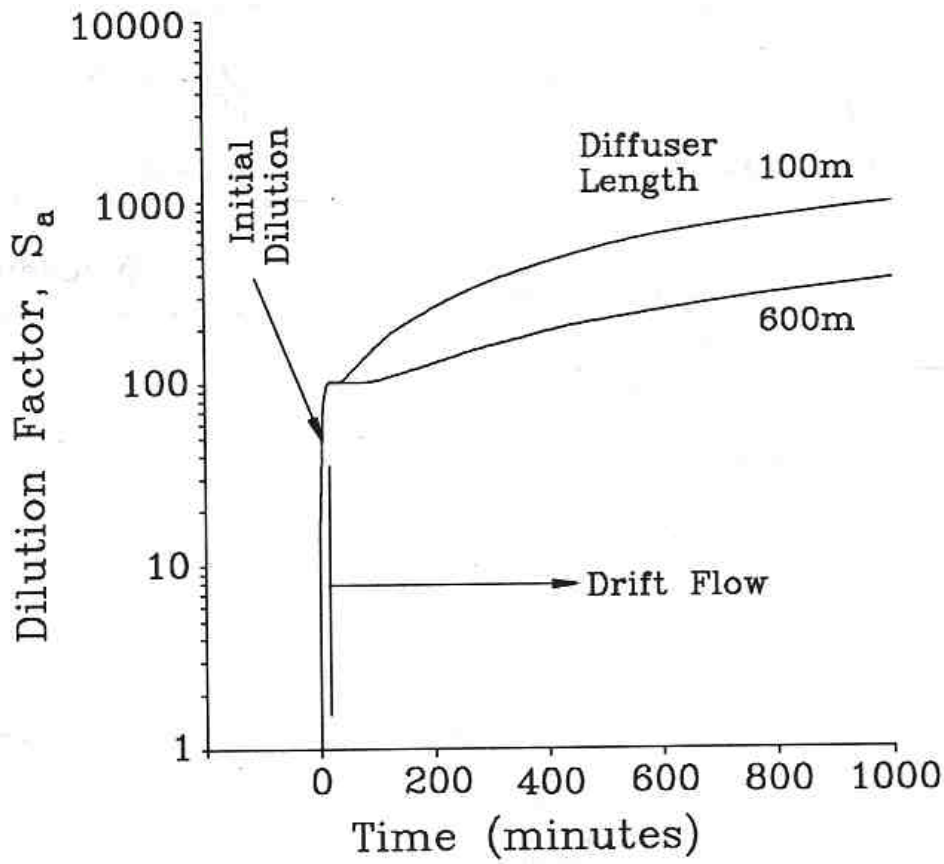

Figure 2. Plume dilution as a function of time.

schematically represents the relative dilution factors achieved in buoyant plumes and in the subsequent drift flow region under low to moderate current conditions.

Ambient currents will also influence the rate of dilution during the buoyant rise of the plume irrespective of jet momentum and buoyancy. As current speed increases so does initial dilution. This is shown in Figure 3 from Baumgartner et al. (1986) for certain west coast conditions using the models in Muellenhoff et al. (1985). UPLUME, not including current, gives constant dilution.

It is useful to compute expected dilutions and plume locations under the vast range of current regimes likely to be encountered near an outfall. The information would be useful in optimizing monitoring programs intended to sample the distribution of ambient values of effluent constituents in analyzing the effectiveness of regulatory controls. Given sufficient data on environmental impacts in the region and accurate exposure data, one could imagine that regulatory agencies might evaluate the societal benefits derived from modifying the definition of critical initial dilution. For example, perhaps the twenty or thirty percentile value of current might be employed, rather than zero current or the ten percentile current, if data show only a slightly increased adverse effect! The increased uncertainty, and risk, associated with calculated values based on these still developing physical models of turbulent dispersion mechanics is not always recognized. It is a cost of attempting to describe more completely the behavior of the plume under actual conditions.

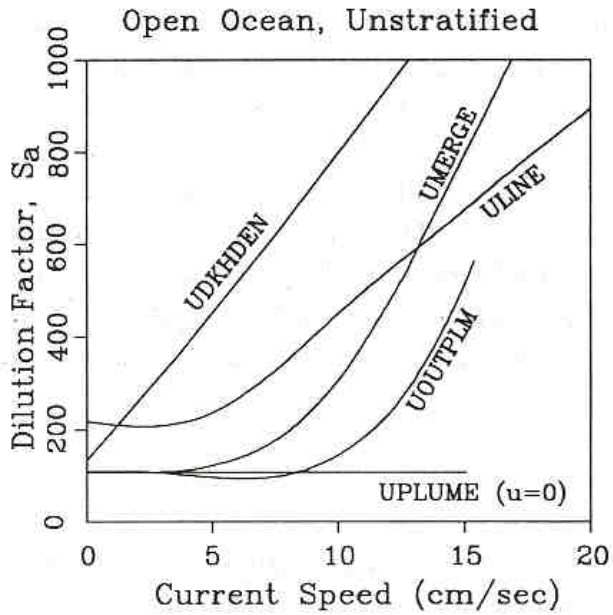

Figure 3. Dilution as a function of current speed.

Critical Initial Dilution

The models described in this report are not constrained by any **regulatory** definition of allowable current speed, although there are limiting current conditions that each model can simulate. In relation to permit requirements of regulatory agencies it is necessary to think of "allowable" initial dilution factors, or "critical" initial dilution factors based on conservative values of parameters in addition to current speed. "Critical" values in terms of EPA's 301(h) permit requirements (USEPA, 1982) include consideration of current direction as well as speed, and other environmental and wastewater factors.

The California Ocean Plan (State Water Resources Control Board, 1988) requires zero current speed to be used in computing initial dilution values intended to predict compliance with permit conditions. Whether intended or not, this regulatory approach results in a predicted initial dilution that is less uncertain than would be obtained when the effects of current are included. In the EPA regulations for a permit modified by section 301(h) of the Clean Water Act (USEPA, 1982), EPA allowed the lowest ten percentile current to be used in computation of the critical initial dilution value. In many coastal settings the ten percentile value is below 5 centimeters per second (cm/sec), i.e., 0.16 ft/sec, or less than 0.1 knot. At current speeds this low there is essentially no effect on the rate of dilution.

Other environmental and wastewater flow parameters that may be considered in establishing critical initial dilutions include spatial limits such as mixing zone dimensions that are smaller than the length scales over which the initial dilution process occurs in nature, high ambient concentrations of pollutants in the dilution water, density stratification encountered during times of the year where human uses or biological resources are especially sensitive, and maximum dry weather flow or other flow episodes that result in minimum dilution or maximum occurrence of pollutant loadings, and decay or die-off rate of pollutants as a function of time. These parameter constraints can be addressed through input to the models by use of the interface PLUMES or through inspection of the output from the models and other information in this report.

Mixing Zone

Permit conditions of regulatory agencies usually allow exceptions within a mixing zone adjacent to the point of discharge. With respect to EPA's 301(h) regulations, the rationale and the precautions associated with mixing zones and the relationships to initial dilution are described in Muellenhoff et al. (1985). The use of the initial dilution models since 1985 in defining mixing zones and in computing allowable discharge concentrations has suggested the need for additional discussion.

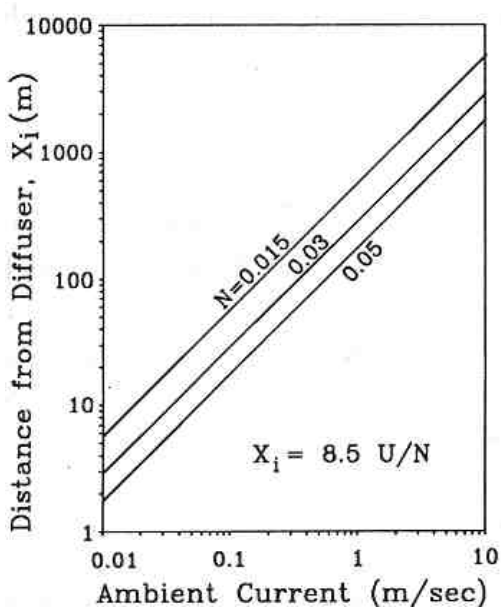

Figure 4. Length of the zone of initial dilution as a function of current speed.

In nature, regulatory restrictions notwithstanding, the initial dilution process occurs over a wide spatial range compared to the length of an outfall diffuser or the depth of water at the discharge site. The effect of current on the scale of the initial dilution process is portrayed in Figure 4. Under low current conditions, e.g. U = 0.1 m/sec, initial dilution is virtually completed before the plume is carried downcurrent a distance X_i equal to the water depth, for example 30 meters when the buoyancy frequency N, a measure of density stratification, is 0.03 per sec. In a strong current the process can extend downcurrent a distance equal to multiples of diffuser lengths (Roberts et al., 1989b). At a current speed of 1 m/sec X_i would be 300 meters.

Recognizing this, what might a regulatory agency prescribe as a mixing zone, that is, a zone in which water quality criteria are permitted to be exceeded? If a conservative posture is adopted, the agency would allow a mixing zone of 30

meters on both sides of the diffuser. If a more liberal view prevails a distance of 100 meters could be established. With the possible exception of riverine settings, it is necessary in most cases to describe the zone on both sides of the diffuser because coastal and estuarine currents during one part of a day are likely to be about 180 degrees opposite those six hours later.

EPA has adopted the conservative posture, at least for marine outfall problems regulated under section 301(h). Thus a smaller area of the environment is removed from the general region protected for unlimited use. Organisms entrained into the plume would be exposed to rapidly decreasing concentrations of pollutants and within minutes, e.g., three, would be in an environment containing pollutants at concentrations within the safe limit. The expectation is that most of the time, e.g., 90% of the time or more, currents are sufficiently high to cause even a greater rate of dilution. Under high currents the concentrations at the boundary of the mixing zone would be expected to be less than the specified criteria values and quite possibly a good portion of the mixing zone would actually meet the necessary criteria.

This expectation has not been rigorously tested. Hydraulic model tests conducted by Roberts et al. (1989 a, b, c) suggested that situations might exist where the expectation is not realized. The model UM can be used to generate simulated data that might be useful to test this assumption. A hypothetical outfall situation is described as follows:

EXAMPLE PROBLEM

Flow: 4.47 m^3/sec	Port depth: 73 m
Number of 8.5 cm ports: 143	Effluent density: 0.836341 sigma-t
Port spacing: 7.3 m	Surface density: 24.0965 sigma-t
Discharge angle: horizontal	Seabed density: 25.0609 sigma-t
Water depth: 76 m	

PLUMES model UM was run for a range of currents, and the plume concentrations at a downcurrent distance of 30 m were interpolated from the output data. (The Zone of Initial Dilution, or ZID, defined in the 301(h) regulations, would be larger but, in general, mixing zone regulations vary from state to state.) The data shown graphically in Figure 5 demonstrate that, as currents increase, the dilution at the boundary increases to a maximum but then begins to decrease.

Assuming this example is somewhat representative, what importance should be attached to the concentrations above a standard level at the boundary when the currents exceed a relatively large value? Organisms entrained into the plume will have traveled with the rapidly diluting wastefield for only a couple of minutes before the concentration is reduced below the standard, whereas with a small current the exposure time in the mixing zone is approximately 10 minutes. Organisms at and beyond the boundary will then be more greatly stressed than entrained organisms in low current conditions. If for example the regulatory authority established the mixing zone boundary to protect a community of benthic organisms from being exposed to concentrations above the standard, then the standard will be abrogated when currents are large.

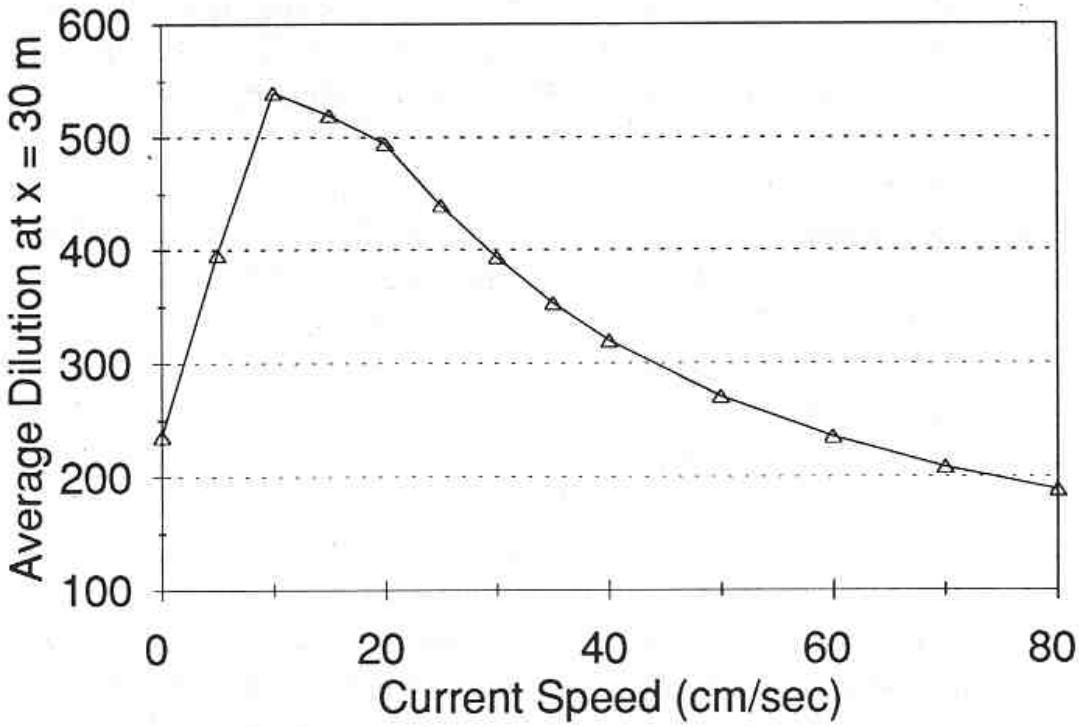

Figure 5. Dilution at the mixing zone boundary as a function of current speed.

Even in unstratified ambients it is possible that high current speeds will cause effluent streams to hug the seabed thus placing benthic resources at greater risk. Under low currents the plumes will rise and be retained closer to the diffuser. Entrained organisms and near-surface resources are more at risk under this scenario. Regulatory agencies may effectively incorporate this knowledge into mixing zone boundaries which are narrower near the surface and wider at depth based on these model simulations.

The term "near field" was adopted in narratives associated with the 301(h) regulations to describe the region near the outfall inside the zone of critical initial dilution, and "farfield" was similarly meant to apply to areas possibly impacted beyond this zone. For most cases "near field" would be consistent with the term "mixing zone".

Dilution Factor

The average dilution factor, S_a, used in some regulatory applications, including the EPA model UM is the reciprocal of the volume fraction of effluent, v_e, contained in the diluted plume. An equivalent way of expressing this term is the ratio of effluent volume plus volume of ambient dilution water, v_a, to the effluent volume, as in Equation 1.

$$S_a = \frac{1}{\frac{v_e}{v_e + v_a}} = \frac{v_e + v_a}{v_e} \qquad \textbf{(1)}$$

Thus in the region immediately outside the discharge orifice the volumetric dilution factor is very nearly 1. In some discussions of this term in other works, e.g. the California Ocean Plan (State Water Resources Control Board, 1988), the factor is considered to be the ratio of the volume of ambient dilution water, v_a , to the volume of effluent discharged, v_e. In this definition the volumetric dilution factor approaches zero near the orifice. Above a value of 30 the difference in the two definitions is progressively less than 3 %, an inconsequential amount for most regulatory purposes.

The former definition, i.e., Equation 1, is used in this report. This is not an arbitrary decision, but rather is based on the general equation used to calculate the contaminant concentration in the plume. Using the continuity equation,

$$c_p\ v_p = c_e\ v_e + c_a\ v_a \qquad \textbf{(2)}$$

where

c_p = Cross sectional average concentration in the plume,
v_p = Volume flux of the plume,
c_e = Concentration in the effluent,
v_e = Volume flux of the effluent,
c_a = Concentration in the ambient dilution water, and
v_a = Volume flux of the ambient dilution water.

Substituting $v_a + v_e$ for v_p and rearranging,

$$c_p = \frac{c_e\ v_e + c_a\ v_a}{v_e + v_a} \qquad \textbf{(3)}$$

The volume fraction, Equation 1, is a useful approximation of the concentration of a pollutant in the diluted plume only if the pollutant concentration in the ambient dilution water is very low compared to the concentration in the effluent. Thus if $S_a = 30$ (which means the effluent is diluted with 29 volumes of ambient water), the concentration of any volumetric tracer or conservative pollutant in the effluent is one thirtieth the concentration in the effluent only if the ambient concentration is zero. In the case of zero ambient concentration Equation 3 reduces to:

$$c_p = \frac{c_e\ v_e}{v_e + v_a} \qquad \textbf{(4)}$$

Dividing both sides by c_e and inverting,

$$\frac{c_e}{c_p} = \frac{v_e + v_a}{v_e} = S_a \qquad \textbf{(5)}$$

Equation 5 demonstrates that for the special case of zero ambient concentration the volumetric dilution factor also describes the dilution of a pollutant. In most regulatory uses of the plume models, however, it is necessary to consider the actual, nonzero, ambient concentration of the suite of pollutants in the effluent. In the remainder of this report the term "effective dilution factor" (S_{aei}) is used to describe the dilution achieved for each pollutant in a plume. That is,

$$S_{ae_i} = \frac{c_{e_i}}{c_{p_i}} \qquad \textbf{(6)}$$

where the index, i, is used to demonstrate that in determining the final concentration of a pollutant in the diluted effluent the effective dilution must be determined for each pollutant individually.

Effective Dilution Factor

It is instructive to recognize that S_{aei} is not necessarily constant for a suite of pollutants in a discharge for any given volumetric dilution factor, S_a. This is so because the ratios c_{ei} / c_{ai} are not necessarily constant, and the volumetric dilution factor is determined only by the density of the plume irrespective of the contribution made by any of the pollutants individually. The effective dilution factor, S_{aei}, can be determined from Equation 6 for each pollutant by first determining the concentration of each pollutant in the plume. The general solution is related to the volumetric dilution factor, S_a , through Equation 3. First, multiply the right side of Equation 3 by v_e / v_e , giving

$$c_{p_i} = \left(\frac{c_{e_i} v_e}{v_e} + \frac{c_{a_i} v_a}{v_e} \right) \frac{v_e}{v_e + v_a} \qquad \textbf{(7)}$$

Next, recalling Equation 5, substitute S_a-1 for v_a / v_e , and $1 / S_a$ for $v_e / (v_e+v_a)$, Equation 7 becomes

$$c_{p_i} = \frac{c_{e_i} + c_{a_i} (S_a - 1)}{S_a} \qquad \textbf{(8)}$$

This is simplified to

$$c_{p_i} = \frac{c_{e_i}}{S_a} + \frac{c_{a_i}}{S_a} - c_{a_i} \qquad \textbf{(9)}$$

which is analogous to equation (1) given in Muellenhoff et al. (1985).

The advantage of Equation 9 is that for many situations the computer program for a plume model needs to be run only once, that is, to obtain S_a. With S_a in hand c_{pi} can be computed repeatedly using paired values for c_{ei} and c_{ai}. If c_{ai} is not uniform over the depth through which the plume rises, an average value can be used to provide an estimate of c_{pi}. However, this is only an estimate as entrainment is not generally a linear function of the vertical position of the plume in the receiving water. The new model, UM, described in this report, accepts a tabular input of the vertical distribution of ambient concentration and computes the actual, effective diluted concentration. Since this model is quick and easy to run, there is only a modest advantage in using Equation 9 to obtain subsequent estimates of c_{pi}.

However with the CORMIX models and with RSB the dilution factors and plume concentrations provided are based strictly on volumetric dilutions and must be corrected for the ambient background. For a first order correction it is possible to assume the rate of dilution is uniform over the rise to the trapping level so that if the ambient concentration is uniform over that depth a simple correction can be applied using Equation 9. In the simple example problem used above to create Figure 5 the pollutant concentration was set at 100 and the ambient concentration was set at a uniform value of 1.6. Thus using a volumetric dilution factor (S_a) of 400 the resulting pollution concentration in the diluted plume computed from Equation 9 would be 1.846 and the effective dilution would be only 54.17! The output from model UM provides the plume concentration along with the volumetric dilution factor. The influence of background on effective dilution is apparent.

Spatial and Temporal Variation of Plume Concentrations

The concentrations of water quality indicators, such as contaminants and desired constituents (e.g., dissolved oxygen) are neither uniform nor steady with respect to the space and time scales involved in regulating the concentrations at the end of the mixing zone. The nonuniformity of constituents in the horizontal extent of an outfall diffuser is generally not investigated and is usually assumed to be uniform, as is the incremental volumetric flux. If nonuniformities along the length of the diffuser are encountered the dilution model can be run for each segment of the diffuser that may be assumed uniform. A separate hydraulic model to compute the distribution of port flows along the length of the diffuser is described in Appendix 2, and is included in the software. Vertical nonuniformity is more commonly encountered in design, performance analysis, and compliance monitoring.

Vertical nonuniformity is important to consider from the standpoint of the constituent

concentrations in the ambient receiving water, i.e., the dilution water mixed with the effluent being discharged. The variations in the vertical are due to physical processes influencing the advection of ambient water into the region of the discharge, and, for some constituents, antecedent biological and chemical processes that have changed the form or concentration of the constituent. Typically, field observations during synoptic surveys are relied on to provide vertical profiles of the water quality indicators. Dissolved oxygen (DO) is an example of one water quality indicator that exhibits vertical nonuniformity in many lake, estuarine, and coastal situations. The concentration of DO in a plume is important to determine because of direct biological effects, and because the strategy for effective regulation of DO at the end of the mixing zone is strongly dependent on the relative influence of effluent constituents and the vertical profile of receiving water constituents. The way in which the dilution models are used to analyze the plume DO concentration illustrates a method for dealing with other ambient nonuniformities.

The Dissolved Oxygen Problem

The DO concentration in a plume is affected by the DO in the effluent, the chemical and biological constituents in the effluent which exert a DO demand, chemical and biological demand factors in the seabed, and by oxygen demand in the water column carried by currents into the region of mixing. The DO demand in the effluent is conveniently represented by the effluent parameter called the Immediate Dissolved Oxygen Demand, IDOD. According to Standard Methods for the Examination of Water and Wastewater (APHA, 1975), IDOD is the amount of oxygen consumed in a 15 minute reaction time. (Later additions of Standard Methods do not include this method because the authors were not able to interpret the significance of the measurement in relation to total oxygen demand.) Since mixing zones established under the EPA regulations for 301(h) permits represent travel times generally of the order of less than 10 minutes, IDOD is a conservative estimate of the mixing zone demand. On this time scale chemical and biological demands in the ambient are inconsequential although for farfield water quality considerations after initial dilution they are frequently decisive. Under these assumptions the concentration of DO in the plume, c_{DO}, is found using the equivalent of Equation 9 with an additional term to represent the immediate demand, viz:

$$c_{DO} = c_{DOa} + \frac{c_{DOe} - IDOD - c_{DOa}}{S_a} \qquad \textbf{(10)}$$

To solve this equation it is necessary to have field data on the c_{DOa} profile; the values of c_{DOe} and IDOD being derived from laboratory analyses. In many cases the c_{DOa} is low near the seabed due to benthic demand, reaches a maximum at an intermediate depth in the water column, and then is constant or slightly decreasing in the near surface layer of the receiving water.

In some coastal regions there are deep permanently anoxic or hypoxic basins. Lakes and reservoirs may also have such basins, perhaps only seasonally. If an outfall is placed in an oxygen-poor basin and the vertical density structure is such that the plume rises into near surface

waters, the resulting DO in the plume will be very nearly the same as the deep water, thus quite likely abrogating a desired DO standard irrespective of the amount of oxygen demand in the effluent. While the violation of the standard is not due to the pollutant discharged in this case, it is due to the discharge of effluent! If aquatic organisms in the surface layers are sensitive to low oxygen concentrations it will matter little to them if the deficit is due to effluent or deep oxygen-poor water forced to the surface by the buoyant effluent. The potential for "forced upwelling" or "effluent pumping", as it has at times been labeled, should be considered in the design of outfalls, both from a standpoint of selecting the site, and of the mechanics influencing the height of rise of the plume. By careful balancing of those design factors which influence final plume concentration, optimum strategies can be developed for achieving ambient standards.

Equation 10 is analogous to Equation VI-7 in EPA's Revised Section 301(h) Technical Support Document (USEPA, 1982). However it is not stated that the tabular listing (page VI-21) of IDOD contributions to the final plume dissolved oxygen concentration are negative contributions.

Recirculation, Quiescent Periods, and Other Temporal Variations

The models reported in Muellenhoff et al.(1985) were steady state models, as are the models used in this report and, as such, they do not take into account temporal variations in any of the variables. For most applications this limitation should not be a problem. In the EPA 301(h) regulations the effective initial dilution is determined for a set of effluent and receiving water conditions that approaches a worst case scenario, that is, there is only a very low probability that there would be physical circumstances under which a predicted final plume concentration would be exceeded. The models can be used repeatedly however to generate a data set for a range of values expected or observed in nature, as done for example to construct Figure 3 showing the effect of different current speeds on volumetric dilution. Although this result is not a time-variable solution to a buoyant plume problem the rate of change in dilution between two current speeds is not an important consideration in regulatory practice, because the effect of current on plume behavior is nearly instantaneous. Thus it is eminently satisfactory to use the steady state model at discrete time steps.

Data sets can be generated to show the frequency distribution of currents and associated dilutions at a discharge site, as in Figure 6 (Baumgartner et al., 1986). From an environmental management perspective it may be important to investigate the distribution of dilutions achieved as a result of seasonal changes. Figure 7 shows the monthly distribution of initial dilution values calculated by UMERGE (Muellenhoff et al., 1985) for incremental changes in tidal currents superimposed on a steady longshore current for a typical U.S. west coast discharge site.

The dramatic effect of current speed, in this case the effect of tidal current, shown in Figure 7 demonstrates that most of the time dilutions at the end of the buoyant plume phase will be greater than in the critical case used to specify permit conditions. In this example the critical dilution appears to be about 35 whereas every month there are values greater than 100. When

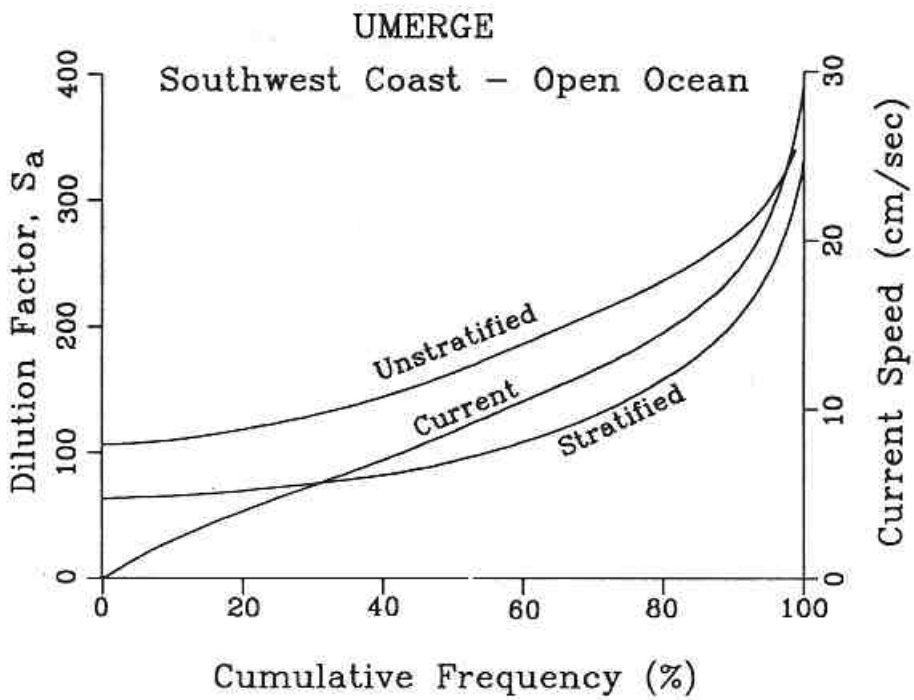

Figure 6. Dilution and current frequency.

field monitoring of the effluent concentrations is required it is important to recognize the range of values that might be expected due to the range of ambient currents occurring as well as variations in the effluent as it leaves the treatment plant.

Just as easily as Figure 7 was generated, a computer code external to the model could be developed to generate a data set of dilutions resulting from variations of other variables, such as wastewater flow and density stratification in the receiving water. Figure 8 is an example of a response surface developed using UM to show the effect, either singly or combined, of variation in the densimetric Froude number, *F*, and the stratification number, *SP*. The Froude number is a convenient way to independently investigate variation in either wastewater flow or the design diameter of the effluent ports in this graphic.

Similar graphical representations of any three selected variables can be useful in analysis, however, there are limitations of unknown importance if the variables chosen are not independent. For example, although it would be possible to construct a response surface for dilution, current speed, and density gradient, which would be accurate in the abstract sense of these variables being independent in the model formulation, it is not likely that the range of density gradients chosen would in nature be entirely independent of the current speed.

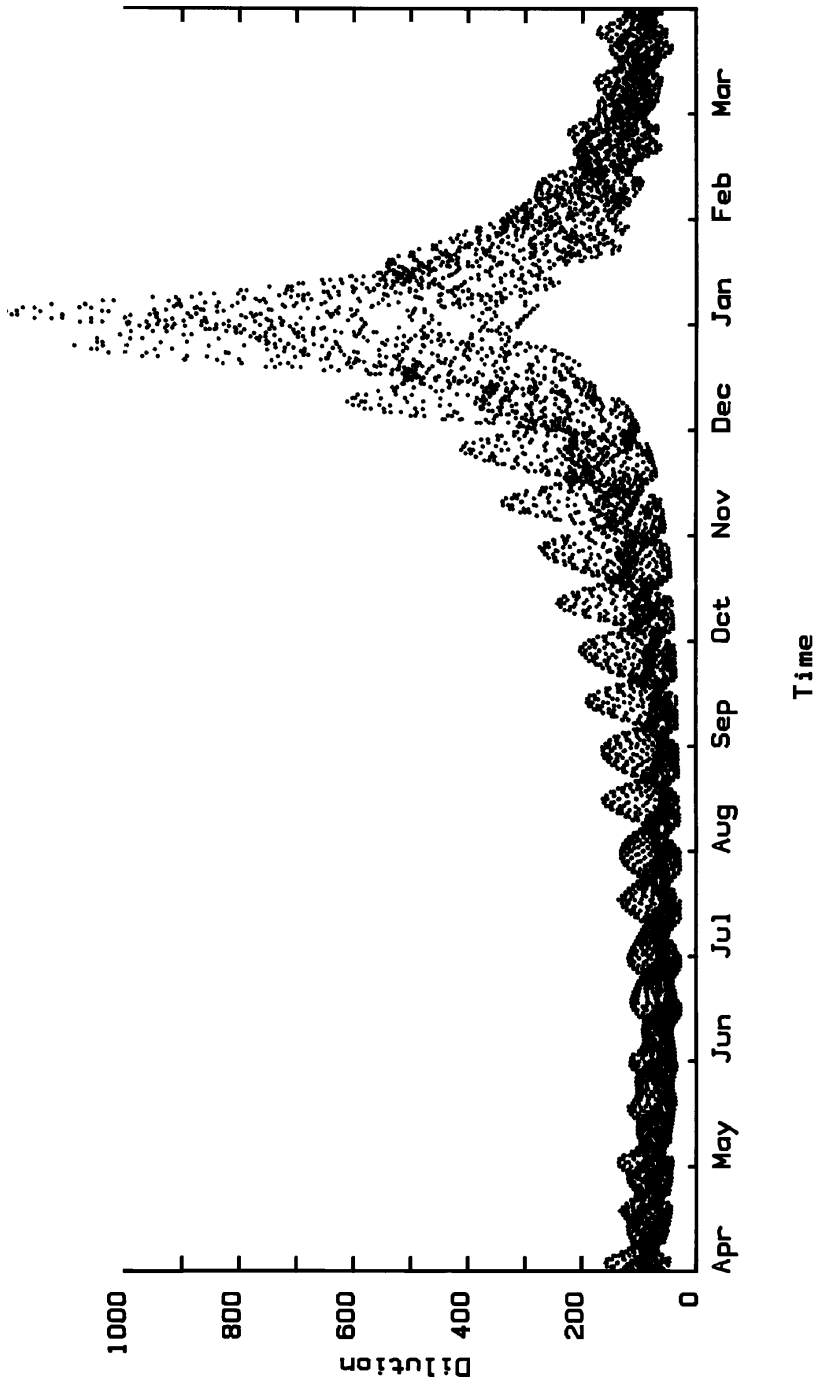

Figure 7. Simulated annual variation in dilution.

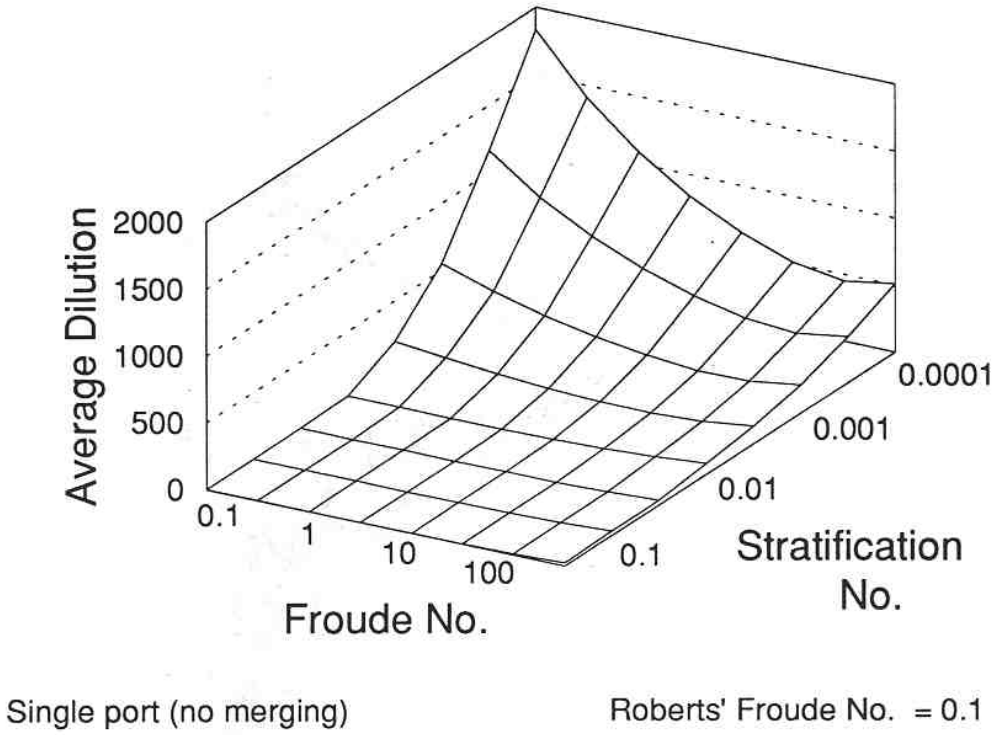

Figure 8. UM dilution response surface in weak current (Roberts' Froude number = 0.1) as a function of Froude number and stratification..

Effect of Wastewater Flow on Dilution

Depending on the densimetric Froude number at the discharge port, the effect of increased effluent flow per port on dilution can be shown to be detrimental, insignificant, or favorable. With low Froude numbers as frequently found with municipal ocean outfalls, an increase in flow causes a decrease in dilution, while at higher Froude numbers, as might be found with modern power plant cooling water discharges, an increase in discharge results in an increase in dilution. According to Rawn, Bowerman, and Brooks (1960), the 1930 data from the Los Angeles outfall provided a guide to the conditions under which the transition occurs (see Figure 9).

If density stratification or shallow water prevents the plume from rising very far, the transition to increased dilution is seen in this graph to occur at lower Froude numbers. This reflects the importance of high jet-like plume velocity near the discharge causing an increased rate of entrainment and a greater horizontal travel before reaching the trapping level or the surface. In deep water the vertical travel of the plume and the entrainment caused by buoyancy over the major portion of the travel distance play an increasingly greater role than conditions near

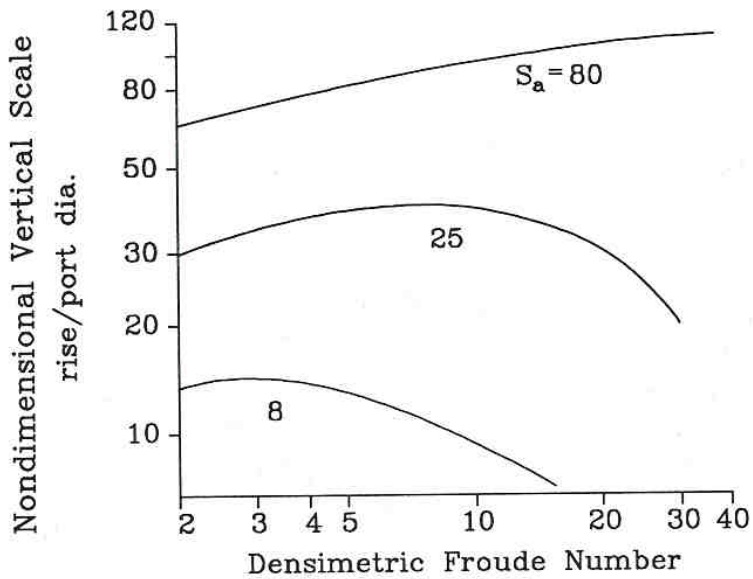

Figure 9. Examples of plume rise, dilution (S_a), and densimetric Froude number (effluent flow) relationships for horizontal discharges (after Rawn, Bowerman, and Brooks, 1960)..

the port in determining the final dilution. In deep water the transition to increased dilutions would be seen only at very high effluent flows.

An example of the effect of wastewater discharge flow on dilution can be seen on the response surface in Figure 10 which has been created from multiple runs of the model UM. For this example the effluent flow rate was increased from 4.65 MGD to 46.5 MGD during simulated conditions of low current and moderate stratification. The increased flow rate resulted in an increase of the densimetric Froude number from 3.16 to 31.6, and a decrease in the Roberts' Froude number from 0.1 to 0.01. By graphically transposing the starting and ending points of the arrow shown on the response surface to the dilution scale it is seen that the dilution would be reduced from approximately 150 to 60.

Actual model output for an example of this type is shown in Appendix 3. The dilutions calculated at maximum rise for these flow rates (cases 1 and 4) agree with the graphical results, however, the output provides a warning that the dilutions are overestimated due to "overlap" of the plume trajectory, an anomalous mathematical behavior noted under some conditions of current, stratification and effluent flow rate (Frick, Baumgartner, and Fox, 1994). See additional explanation in the chapter on UM Model Theory.

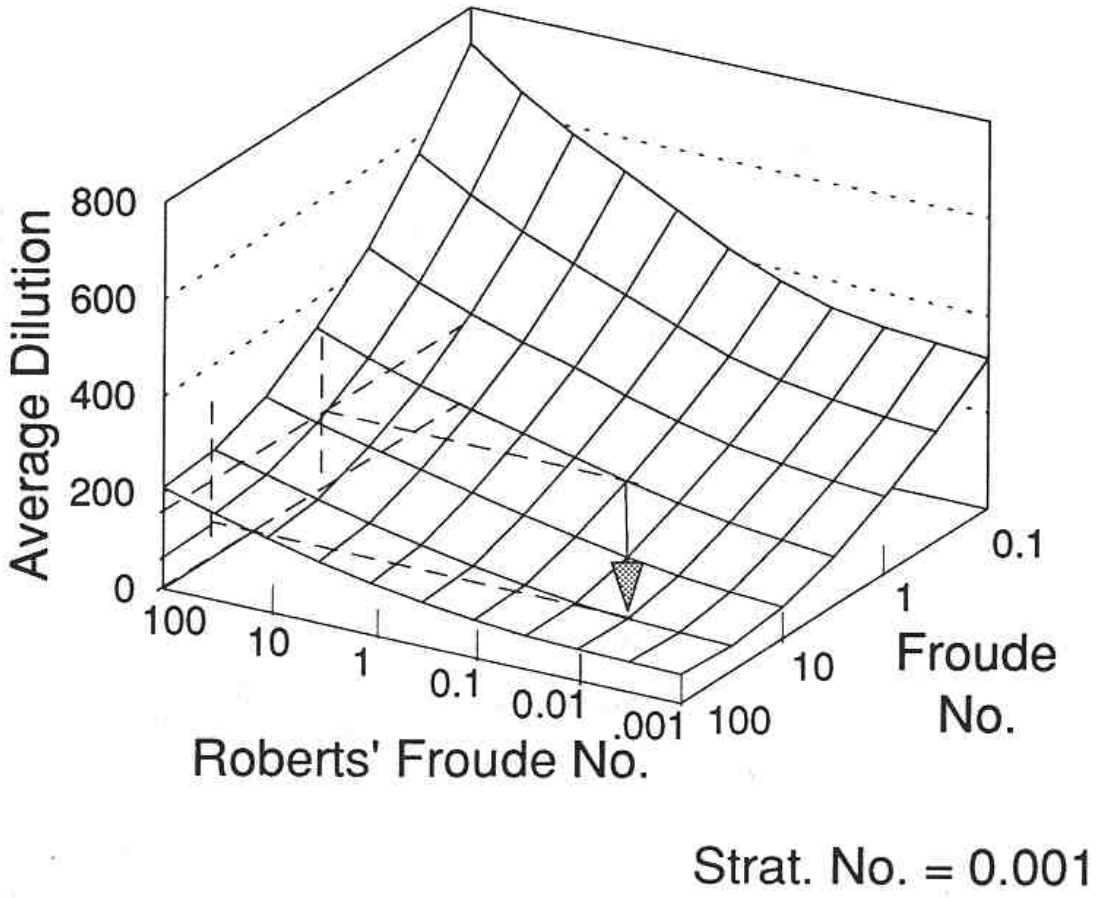

Figure 10. Dilution response surface as a function of Roberts' Froude number and the densimetric Froude number.

A similar response surface could be generated to represent dilutions at the point in the plume trajectory where overlap begins, or to maximum rise whichever occurs first. For this example the results would have been graphically similar to the UM output of Appendix 3 summarized in Table 1. Table 1 also shows output from model RSB, although there are cautionary messages provided in this output also. (RSB output is not shown in Appendix 3).

Depth as a Factor

Depth as a governing factor in the effective placement of ocean outfalls has taken on significance that is not always warranted. It is true that all other things being equal, the greater the extent of vertical travel experienced by the plume, the greater is the amount of entrainment. If a location is chosen with greater depth but poorer circulation, the net result may be less effective dilution of wastes than placement in a shallower but more open coastal area. This is the major

concern with placement of outfalls in fjords, embayments, and, in some cases, estuaries, but this consideration must also be kept in mind when canyons, trenches, and deep basins offshore are considered as outfall sites. The implications for seabed accumulation of effluent particulate matter may be more important in the long run than the water column implications of re-entrained effluent.

Table I. Dilution factor, S_a, predicted by UM and RSB effluent flow.

Q (MGD)	Dilution Factor UM	RSB
4.65	89.3	88.5
10.0	70.1	68.2
21.6	58.1	52.8
46.5	53.7	40.9

Offshore Distance and Depth

The rationale for great depth as a factor in design of ocean outfalls seems to have been recognized empirically as a result of observations by A. M. Rawn on the Los Angeles outfall built in 1937 (Pomeroy, 1960). The primary consideration evidently was to reduce nearshore pollutant (coliform) concentrations through greater travel times, and thus more die-off, associated with outfalls further offshore. Greater depth, at least in the Southern California Bight was a gratuitous benefit of offshore distance. Through thoughtful analysis of monitoring data Rawn and coworkers recognized that lower beach coliform counts in the summer were in large part related to summer density stratification at the discharge site. In designs for subsequent outfalls submergence of the diluted sewage field was a conscious objective in addition to distance from shore (Brooks, 1956). This dependence on depth took on unique significance in the early legislative history of the 301(h) amendment, and was even proposed as the basis for granting waivers in estuaries! EPA scientists suggested that physical criteria relating to effective seaward displacement of pollutants from estuaries would be necessary in addition to depth and these were then included in the final language.

Submerged Drift Flow, Upwelling, Wind Drift

The practice of designing diffusers to retain the drift field in the pycnocline, a region of large vertical gradient in density, below a surface layer may result in adverse implications for nearshore water quality due to characteristic upwelling of deep water along some major continental margins. This may not be a problem in the Southern California Bight, but needs to be considered when exporting southern California technology to other locations. It has been mentioned as a factor to be considered in outfall designs for the Oregon coast (Behlke and Burgess, 1964). The concentration of contaminants carried nearshore may be higher than if the outfall had been designed to take advantage of greater dilution offered by the full depth of water. This is a tradeoff to be considered in light of the potential damage caused by onshore drift of surface waters under prevailing winds in certain parts of the year.

By careful attention to wind, current and density patterns, it may be possible to design an outfall so that the plume is submerged when there is the least chance of upwelling, and above the pycnocline when there is the least chance of onshore winds. Most outfalls do not have the design

or operational luxury to allow for opening or closing some of the ports. For those that do there is an additional option for adjusting the height of rise of the diluted plume.

Dye Tracing of Plumes

Dye tracing is a well known technique used in hydraulic models and prototype outfall settings, although the cost of added tracers in prototype situations is considerable because of the large volumetric flow rates and large dilutions usually achieved within several tidal cycles. The rate of dye addition (Q_d) to the effluent flow v_e needed to provide a dye concentration of c_d following dilution of S_a is:

$$Q_d = \frac{v_e \; c_d \; \alpha_a \; S_a}{W \; \alpha_d} \qquad \textbf{(11)}$$

where
α_a = specific gravity of diluted plume
α_d = specific gravity of dye solution
W = weight fraction of dye in stock solution.

The required dye rate in gallons per hour is shown in Figure 11 for various dilution factors and effluent flows in MGD to achieve an ambient dye concentration of 1 ppb. Figure 11 is computed by dividing Equation 11 by 2.4×10^4. Rhodamine WT, typically used in dye studies, is available as a 20 % solution (α_d = 1.19) in small (15 gallon) drums.

Spatial Averages and Discrete Values

Some buoyant plume models produce dilution factors in terms of the centerline concentration, sometimes referred to as the "minimum" dilution for the cross section of the plume at a given distance downstream from the orifice. As the plume radius continues to expand with increasing distance, the minimum dilution progressively increases. For example the centerline (minimum) dilution at a distance of 6 meters from the diffuser port may be 6 while 10 meters from the orifice the minimum dilution would be more like 9. Some models calculate an average dilution for the cross section of the plume and this of course also increases downstream. The average dilution is always larger than the minimum dilution. The appropriate average is termed the flux-average dilution found by weighting the concentration distribution by the velocity distribution over the cross section of the plume.

In some models the physics of the dilution process is based on the centerline mass concentration so that the resulting calculation of average dilution is external to the physics. That is, if a modeler assumes the effective width of a single round plume is defined by the five percentile value of a Gaussian distribution, the average dilution will be less than if the 33 percentile value is chosen. In either case the centerline concentration would be the same. For this

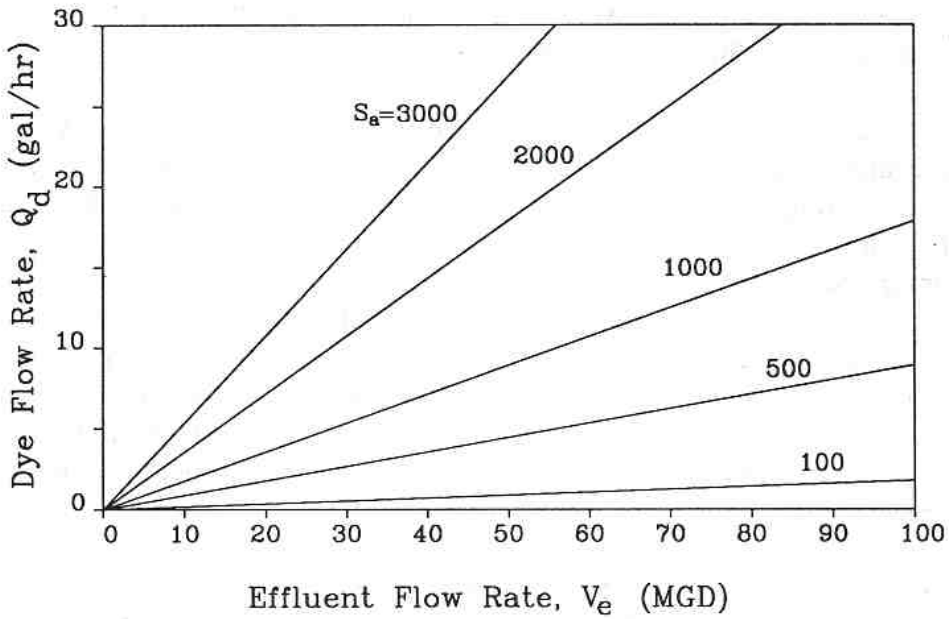

Figure 11. Dye flow rate to achieve 1 ppb in seawater with 20 % Rhodamine WT.

reason they prefer to compare model results in terms of the centerline value rather than average values. However, both values need to be considered in field or lab verification studies, and both values may be useful for regulatory purposes.

In other models a uniform cross sectional or average concentration (referred to as a "top hat" profile) equivalent to the centerline concentration is assumed. Thus, UM uses an assumed profile to help establish minimum dilutions from predicted model average dilutions. The relationship between the profiles is discussed further in following chapters: "Example: A CORMIX1 Comparison, Density, and Stability," and "UM Model Theory." While minimum dilutions are often of interest to regulators, average dilutions are especially consistent with the dynamic requirements of plume theory (Frick, 1984).

Regulatory Use

Regulatory interest may be appropriately directed toward both average values and discrete values. Unfortunately the state of the art of regulatory practice is not as sophisticated as plume modeling and is generally constrained by lack of information on the temporal and spatial scales of aquatic organisms' responses to exposure conditions in natural settings. For some parameters California (State Water Resources Control Board, 1988) and the USEPA (1986) specify maximum allowable instantaneous and several temporal average values. If an applicable criterion for a

certain biological resource near the outfall is an instantaneous value, a discrete value obtained over 5 to 30 seconds, as could be achieved by sampling methods used for plume studies in the field, would be appropriate. Many such samples would be taken to attempt to find the highest concentration of pollutants, i.e., the centerline value.

Additionally it might be argued that a biological resource at risk at any moment is appropriately evaluated over an expanse of space so that a spatial average is required, again evaluated in a short time period. The time period over which this averaging would take place is unfortunately not easily defined in relation to "instantaneous". It certainly is not seconds because it is impractical to acquire these data synoptically across the expanse of even one plume diameter let alone a multiport diffuser. If the data are obtained in an hour or two during slack tide, calm seas, and low currents, it is possible that the values will not be greatly different from one plume to the next in the same diffuser. Depending on the biology of the resource, either the maximum concentration (the minimum dilution) or the flux average dilution might be the appropriate value to use in determining compliance with "instantaneous" criteria applied to a spatial resource expanse.

Criteria that are expressed in terms of temporal averages (daily to semi-annual) suggest that plume concentrations be assessed extensively in three dimensions, both at the boundary of the mixing zone and in some cases at sensitive biological resource locations down-current. Current speed and direction play significant roles when assessing the concentrations at the boundary.

By incorporating data on the cyclical variation of effluent composition, density profiles, and current direction it is possible to construct a running six month average (or median) for a number of points on the mixing zone boundary. The six month average is expected to be quite variable at these points, and the point with the highest exposure frequency may not have the highest average concentration.

Beyond the mixing zone there may be regions where current streams of diluted effluent, leaving the zone at different times in different directions, would converge over a reef, a kelp forest, or a swimming area. Thus if frequency and duration are important exposure characteristics in resource response, the exposure may be more critical even if the concentration (intensity) is lower, as it almost surely will be. In this case current direction is important to understand on a larger scale so that circulation patterns are evaluated. Some formal applications of this "visitation frequency" approach (Figure 12) have been used in regulatory assessment of criteria that are presumably "instantaneous" (Roberts, 1990). Depending on the size and nature of the resource to be protected either discrete or spatially averaged values might be appropriate.

The regulatory authority may not need to prescribe specific criteria for each of several segments along the mixing zone boundary. More likely they will be interested only in the highest six month average concentration wherever and whenever it occurs. Thus the formal methods for determining a relationship between frequency of occurrence, intensity of the stress (concentration), and duration of the exposure for plume performance at the mixing zone boundary are not rigorously established. However, designers, environmental scientists, and regulators should assess

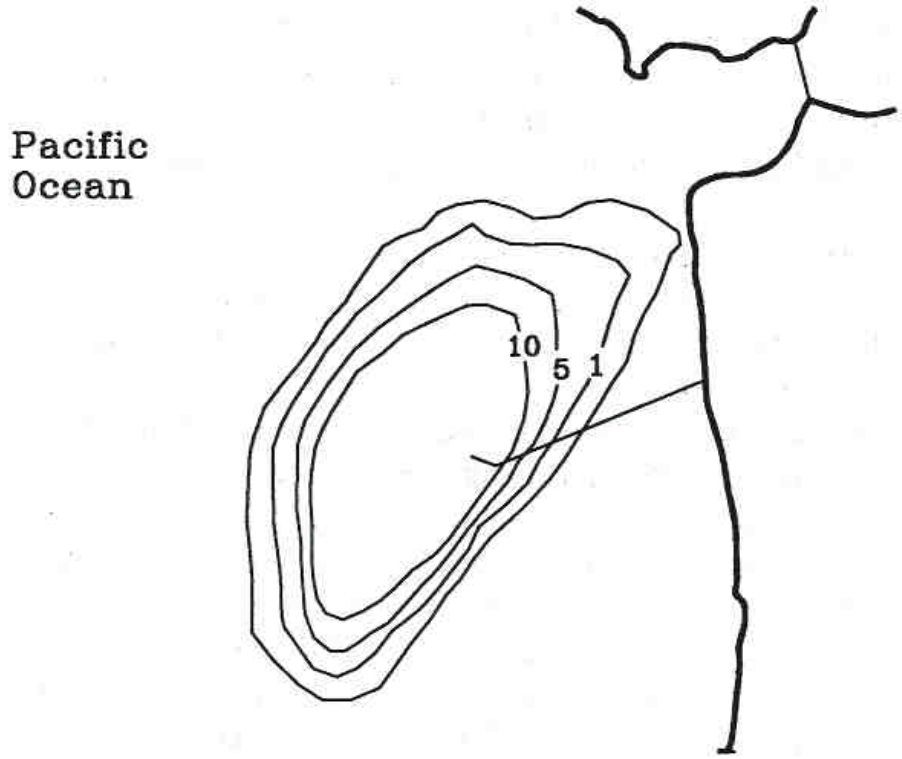

Figure 12. Visitation frequency (percent) of effluent about the San Francisco Southwest Ocean Outfall.

these performance characteristics conceptually, and possibly with a well chosen suite of model simulations, to conscientiously achieve responsible regulations and to guide improvements in the state of the art. USEPA (1986) provides a method to evaluate the appropriate relationship for ammonia in freshwater streams, which may be taken as an indication that frequency, intensity, duration relationships developed for evaluating outfall performance would be useful in improving regulatory practice.

Aside from the question of whether discrete values or cross sectional averages are used to test compliance with criteria, the way in which field samples are used to verify or compare with model results is an important consideration.

Verification Sampling

In laboratory or field verification studies of plume performance the average value is measured or captured in a sample bottle only by chance. Characteristically the field value measured is from a very small spatial region and represents a signal over a certain time span. A large number of samples is sought from the same cross section in order to arithmetically compute an average. In the laboratory, using a single plume, this is relatively easy to do. But in the field where multiple

plumes are usually involved, and a moving flow field too deep below the surface to see is being sampled by a moving sampler from a moving boat, it is quite uncertain what portion of the cross section the value represents. Attempts to acquire a large number of samples from a different radial position of the same cross section are frustrated because of the relative horizontal motions involved. Surface waves and possibly internal waves in the pycnocline can also cause the sample to be obtained from a shallower or deeper cross section.

For these reasons field verification studies are best attempted for a cross section as far from the orifice as practical as long as the region is still within the range where the buoyant plume physics apply. Nearer to the orifice the values are changing more rapidly and the dimensions of the plume are much smaller, making it much harder to get the sampler in the right place, or even in the plume. In addition it is best to conduct the study when currents are low so that the plume rises nearest to the surface, shortening the interval between samples, as the sampling device need not be lowered so far. Placement of the sampling device may be improved because it may even be possible to see the plume. Aside from the use of the data for verification of the physics, samples taken during low currents may be especially useful for verification of regulatory compliance. Field verification data taken near the end of the initial dilution region can be compared with controlled laboratory simulations for similar conditions, and then, if necessary, the laboratory verification data can be relied upon for estimation of field values closer to the orifice.

ENTRAINMENT FROM OTHER SOURCES AND RE-ENTRAINMENT

Regulatory Background

In drafting modifications to the Federal Water Pollution Control Act (Anon., 1982), the United States Senate (Anon., 1983) proposed strengthening the authority of the Environmental Protection Agency (EPA) to deny waivers from secondary treatment for publicly owned treatment works (POTWs) discharging partially treated wastes into estuaries. Concern was expressed for re-entrainment of contaminants discharged previously from the POTW under consideration, and also for entrainment of contaminants discharged by other sources. Amendments to section 301(h) of the Act appearing in section 303 of the Water Quality Act (WQA) of 1987 (Anon., 1987) addressed these concerns:

> Section 301(h) is amended by striking out "such modified requirements will not interfere" and inserting in lieu thereof "....will not interfere, alone or in combination with pollutants from other sources..."

and further on:

> Section 301(h) is further amended by adding "....marine waters must exhibit characteristics assuring that water providing dilution does not contain significant amounts of previously discharged effluent from such treatment works."

These amendments suggested that EPA would need to revise the methods used to calculate compliance with water quality standards at and beyond the boundary of a mixing zone. Three topics needed to be addressed:

1. Definition of "significant amounts"
2. Entrainment of contaminants from other sources
3. Re-entrainment of contaminants from the proposed discharge

The water quality standard to be met is most easily assessed if it is expressed in terms of a concentration of a pollutant, i.e., a numerical criterion. For example, the California Ocean Plan (State Water Resources Control Board, 1988) contains such limitations, a few of which are listed in Table II, along with background seawater concentrations. The questions raised by the 1987 WQA amendments concern the proper value to use for the ambient (background) concentration

Table II. Concentrations of contaminants in coastal waters of California.

Contaminant	Allowable Instantaneous Maximum, C_{si}	Background Seawater Concentration
Arsenic	80 ug/l	3 ug/l
Mercury	0.4 ug/l	0.0005 ug/l
Silver	7 ug/l	0.16 ug/l
Zinc	200 ug/l	8 ug/l
Ammonia (N)	6000 ug/l	0
Toxaphene	0.021 ug/l	0
DDT and derivatives	0.003 ug/l	0

for certain environmental settings, and how much is too much for a given discharge.

Significant Amounts

The definition of significant amounts is easily resolved by use of mathematical models such as UM. That is, significance, in the sense of "importance", rather than a statistically computed value, is eloquently expressed in the test of compliance against a numerical standard in this model. If for a given setting Equation 9 provides values of c_{pi} that are lower than the values of c_{si}, then indeed the diluting water does not contain significant amounts of previously discharged effluent. Thus the question of how much re-entrained effluent is allowable is operationally defined with the types of models that were already in use in 1987, and at least for this purpose the 1987 revisions did not require a change in the models or their application. The major question is, "What is the proper value to use for each c_{ai}?"

Relationship of Ambient Dilution Water to Plume Concentrations

The following discussions is intended to show that the amount of effluent that is allowed to be re-entrained is a variable amount depending on the value of the standard, the amount of the contaminant in the effluent, and the volume of entrained diluting water. This can be seen by rearranging the terms of Equation 8 as follows:

$$c_{p_i} = \frac{c_{e_i}}{S_a} + \frac{c_{a_i}\,(S_a - 1)}{S_a} \qquad \textbf{(12)}$$

The requirement that the plume concentration of contaminant be less than the standard for each contaminant can be expressed in the following inequality:

$$c_{p_i} < c_{s_i} \qquad \textbf{(13)}$$

where c_{si} is the numerical value for the ith standard. Substituting the expression for c_{pi} from Equation 12 into Equation 13

$$\frac{c_{e_i}}{S_a} + \frac{c_{a_i}\,(S_a - 1)}{S_a} < c_{s_i} \qquad \textbf{(14)}$$

For cases where the ratio $(c_{ai}/c_{si})/S_a$ is less than 0.02 there would be less than a 3 % error writing Equation 14 as:

$$\frac{c_{e_i}}{S_a} < c_{s_i} - c_{a_i} \qquad \textbf{(15)}$$

Whether Equation 14 or Equation 15 is used, it is helpful to visualize the initial dilution requirement in this form for three reasons. First, it clearly shows that a certain standard may be met with different sets of values for S_a, c_{ei} and c_{ai}. For example, if one effluent has an ammonia nitrogen concentration of 120 mg/l and the local ambient is 3.9 mg/l, the California instantaneous allowable maximum of 6 mg/l would be met if an S_a of 60 were achieved. Another outfall, or the same outfall at a different time, achieving an S_a of 60 could meet the standard with an effluent value of 305 mg/l if the local ambient were 0.9 mg/l!

Second, the value of the ambient concentration is seen to be of the same relative importance as the designated standard value in determining compliance. Thus if one locality has a standard one unit higher than another, but the ambient is also one higher, the necessary ratio of c_{ei}/S_a is the same. In other words, both dischargers have theoretically the identical options of reducing c_{ei} or building a more efficient diffuser or any favorable combination of these options. And if one locality has a standard one unit higher, and an ambient one unit lower, the discharger at this

location would have to meet a less stringent ratio of c_{ei} / S_a, i.e., it is two units higher. This relationship is shown in Figure 13.

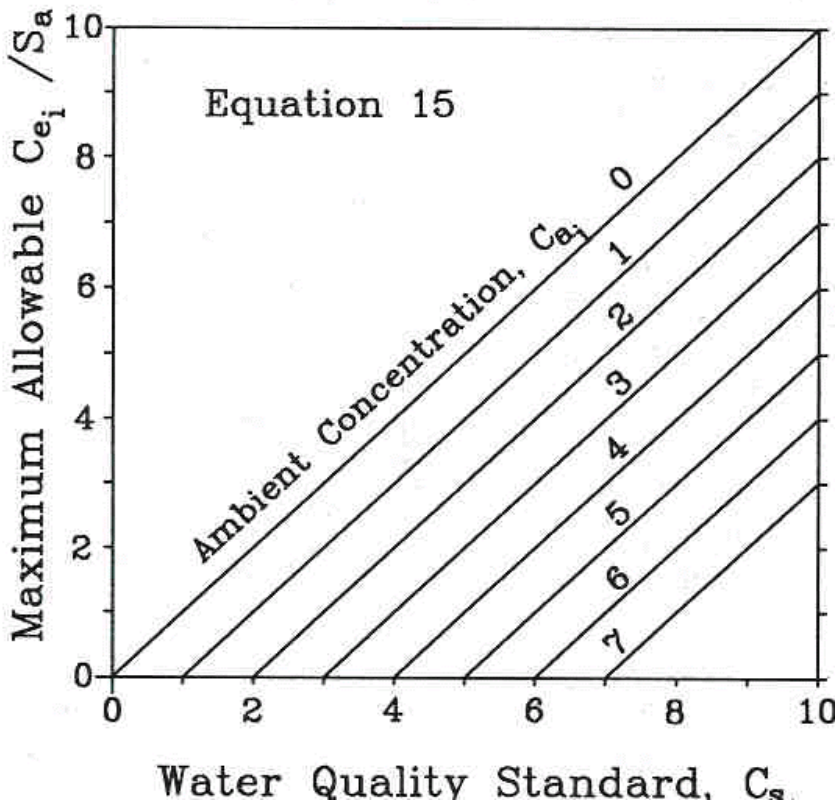

Figure 13. Maximum ratio of effluent concentration to S_a for standard compliance and dependence on ambient concentration.

Third, notice that S_a is not subscripted with an "*i*" meaning that S_a is not dependent on the contaminant under consideration, as explained previously. It may be helpful to think of a "contaminant specific effective initial dilution" as the ratio of the concentration of a specific contaminant in the effluent to the concentration resulting after the volumetric process of critical initial dilution is achieved, i.e., c_{ei} / c_{pi}. By rearranging Equation 12 and again accepting an error no greater than 3 % for dilution factors greater than 30, Equation 12 becomes:

$$\frac{c_{e_i}}{c_{p_i}} = \frac{1}{\frac{1}{S_a} + \frac{c_{a_i}}{c_{e_i}}} \qquad \textbf{(16)}$$

Expressed in this way it is clear that the effective dilution of the specific contaminant, limited by regulation to less than a given numerical standard, depends on both S_a and the ratio c_{ai} / c_{ei}. Figure 14 graphically depicts that the ratio c_{ei} / c_{pi}, the contaminant specific effective initial dilution, is dramatically reduced below S_a as the ratio c_{ai} / c_{ei} increases.

This analysis has shown that the computational technique employed to test compliance with numerical water quality standards does take into consideration the entrainment of contaminants existing in the ambient dilution water. Thus the Senate revisions, contrary to first impressions, did not require a change in the EPA evaluation procedures to determine "significant amounts" of previously discharged effluents.

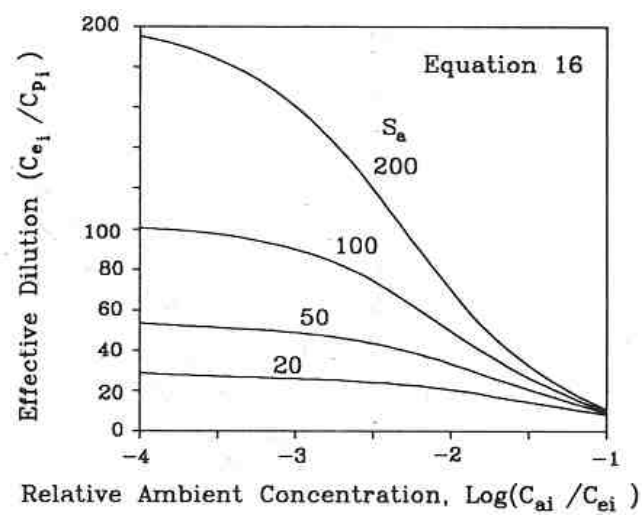

Figure 14. Effect of ambient concentration on effective dilution.

What is yet to be shown is how the value of c_{ai} may be determined or estimated to reflect the influence of other discharges nearby. The first requirement is for regulatory instructions to explain clearly that c_{ai} must accurately reflect the quality of the water entrained, i.e., the water adjacent to the diffuser, not the water at some remote, pristine location. Thus, for example, the "ambient" values in Table II are not likely to be generally useful, and may be inaccurate for California coastal discharges.

Entrainment From Other Sources

In the case of existing discharges it is not necessary to employ mathematical models to assess the amount of entrainment from other sources, and the amount of re-entrainment of previously discharged effluent, because field monitoring data will reflect the combined result of these factors. A priori assessment is needed in cases where a major change in effluent quality is proposed, or the

outfall is to be modified or relocated, and models are useful for this purpose.

In the preceding sections it is shown that the effect of entrainment from other sources is properly incorporated in mathematical models such as UM as long as a proper data set for the ambient concentration of specific contaminants is used for input. Data available for an existing outfall may be useful for the relocated site if it is within the region covered by sampling stations, and sufficient vertical detail is provided in the data set. The presumption is that the new site or the modified outfall (e.g., longer or more ports) would provide better critical initial dilution. Since the data set would reflect both entrainment from other sources as well as re-entrainment of effluent, the data set would provide a conservative estimate. If the new site is outside the region sampled, new monitoring stations could be established and coastal circulation models could be employed to assess transport of pollutants from known sources in the region.

Entrainment into the plume of an outfall from other point and nonpoint sources is not generally a problem in the open ocean because of many factors. In most cases there is a large distance between point sources, providing ample opportunity for diluted waste to be dispersed and carried away from the region of entrainment of another outfall. Also, the volume of nonpoint sources of pollutants discharged directly to the ocean is small. Greater care is now given to locate modern ocean outfalls in well-flushed offshore environments rather than near shore. The volume of coastal waters available for dilution of point and nonpoint sources is great. For example, a 100 km section of coastal shelf out to a distance of 10 km with an average depth of 25 meters contains 25×10^9 m^3 of water, about 5000 times the daily effluent flow that might be generated by a municipality of 10 million people.

For a simple generalized case of contaminants transported from a source, for example another outfall, the concentration contributing to the ambient at the new site can be determined from Equation 17 (Brooks, 1960):

$$c_{\max} \;'\; c_{p_i}\, erf\left(\sqrt{\frac{U\, b^2}{16\, \varepsilon_o\, X}}\right) \qquad \textbf{(17)}$$

where

c_{pi} = Plume concentration at the end of initial dilution
c_{max} = Centerline (maximum) concentration at distance X
$erf(\ )$ = Standard error function of ( )
U = Current speed in the X direction
b = Width in the Y direction (orthogonal to X) at the end of initial dilution
ε_o = Constant Horizontal (Y direction) eddy diffusivity
X = Travel distance

Computed in this way, c_{max} is a conservative estimate for open coastal environments, and an appropriate estimate for near coastal and inshore waters. In some open coastal situations the farfield centerline dilution, c_{max}, is appropriately estimated using a 4/3 power law to continuously

increase the coefficient of lateral dispersion as the width of the field increases (Okubo, 1962). Further details, including the relationship between ε_o and the farfield diffusion coefficient input in PLUMES, are given in the chapter entitled "Farfield Algorithm."

PLUMES automatically computes the farfield centerline dilutions according to both equations, providing a table of output data under column headings "4/3 Power Law" and "Const Eddy Diff". Corresponding data columns provide the centerline farfield pollutant concentrations using the first order decay coefficient (or T-90) provided by the user, however, the RSB model does not calculate decay in the near field. If ambient concentrations are specified they are factored into the mass balance as ambient fluid is entrained and they are subject to first order decay as well. (Again, RSB does not include ambient concentration in the near field).

In other cases, for example involving ULINE predictions, these dilution factors would assume negligible contribution from contaminants in the ambient water, thus they must be reduced to represent the effective dilution at the down-current site. Figure 14 can be used for this purpose, substituting c_{pi} for c_{ei} in the abscissa term and c_{pi}/c_{max} for c_{ei}/c_{pi} in the ordinate term. These dilution factors are minimums, that is, a cross-field functional form such as a Gaussian curve should be used to estimate the cross sectional average.

It must be recognized that the dispersing plume from one outfall will contaminate near surface waters while the principal source of entrainment for another plume is the deeper waters. Verified two-layer circulation models for the coastal segment under consideration may be useful to estimate the vertical exchange of contaminants as well as horizontal migration, thus providing an estimate of distant deep water quality.

Diffuse source inputs and episodic events are difficult to deal with in assessing the quality of ambient water expected to be entrained into new outfalls. During major storms that may occur as frequently as two or three times per year in the northeast and northwest, annually in the southeast, and perhaps once in ten years in the southwest, (1983 in the Los Angeles Bight, 1988 in Hawaii), storm runoff flushes riverine and estuarine contaminants into the coastal waters. Wind driven currents and waves re-suspend coastal sediments and distribute contaminants throughout the waters of the nearshore continental shelf, in many cases causing impairment of water quality entrained into ocean outfall plumes.

Mathematical models of coastal circulation may be able to predict dispersion of a given slug of contaminants washed out of an estuary up the coast from an outfall. Under storm conditions large dilution factors would be expected, however it is unlikely data are available to quantify contaminant levels in estuarine discharges. Direct land runoff and runoff from combined and storm sewers discharging directly to the ocean complicate both the analysis of transport and dispersion calculations as well as specification of contaminant levels.

Single-layer circulation models are likely to be inadequate in assessing runoff related effects. Depending on the concentration of dissolved and suspended materials, the bulk density of the runoff-contaminated coastal waters may be sufficiently low so that a short time after subsidence

of the storm, deep denser offshore water will gradually move in toward shore and the turbid storm water will be carried in a thinner lens on or near the surface. Since a large percentage of the water entrained into the plume occurs at depth, there may be considerably less entrainment of contaminated storm water into the plume than would appear to be the case as one views the situation from the surface (or from the air). Mathematical models of coastal circulation may not be as useful for the period just on the heels of the storm event because of the difficulty in dealing with multi-layer flows in the high energy coastal environments. Because of the importance of entrainment at depth in achieving the proper degree of initial dilution before reaching the level of buoyant equilibrium, it is not appropriate to use a one-layer model which assumes the water column is completely well mixed under conditions of low currents.

During the storm event it is reasonable to expect that water quality values related to human use of the marine resource in the vicinity of the outfall might well be suspended de facto. For example, sport fishing and scuba diving are not likely to be engaged in near the outfall during a coastal storm. Consequently no harm is expected to be done to this use if effective dilution during the storm is impaired by entrainment of poor quality ambient water.

No references have been identified describing the behavior of marine organisms during storm events and their response to the mixture of effluent and runoff constituents. Their sensitivity must be considered irrespective of the suspension of human uses. There may be sufficient resiliency in coastal ecosystems so that short period perturbations can be accommodated. The incremental perturbation due to entrainment of runoff-contaminated ambient may be either small or large compared to average shelf conditions, depending on the circumstances of each event and each locality. It should be recognized, however, that even with entrainment of contaminated dilution water, the amount of dilution will be significantly increased over that predicted by conservative plume assessments specified by EPA due to the much greater energy dissipation occurring during storms. The net effect may be that organisms will experience a much lower concentration of pollutants during a storm than in the average case.

Given the concern over the inapplicability of models for the complex cases of shelf advection of pollutants in a variety of conditions, monitoring data may be the best option for estimating ambient quality under all conditions. In light of the generally poor water quality data base available in coastal shelf areas, if there is indeed a national priority for improvement of methods to estimate entrainment of other sources into extant outfall dilution fields, there is an opportunity to build a monitoring network that will serve a host of other highly important coastal resource issues. A report of a panel convened by the Marine Board (Eichbaum et al., 1990) contains recommendations for improvements in this area.

One important advantage of the use of field data to determine the quality of dilution water over the use of model simulations is that it is an operationally responsive approach. As new data are obtained, management options for control of the point source or the remote source, or both, can be balanced.

Re-entrainment from Existing Discharge

In addition to contamination of dilution water from other sources there are circumstances under which an existing discharge can re-entrain a portion of previously discharged effluent. However, the farther offshore an outfall is located the less this is likely to be a problem. Coastal currents and winds, which dominate replenishment of coastal waters with relatively clean offshore water, are not likely to be suppressed to the extent that flushing of diluted effluents is materially impeded for long periods of time. Under critical conditions of low wind and current, diluted effluents rise to the surface or to a level of buoyant equilibrium in the pycnocline. Water which is entrained between the discharge on the seabed and the spreading layer is not contaminated with previously discharged effluent due to the density stratification, thus C_a is not increasing with time. Tidal currents typically have a rotational character so that previously discharged effluent is carried some distance inshore on one reversal past the discharge point and offshore past the diffuser on the next reversal. Again, under stratified, low current conditions the effluent rises nearly to the surface or at least into the upper mixed layer. It does not remain at depth where the majority of entrainment takes place.

In shallow coastal settings where some outfalls historically had been placed, vertical turbulence is sufficient to reduce the degree of density stratification. If the discharge site happens to be between headlands the replenishment of shelf water by deep ocean water may be significantly restricted. In either of these settings partially diluted effluent can be returned to the deeper water levels and effective dilution can be substantially reduced. EPA has provided the model DECAL (Tetra Tech, 1987) to deal with this problem in a general coastal setting, i.e., not necessarily near shore, however it is restricted to cases where vertical turbulence is sufficient to cause complete vertical mixing near the outfall. Coastal circulation models and monitoring data as discussed in preceding sections may be used for these cases as well.

Relocation of the terminal end of an outfall to a site further offshore is frequently considered among the options to reduce environmental impacts of wastewater disposal. Another possible scenario for relocation of an outfall is lateral displacement upcoast or downcoast from the present location at about the same distance offshore. The rationale might be to minimize distance to the location of a new treatment plant, or any number of water and sediment quality considerations. If topographic and bathymetric features are similar at the former and proposed site, the circulation features will be similar. Re-entrainment could then be estimated taking into account any differences associated with the characteristics of the new diffuser. Monitoring data on conditions around the outfall to be replaced would be useful in estimating the degree of re-entrainment.

Entrainment and Re-entrainment in Estuarine Discharges

The above discussion focuses on open ocean conditions. For estuarine discharges the use of Equation 17 may not be appropriate as advection and turbulent mixing is not so conveniently described by this simple model. Monitoring data and estuarine circulation models may be useful, although point and diffuse sources may not be well characterized.

Compared to waste discharges along a stretch of open coastline, discharge of effluents into an estuary almost surely guarantees recirculation to other points in the system, and the entrainment of effluents from other sources into the plume generated by the outfall in question. Estuarine water quality analysis techniques have improved steadily since an EPA resource management assessment was made in 1971 (Ward and Espey, 1971). The assessment of research needs to support a national estuarine research strategy (Menzie and Associates, 1986) cites examples of additional model development that is still needed, but the state of the art is sufficient already for many management purposes. It is possible to adapt available models to many if not most estuarine problems and to conduct simulations with computers available to every modern regulatory program.

EPA maintains an estuarine modeling repertoire and provides computer programs and documentation manuals to potential users. These can be used to estimate the steady state concentration of contaminants at a variety of sites in the estuary given the mass loadings and input locations. Some models may be able to simulate varying concentrations of pollutants within a period of critical conditions such as portions of a tidal cycle. As water quality criteria become sophisticated enough to address short time variations the demand for detailed data on time varying mass inputs will begin to limit the utility of the models. Simulations conducted for all source inputs except the extant outfall, compared to simulated water quality in the absence of inputs, will show the effect of "other sources" on the quality of water entrained in the outfall.

For access to the EPA Athens Laboratory Center for Exposure Assessment Modeling (CEAM) Bulletin Board Service (BBS) call (706) 546-3402. The communications parameters needed are 14400/1200 baud, no parity, eight data bits, and one stop bit.

Monitoring data would be useful for verification of the modeling results except for the fact that monitoring data will include the contribution from the extant outfall. For example, if several of the other sources contribute nitrogen, monitoring data could not partition the estuary-wide distribution of nitrogen since a municipal outfall also contributes nitrogen. It would be rare, and extremely valuable, if baseline monitoring data were available over long enough periods of time to provide some verification of the pristine case.

Use of an Intrinsic Tracer

There is a possibility, though unlikely, that a surrogate approach to partitioning of contemporary monitoring data may be useful. If the effluent were the unique (ambient effectively zero) source of any water quality constituent whose physical, chemical and biological fate mechanisms were known, or could reasonably be assumed to be inconsequential, the distribution of this tracer throughout the estuary could serve as a proportional marker for any other constituent in the outfall.

Thus if the tracer was at concentration 10 in the outfall and contaminant "X" was at concentration 4, then at some point in the estuary where the concentration of tracer was found to be 0.1 and the concentration of "X" was found to be 3, the amount of "X" from other sources could be found by solving Equation 9 first for S_a using the tracer data and then solving Equation 9 for c_a using the contaminant data and the value found for S_a. Of course the behavior of the surrogate and the contaminant "X" must be the same or adjustments to the correction have to be made to account for any differences in coagulation, adsorption, decay etc. While easily stated, this environmental behavior question may limit the practical use of the approach. No literature citations have been found that report use of this technique although in a practical sense it is of the same form of approach as injecting dye or some other tracer to determine the estuarine distribution of outfall constituents generally.

Salinity as a Surrogate Effluent Tracer

Under some specialized situations the distribution of salinity, which is more easily verified than nonconservative pollutants, can be an effective surrogate for a nominal effluent constituent in the water column. The simplest case is when an effluent is proposed to be discharged near the major freshwater inflow to the estuary.

In the case of a discharge near the entrance, salinity may be an approximate surrogate only if the wastewater flow is very much smaller than the incoming seawater volumetric flux during periods of small tidal exchange.

Unfortunately, neither case deals with the question of environmental fate factors (adsorption, speciation, decay), and surrogate values based on salinity have to be modified to account for evaporation, direct rainfall, and other influences on the salinity value. Nor are salinity distribution patterns useful for estimating particulate sedimentation values, which may be the most important consideration because the 301(h) modified permit usually results in greater suspended solids emissions than would be achieved with full secondary treatment.

FRESHWATER DISCHARGES OF BUOYANT EFFLUENTS

The buoyant plume problems of major interest to scientists and regulators have typically involved the discharge of lighter material into a denser environment, such as a smoke plume in the atmosphere or freshwater sewage effluent discharged into the marine environment. The models developed for these cases are also able to handle the discharge of heated water into a colder lake because of the slight density difference associated with temperature differences.

The models may be employed in some riverine situations as well as in lakes. That is, if the effluent is warmer than the river and is discharged at depth, the effluent would be expected to behave as a buoyant plume. The relative size of the diffuser ports in relation to the depth of the river may be important in achieving the dilution factors predicted by the models. Muellenhoff et

al. (1985) recommended the depth be greater than ten times the port diameter, although there is no strong experimental or observational basis for this rule. Rather it is based on the knowledge that plume models were developed for deep water discharges and modelers are not confident in extrapolating verification data from deep water situations to shallow water applications.

For riverine situations in which the effluent is discharged through a multiport diffuser placed along the stream bed in the direction of flow rather than across the current, only the RSB (line source) model in this report may be applicable for analysis of the dilution field.

Industrial wastes discharged to rivers or lakes may have bulk densities greater than the receiving water due to high concentrations of dissolved contaminants. But if an effluent is substantially warmer than the lake or river the net result might be a lesser density and a positively buoyant plume would develop from a discharge at depth. However, modelers should be aware of the nonconservative nature of heat in describing the density of an effluent at the discharge point. The wastewater temperature at the diffuser port may be significantly lower than at the treatment plant due to heat lost as the effluent runs through an underground and underwater sewer. However, for large discharges this effect tends to be negligible.

Because most rivers will not have density gradients it is likely that warm water plumes will reach the surface of the receiving stream, and the surface plume will be subject to heat exchange with the atmosphere. The models in this guide do not incorporate atmospheric heat transfer functions so that any temperature output generated after the water surface is encountered must be accepted with caution. For short time periods atmospheric heat exchange will not make a large difference.

The subjects of subsurface and surface discharges of large heated effluent flows as for example from thermal electric power plants are treated in many reports.

The special phenomenon of nascent dense plumes, initially buoyant thermal plumes discharged into near-freezing freshwater, which rise briefly before becoming dense and sinking to the bottom are discussed in the next section.

NEGATIVELY BUOYANT PLUMES

Many industrial wastes whether discharged to fresh or marine waters have sufficient dissolved or suspended solids concentrations so that the bulk density is greater than the receiving waters into which they are discharged. The cases can include wastes discharged horizontally or at an angle (including 90 degrees) downward from the surface or upward from the seabed. Simple plume models such as UPLUME (Muellenhoff et al., 1985) have been used to fashion a surrogate solution to the problem of predicting trajectories and dilution factors for vertical discharges of negatively buoyant wastes. This has been accomplished by recasting the problem in terms of an analogous positively buoyant case.

It may help the reader to appreciate this approach by pointing out that many laboratory experimental data sets, and photographs, of positively buoyant plumes rising from the bottom of a simulated stably stratified ocean are in fact results from a negatively buoyant plume discharged from the surface, sinking toward the bottom! The laboratory experiment is set up this way for the physical convenience of the modelers. The photographs are typically presented in published reports upside down so that they visually depict the conceptual problem being addressed. The proper analogy is effected by due regard to the density differences between the plume elements and the local ambient so that the forces acting on the plume element are the same regardless of the direction of motion. Thus a freshwater plume rising from the seabed is simulated physically by a heavy liquid sinking in a lighter fluid. The mathematical simulation is analogous, and the printout from the computer program is an equivalent, surrogate solution.

An example of the above approach is the simulation of dilution factors computed for near surface, downward discharge of drilling fluids into a marine ambient by Ozretich and Baumgartner (1990). In this example the mathematical models PLUME, OUTPLM, and DKHPLM, which would accept only positively buoyant discharges directed up from the seabed, were provided input for a surrogate freshwater discharge into an ambient having an initial density difference and a density gradient equal and opposite to the prototype situation. The mathematically simulated results were comparable to data from a physical model of heavy fluids discharged downward from the surface, i.e., exactly as in the prototype.

Extrapolation of the usual plume model results to cases of very large solids concentrations, and slurries or solutions with very high specific gravities compared to the ambient fluid may violate the Boussinesq approximation which is generally assumed. This assumption, incorporated in plume models to simplify calculations, requires that density differences between the plume and the ambient must be small compared to the density of the fluid. For example, the specific gravity difference between sewage and seawater compared to seawater is approximately 0.02. Sewage sludge is about the same, whereas drilling fluids used in offshore oil exploration could have a ratio of as high as 0.5! Clearly 0.5 is not a small difference compared to 0.02, but there has not been a rigorous examination of the importance of the Boussinesq assumption in plume modeling, or for that matter what a useful criterion is for judging "small." Morton (1959) pointed out that density differences are rapidly dissipated within a short distance from the orifice, suggesting that violation of the Boussinesq approximation is not very serious for the major flow region. Fluid modeling studies by Roberts (1977), and by Roberts, Snyder, and Baumgartner (1989 a, b, c) show no effect of the ratio over a wide range.

In the hydraulic model studies of drilling fluids reported by Ozretich and Baumgartner (1990), drilling muds with specific gravities as high as 2.17 were adequately modeled by the model PLUME (Teeter and Baumgartner, 1979) as judged by comparison to measured depth of penetration to the level of buoyant equilibrium. The ratio of predicted to observed depths averaged 0.93 (standard error = 0.03) for 27 trials.

The model UM described in this report will accept direct input matching all physically observed positively or negatively buoyant plumes discharged at any angle from either the surface

or the seabed. Furthermore it does not depend on the Boussinesq assumption. Other models accessed through the PLUMES interface may or may not produce output for certain negatively buoyant cases, and output which appears complete for other than positively buoyant plumes discharged from the seabed must be considered carefully by the user.

Nascent Density: Thermal Discharges to Cold Water

A special class of negatively buoyant plumes is nascent dense plumes, plumes which begin as buoyant plumes but reverse buoyancy, becoming dense and sinking to the bottom or to some more deeply submerged trapping level. The best known examples are thermal freshwater plumes discharged to freezing ambient freshwater (Frick and Winiarski, 1978; Frick, 1980). The behavior, which can also occur in brackish water up to a salinity of approximately 14 o/oo, occurs because the plume, as its temperature cools by mixing with water near the freezing point, becomes denser than the ambient because the maximum density of freshwater is around 4 C. Thus, if the temperature of the ambient is less than 4 C, the potential for the nascent dense plume phenomenon exists.

The nonlinear equation of state used in UM may be used to model nascent dense plumes, as explained in the chapter entitled: "Example: CORMIX1 comparison, density, and stability".

PARTICULATE DISCHARGES

Particulates in fluid discharges may vary from 10 ppm in municipal secondary effluent to over 100,000 ppm in drilling fluids. The mass of solids may contribute to the bulk density of the fluid, influencing the transient behavior of the plume and its equilibrium position. For municipal effluents this contribution is neglected because of the low concentration of particulates.

Simple plume models (e.g., UPLUME) have also been used to analyze the behavior of municipal sewage sludge in relation to alternative discharge methods such as pumping from barges. Comparison of the mathematically simulated results to small scale hydraulic models results demonstrated that sewage sludges containing between 2 to 6 % suspended solids have essentially the same properties as aqueous solutions of the same bulk densities. As the buoyant equilibrium level is reached in a density stratified ambient fluid the particulates begin to separate from the diluted sewage field, some rising, some settling, with or without flocculation. See Figure 15.

The physics of plume models does not attempt to describe the behavior of particulates within the buoyant plume region or following equilibrium, except to the extent they behave as part of the fluid continuum. Models are available (Tetra Tech, 1987, Bodeen, et al., 1989) to simulate the dispersion and settling of sewage effluent particulates based on pioneering work of Hendricks (1982, 1983) in the Southern California Bight. These models may be applicable for analysis of other types of particulates. It should be borne in mind that the equations of state used in UM, RSB, and CORMIX are not necessarily appropriate for the fluids at hand. (Some additional

amplification on this point is found in the section entitled: "Example: CORMIX1 comparison, density, and stability.")

It may be possible to influence the behavior of particles in relation to the physics of sedimentation by adjusting the discharge conditions at the diffuser port, especially the exit speed. High exit speed may break up agglomerated particles causing them to behave as discrete particles at the equilibrium level. Low exit speeds may preserve the integrity of agglomerated particles and enhance the flocculation of others prior to arrival at the equilibrium level. This is a separate area of research beginning to be questioned. Attention so far has been focused primarily on the interactions of particulates following the transition from plume mixing to ambient turbulent transport (Hunt, 1990). Whether or not discrete or agglomerated particle are the more environmentally benign form has not been rigorously established, although a task force report of the Marine Board suggests dispersal is preferred to seabed accumulation (NRC, 1984). This recommendation is based on broad physical considerations rather than detailed ecological considerations which may be preemptory.

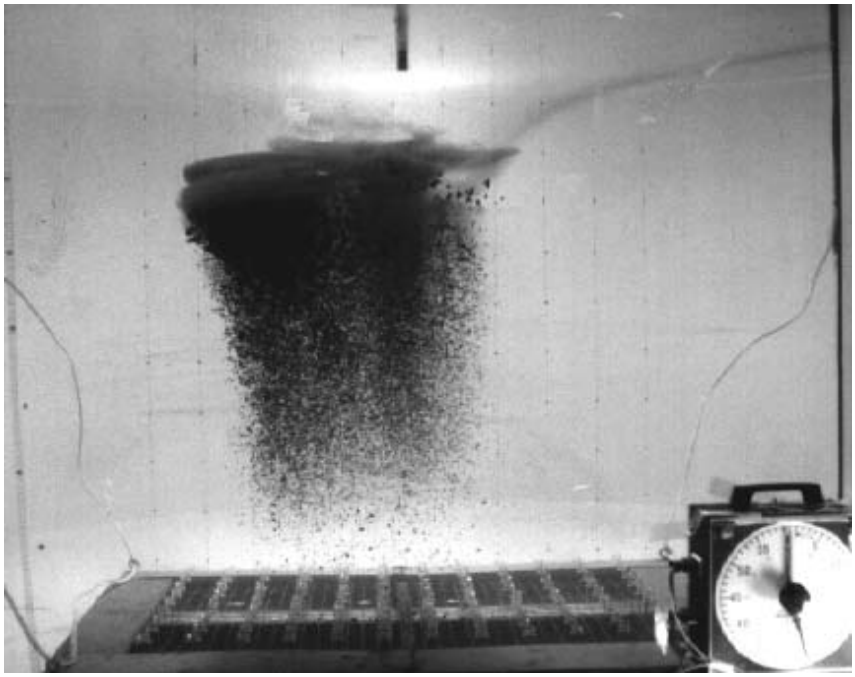

Figure 15. Separation of plume and flocculating particulates.

USER'S GUIDE TO THE PLUME MODEL INTERFACE, "PLUMES"

SYSTEM REQUIREMENTS AND SETUP

PLUMES is designed to be used on IBM compatible PCs running under DOS. The program does not make use of graphics but does require a color monitor. The memory requirements of PLUMES are modest, less than 200 K, and should not interfere with other resident programs. The latest advisories are contained in a file called **READ1st.exe**, which, as its name implies, should be read first. READ1st.exe contains information on how to unzip the program and document files. Information describing a few supplementary files is also found there.

PLUMES can be run from the A: prompt using the diskette provided, however, the tutorial notation assumes that it is installed on a hard drive, generally Drive C. We suggest that you create a new directory on which to install PLUMES. If this new directory is a sub-directory of the root directory the following procedure could be used at the C:> prompt to create a sub-directory called, for example, MODELS, and to change to the new directory. At the prompt type "mkdir MODELS" followed by a carriage return (i.e. the Enter key: <enter>). The installation commands might look like this:

```
C:> mkdir MODELS
C:> chdir MODELS
C:\MODELS> a:PLUMEPRO
```

After each command an <enter> is implied. The mkdir (or md) command makes the PLUMES sub-directory, the chdir (or cd) command moves you to the new PLUMES sub-directory. The A:PLUMEPRO command executes the self-unzipping executable file by that name on the A: drive. (Substitute the appropriate drive designation). At this point, the program, PLUMES.exe, may be run by typing at the prompt:

```
C:\MODELS> plumes
```

The case of the command is unimportant.

For further guidance on setting up the directories consult the DOS reference manual.

INTRODUCTION

PLUMES is a computer implementation for preparing input data and controlling two plume models, RSB and UM, and two farfield algorithms. RSB and UM are relatively sophisticated mathematical models for analyzing and predicting the initial dilution behavior of aquatic plumes discharged from diffusers or (UM only) single ports. The farfield algorithms are relatively simple implementations of the Brooks farfield dispersion equations.

The interface itself presents a spreadsheet environment, scoreboard-like in appearance, that allows you to describe effluent parameters, environmental conditions, diffuser design features, and program controls in an organized but flexible manner. The various program elements are intended to work together to help reduce the amount of time required to analyze various plume problems, or cases. For example, the interface provides limited control over output format to help in writing reports. The goal is to make it easier to explore options, conduct sensitivity analyses, and generally produce more in-depth project reviews, designs, or assessments.

In addition, PLUMES can provide the corresponding CORMIX1 flow categories based on the CORMIX1 classification scheme (Doneker and Jirka, 1990). Thus, PLUMES can offer recommendations on model usage that go beyond the built-in models — including in its appraisal EPA CORMIX1, CORMIX2 (Akar and Jirka, 1990), and CORMIX3 (Jones, 1990), for single port discharges, diffusers, and surface discharges respectively. More comprehensive recommendations on model usage are provided in Appendix 1.

The software is bundled with several stand-alone models: UPLUME, ULINE, and PLUMEHYD. UPLUME and ULINE are initial dilution models described by Muellenhoff et al. (1985). PLUMES supports them by providing a way to create UDF files from the input data. PLUMEHYD may be used to analyze the hydraulic performance of simple, linear diffusers; it is described in Appendix 2.

The PLUMES interface uses several main structures to display information, activate various functions, and control the resident models:

- the case (or record)
- cells
- pop-up menus
- dialogue windows
- help windows
- configuration string

which are described in the next section. In addition, various specialized built-in features are included to support the analytical process. Perhaps the most unique specialized capability is the conflict resolution feature which allows many ways of defining the problem, i.e. entering different sets of variables, and, consequently, must be able to detect instances of conflict when they occur and help to remedy them. The following tutorial chapter demonstrates the conflict resolution mode.

Another feature is a units conversion capability to minimize the need for a calculator.

The structure, commands, special capabilities, and the plume models themselves work together to help you analyze initial dilution, mixing zone, and farfield dispersion problems. The level of refinement available in each of these zones varies considerably, being relatively high in the near field simpler and approximate in the farfield.

PLUMES STRUCTURE

When PLUMES is started, introductory information is displayed which must be acknowledged by pressing any key. Once acknowledged, the main screen, often referred to as the **interface level** or simply the interface, appears. An example of the interface is given in Figure 16. The screen represents a single problem, or **case**, which, as the information in the upper right corner implies, could be just one record in a file of many cases.

A color monitor is required. Color is used to help organize the input and enhance the readability of the interface.

```
 Jun 19, 1992,  11:35: 6  ERL-N PROGRAM PLUMES, Jun 10, 1992   Case:   2 of   2
 Title   Sand Island validation: no blockage                          non-linear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
     4.469       285   0.01568     7.315       0.0        25       500      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      70.1     0.085   0.08500     2.763     2.763     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
      0.84       0.0       1.0    -2.893       100     55.26     18.40 2.044E-14
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90     7.315     24.080.00001000  0.000453      0.15    2763000.00004871
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0      1e-5     22.99     34.99     26.18         0   0.01217    0.2652
     30.48      1e-5     23.18     35.00     25.60         0 buoy flux puff-ther
     45.72      1e-5     23.40     35.02     24.95         0  0.004159     35.60
     60.96      1e-5     23.49     35.00     24.60         0 jet-plume jet-cross
     76.20      1e-5     24.47     35.02     21.22         0     1.472     20810
                                                            plu-cross jet-strat
                                                            4.159E+12     4.136
                                                            plu-strat
                                                                6.932
                                                              hor dis>=

CORMIX1 flow category algorithm is turned off.
                                                             0.0 to any  range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: sandis.var;
```

Figure 16. The PLUMES main screen, or interface level. (Software version is in color.)

The greater part of the interface is occupied by **cells**. In general, each cell has a short **label** and a space beneath it for **numeric data** (the value of the mathematical variable). The title cell, occupying the second line, is longer and is suited to alphanumeric input. In the main body of

green ambient cells, which define conditions in the receiving water, vertically stacked cells share common labels.

The cells are organized into colored blocks. Outfall structure variable labels are on magenta background; effluent characteristics, brown; miscellaneous variables, gray; ambient variables, green; and specialized information, red. The actual colors depend on the brand and settings of the monitor in use. There is also a multipurpose **"pause" cell** (identified initially by the header "hor dis>="), near the lower right hand corner of the interface, which may be used with UM to control output of information under specified conditions (useful for specifying dilutions at the mixing zone boundary). The color of the numeric information in the cells is either displayed in yellow or in white, depending on whether the information was entered manually (or selected from a default value) or was computed by PLUMES. Yellow variables are independent variables; white ones are dependent. **Only some of the cells, which you select to suit the problem (independent cells), need to be specified — PLUMES computes the rest (dependent cells)**. This flexibility makes it possible to define problems in a variety of ways.

At the top of the interface is a clock, the PLUMES version identification, the case counter, and the Equation-of-state-window (showing linear or nonlinear). At the bottom are three lines of data: the first is reserved for the **CORMIX flow classification** predictions and modeling recommendations, the second is the **dialogue line**, and the third contains basic help information, **program configuration identification**, and the name of the file of cases in use.

The dialogue line may be passive, displaying useful information that is relevant at various times, or it can be active, awaiting instructions to continue. Sometimes you are alerted to new information in the window by sound. An example of a passive message explaining how to use the menus after the F1 key is pressed is shown in Figure 17. When action is required, the options will

```
Hit bolded letter or arrow keys and <CR>; use control sequences for speed
```

Figure 17. An example of the dialogue line.

be displayed or a cell will be provided for inputting string information, such as a file name. The latter often display a default string which may be accepted or simply typed over, referred to as "typeover" input. Explanations of messages may be found in Appendix 4.

Except for some of the editing commands which are described only in the Miscellaneous Editing Commands section, the **commands can be selected from several menus**, the main one of which is shown in Figure 18 as it appears as a window on your screen. The menus are provided mainly as a memory aid, and, in general, it is faster to use the keystroke form of the commands at the interface level. The < symbol after some of the commands on the main menu indicates the presence of sub-menus. The mode of implementation is explained subsequently.

```
 Jun 11, 1992,  19:57:49  ERL-N PROGRAM PLUMES, Jun 10, 1992   Case:   1 of   1
 Title   Sand Island validation: (no blockage) TRR case.              non-linear
  tot flo+)))))) Main menu )))))), spacing  effl sal effl temp   far inc   far dis
     4.46* run rsB program     *   7.315       0.0        25       500      2000
 plume de* run Um program      *otal vel horiz vel vertl vel asp coeff print frq
      70.* show Independents   *   2.763     2.763     0.000      0.10       500
 port ele* units Konversion    *effl den poll conc     decay  Froude # Roberts F
      0.8* List equations      *  -2.893     6.1e8                18.40 2.044E-14
 hor angl* get Work file       * current   far dif   far vel K:vel/cur Stratif #
        9* fill New file       *00001000  0.000453      0.15    2763000.00004871
     dept* add to Output       *salinity      temp  amb conc  N (freq) red grav.
       0.* cell Precision      *   34.99     26.18         0   0.01217    0.2653
     30.4* shallow/surface Z   *   35.00     25.60         0 buoy flux puff-ther
     45.7* configuRe models  < *   35.02     24.95         0  0.004159     35.61
     60.9* moVement commands < *   35.00     24.60         0 jet-plume jet-cross
     76.2* miscellanY menu   < *   35.02     21.22         0     1.473     20820
         * <esc>               *                               plu-cross jet-strat
         .))))))))))))))))))))-                                4.159E+12     4.136
```

Figure 18. The main pop-up menu superimposed on the PLUMES interface.

The most pervasive help screens are the **cell definition windows**. These come up by issuing the **<List equations>** (^L) command on the main menu. The information provided is specific to the cell identified by the cursor and has one of two forms. An abbreviated form is used when the file EQNS <u>is not</u> in the current directory; it consists only of a definition of the cell and descriptive notes. With the file in the current directory, a second form adds the equations that are used by PLUMES to define dependent (white) variables. The extended form, in this example showing the equations and terms involved in various methods for computing density, is shown in Figure 19. If file EQNS is not in the current directory because it was not copied or was deleted, it may be restored from the original disk.

The Configuration string, which may vary from case to case, appears in the middle of the bottom line of the interface. Each character in the string is a mnemonic for different program attributes. Changing the string will cause the program to work in one of several fundamentally different ways. For example, the "O" in "ATNO0" in Figure 16 indicates that the plume model UM, under overall control of the PLUMES interface, will terminate the initial dilution phase (near-field) if and when the mathematical condition of element overlap is encountered.

INTERFACE CAPABILITIES

It is easy to be unaware of some of the special capabilities available in PLUMES because all are not controlled directly. However, understanding them will enhance the use of the system. The more notable ones are described below.

- an unstructured data input environment
- a conflict resolution mode for resolving many over-specified input conditions
- a configuration file

```
Help for variable:  den =  effl den  sigmat

    Effluent density.  When calculated from temperature and salinity,
    the salinity is assumed to have the composition of sea salt.  If the
    density is independent, a linear equation of state is assumed (see
    Example 2 in the manual for more detail).

Equations and variable definitions:
 den = (dena+1000)/(1.0 +vel*vel/(g*dia*abs(Fr)*Fr) - 1000
       { note single use of abs to retain sign }
     = (dena+1000)/(1.0+gp/g)-1000
     = dena -SP*(dena-da1)*dia/pdep
     = sigmat(s,t).
   da1  : surface (level 1) density
   dena : ambient density at plume depth
   dia  : plume diameter
   Fr   : densimetric Froude number
   g    : acceleration of gravity
   gp   : reduced acceleration of gravity
   pdep : plume depth
   SP   : stratification parameter
   t    : plume temperature

<key> for more    [ for the continuation page below ]
   vel  : plume vena contracta velocity
   s    : plume salinity
   den, dena, etc. expressed in sigma-t units
<key>
```

Figure 19. Example of a "cell definition window." The help window for the plume density cell.

- selection from multiple solutions to governing equations
- display based on significant digits

Perhaps the most outstanding feature of the interface is its **unstructured data input environment**. The user is free to move about, skipping over cells, just as in a spreadsheet program. This facilitates "what if" inquiries.

The unstructured environment would not have much purpose if all the cells had to be filled in anyway. But, in fact, only some of the cells need ever be filled. The reason is that PLUMES provides redundant variables as a convenience. For example, there are cells for the total flow, number of ports, and port flow. Since it is assumed that all ports have equal flow, only the first two cells are necessary to specify the port flow. (Given that they are specified, the port flow should not have to be input, in fact, it would be potentially incorrect to do so because the value could be inconsistent with the total flow, which, as is explained below, would be brought to your attention by the conflict resolution algorithm.) In this case the total flow and number of ports are displayed as independent variables, i.e. in yellow, while the calculated (dependent) port flow cell is displayed in white.

For even more flexibility data can be entered into cells defined previously. This capability facilitates sensitivity analyses. If the superseded value was yellow (independent), the affected dependent (white) cells are simply recalculated. However, things are more complicated when a

white cell is superseded with new information you entered. In this case the overspecification alluded to above will, in general, cause the data set to be inconsistent. In the above example, the product of the port flow and the number of ports would no longer equal the total flow. **PLUMES detects most such inconsistencies[1] and goes into a conflict resolution mode** in which you select (space bar to move to the selected variable, followed by the "D" or delete keys) which variable is to be calculated (dependent).

PLUMES maintains a **configuration file** called **SETUP**, an ASCII file that is created if it is not present in the current directory. It is routinely updated and stores information on the last use, including the location of the cursor, and the variables on the output table list. PLUMES attempts to find and read the file each time it is run.

Some of the equations used to define dependent cells in the interface have more than one solution. A good example is density as a function of temperature and salinity. It is well known that the greatest density for fresh water at standard temperature and pressure is around 4 C. Thus, there is a range of densities smaller than the maximum density in which temperatures both less and greater than 4 C are compatible. Whenever this occurs, **PLUMES provides for the selection of the desired solution from the multiple solutions to the governing equations**. The same occurs when the dependent variable is the solution to a square root, in which case the proper root, either positive or negative, must be selected.

The interface **displays numbers to 3 or 4 significant digits**. This capability assures that information is not lost due to formatting deficiencies. Numbers that cannot be displayed to the proper precision within the allotted space are converted to the "E" format of scientific notation, e.g. 1.4×10^{-8} is displayed as 1.4E-8. The "E" format may also be used to enter data. The **<cell Precision>** command may be used to show extra precision.

COMMANDS

Conventions

Control over the interface is exercised through a system of commands which may be issued at any time. The **commands are listed on a series of menus** and can be implemented by bringing up a menu or by holding the "control" key and striking an appropriate letter key. The former is convenient for remembering the commands while the latter is faster. Thus, the "run rsB program" command, which is listed on the Main menu, can be issued at the interface level by simply holding down the control key and then pressing the letter B, also denoted by ^B. (The case of the letter is irrelevant, i.e., ^B = ^b.)

[1] Strictly speaking, instances of over-specification are detected only when at least one of the defining variables of the offending cell is independent. However, a special command is available for checking the consistency of all variables, irrespective of their independent/dependent lineage.

There is only one way to access the Main menu directly, which is not to say the commands, and that is with the "**F1**" key. From the main menu the commands, which include bringing up the sub-menus, may be issued by hitting the chosen highlighted key, or, using the arrow keys to move to the chosen command and selecting it with the enter (carriage return) key or the space bar.

In the catalogue of commands to follow commands will be enclosed by < > brackets, to indicate they are keystrokes. Thus <run rsB program> or <B> are equivalent. For commands issued directly from the interface level without going through <F1>, sequences are harder to represent, for example, <control><B> does not convey very well the fact that the keys are to be depressed simultaneously. For such cases the notation ^B is more useful and will be used extensively. For sub-menus, the chosen highlighted letter can be added to the key sequence. For example, to use the <cHeck consistency> command on the Miscellany menu from the interface press ^Y followed by ^H or <H>; this sequence is summarized as ^YH. If a command is issued which is invalid in context, PLUMES will send a reminder to the dialogue window. The commands are case insensitive.

In the following listing, the name of the command as it appears on the menus is given, followed by the interface level keystroke command sequence and a brief description of the command itself.

The Main Menu

The Main menu (Help, <F1>) is shown in Figure 20.

```
+))))) Main menu )))))),
* run rsB program     *
* run Um program      *
* show Independents   *
* units Konversion    *
* List equations      *
* get Work file       *
* fill New file       *
* add to Output       *
* cell Precision      *
* shallow/surface Z   *
* configuRe models  < *
* moVement commands < *
* miscellanY menu   < *
* <esc>               *
.)))))))))))))))))))))-
```

Figure 20. The Main menu.

<run rsB program>, ^B:
Instructs PLUMES to run RSB, (Roberts, Snyder, Baumgartner, 1989 a,b,c). Subsequent dialogue window prompts ask you to specify the number of cases to run and the destination of the simulations. The console or monitor can be specified by typing the word "console" (without the quotes) or simply press space bar if the console is the default output device. Or type "prn" for printer or any acceptable (i.e. limited to the current directory) DOS file name.

<run Um program>, ^U:
Run the UM model. Subsequent dialogue window prompts ask you to specify the number of cases to run and the destination of the simulations (console, printer, or disk file). (See explanation of the ^B command above.)

<show Independents>, ^I:
Typically, PLUMES can use several equations to define dependent cells. ^I examines each of these and, in turn, identifies all the potential defining variable sets for the cell in which the cursor is located. The cell's independent variables are revealed by black hatching of the background color of the cells' labels. ^I is useful for establishing which data (cells) will define the cell at the cursor for which data may be unavailable. For example, you might only be using the interface to calculate salinities and wish to determine the appropriate cells to input. (REMINDER: the variables in the defining set can themselves be either independent or dependent.)

<units Konversion>, ^K:
Allows you to change the input units of a cell to one of the units shown in the dialogue window. After the desired unit appears in the dialogue window, you may input the value in its native units. Upon leaving the cell the value is automatically converted to the system units (primarily SI, i.e. kg, m, sec, C). Subsequently, the conversions will appear in the dialogue window whenever the cursor is moved back into the cell.

<List equations>, ^L:
Provides a definition of the present cell. An example is given in Figure 19. The header name is displayed at the top of the screen in the cell's interface color. If the file EQNS is in the current directory, the set of equations that define the cell, together with variable explanation, is also provided.

<get Work file>, ^W:
Used to specify a new working file of records, or cases. A typeover window is provided for file name input. The <9> key may be used to cycle through existing .VAR filenames in the present directory. The existing active file is stored and the new file is opened. The new file name replaces the old one at the bottom of the interface after the word "FILE". If the file does not exist it is created and filled with default data. The length of the new file is checked to help ascertain that the appropriate format exists.

<fill New file>, ^N:
Directs the interface to create a new file of records from the current file of records. You are asked for a new file name (existing files are rejected). The filename extension, .VAR, is recommended (see the <get Work file> command above). You must specify which records are to be copied to the new file. The numbers of the cases must be separated by blanks (spaces, not commas) but may be in any order. Sequential cases may be specified by connecting their beginning and end members with "..", e.g. the sequence 5 3..7 1 causes the cases 5, 3, 4, 5, 6, 7, and 1, in that order, to be copied to the new file. The command is useful for reorganizing your case files.

<add to Output>, ^O:
For the UM model ^O allows cells to be added to the list of cells that are displayed as output.

Affected cells are highlighted by a blue rectangle in the first character of the cell label. Certain auxilliary variables, like centerline dilution, may be added or removed by using the ^YS command on the Miscellany menu.

<cell Precision>, ^P:
Increases the precision to which dependent cell values are expressed. Up to six significant digits may be displayed.

<shallow/surface Z>, ^Z:
This command allows the analysis of single port plumes into very shallow water. Usage is explained in the unofficial accompanying file called EGSFC.WP.

<configuRe models < >, ^Rx:
Displays the Configuration menu. The "x" indicates another key is to follow. If ^R is pressed at the interface level, the Configuration menu will appear after a timed delay if the "x" has not followed in the allotted time.

<moVement commands < >, ^Vx:
Displays the Movement menu. The "x" indicates another key is to follow. If ^V is pressed at the interface level, the Movement menu will appear after a timed delay if the "x" has not followed in the allotted time. Some mnemonics of some of the editorial commands are also displayed. **Note: the ^V prefix is not required.**

<miscellanY menu < >, ^Yx:
Displays the Miscellany menu. The "x" indicates another key is to follow. If ^Y is pressed at the interface level, the Miscellany menu will appear after a timed delay if the "x" has not followed in the allotted time.

<esc>
The null command. Returns the interface level. At the interface level it is used to quit.

The Configuration Menu

The configuration prescribes one of several possible running modes for the interface, UM, and RSB. The settings are identified in capital letters and numbers after the word "Configuration". Defaults are provided if the file SETUP is missing, otherwise they are read in from SETUP. The menu is shown in Figure 21. Unlike other menus which disappear after a command is selected, the configuration menu remains on the screen until <esc> is hit, allowing the entire configuration string to be edited in one pass. It can be accessed with <F1> followed by <R>, or ^R. Once the commands are known, it is more convenient to use the command sequences given below.

<Auto ambient>, ^RA:
Possible settings are A (on) and N (off) in the first character of the configuration string, e.g. **A**TNO0 or **N**TNO0. In the ambient block starting with the line below the surface ambient line, while moving from cell to cell, Auto ambient (on) will fill the cell with the value immediately above it if that value is independent (yellow). This is a convenient way of filling out the ambient block when many of the values are similar. The provided values can be edited. The default is A (on).

```
+ Configuration Menu ),
* Auto ambient        *
* Brooks eqn input    *
* Cormix1 categories  *
* Farfield start      *
* Reversal set        *
* Show configuration  *
* bEget configuration *
* <esc>               *
.)))))))))))))))))))))-
```

Figure 21. The Configuration menu.

<Brooks eqn input>, ^RB:
Possible settings of T or R are identified by the second character in the configuration string at the bottom of the interface level. The R setting (reset), e.g. N**R**CO0, indicates that PLUMES will prompt you to approve or change the inputs (wastefield width and origin distance). This allows the farfield model to be run independently of the initial dilution models. The default T setting (transmitted) establishes the initial dilution model results as farfield model inputs.

<Cormix1 categories>, ^RC:
Possible settings of C or N are identified by the third character in the configuration string at the bottom of the interface level. The C setting, e.g. NT**C**O0, indicates that PLUMES will attempt to define CORMIX1 flow class corresponding to the input conditions. Recommendations for model usage are also presented. The default N setting, e.g. NT**N**O0, specifies that no classification is attempted.

<Farfield start>, ^RF:
Possible settings of M, O, or P are identified by the fourth character in the configuration string. When using UM, the settings determine at which point the farfield dispersion model is initiated. When the command is issued the prompt shown in Figure 22 appears in the dialogue window. Using the M, or Max-rise option, e.g. ATN**M**0, the initial dilution phase is terminated when the plume reaches maximum rise (or the surface), after which the farfield model is initiated. The default value is O (Overlap), e.g. ATN**O**0, which specifies the farfield model begins when the plume element can no longer be consistently defined due to geometric constraints (Frick, Baumgartner, and Fox, 1994). This condition, sufficiently pronounced, is associated with upstream anvil formation (Frick et al., 1990). The P (Pause criterion) option, e.g. ATN**P**0, initiates the farfield model when the condition in the pause cell, set by the ^YS command, is met.

```
Start far-field at Max-rise, Overlap, or Pause criterion?
```

Figure 22. Farfield configuration options.

<Reversals set>, ^RR:

Plumes rising in stratified receiving waters frequently trap at an intermediate level, a level of zero net buoyancy. Generally, plumes will traverse, or overshoot, this level and perform wavelike motion because they still have vertical momentum. Thus, above and below the trapping level the buoyancy will switch from positive to negative or vice versa. This reversal in buoyancy will ultimately slow the vertical motion to a standstill before reversing again. Each reversal point is a crest or trough of the wave.

The <Reversals set> setting specifies how many extrema are to be modeled before the farfield model takes control. The farfield setting must be M or P. If the number of reversals (the last character in the configuration string) is set to zero, e.g. AONO**0**, PLUMES will determine the number of reversals to be one, 1, for buoyant plumes and two, 2, for negatively buoyant plumes. The reason for this option is that normally rising plumes usually entrain much more vigorously between discharge and maximum rise than they do in the farfield, thus the initial dilution region is confined to the region between discharge and the first reversal (i.e. maximum rise). Negatively buoyant discharges are frequently discharged upwards and pass through maximum rise before their turbulence is dissipated, hence it is appropriate to continue relatively active entrainment through the subsequent sinking region. In any case, by specifying a nonzero integer between 1 and 9, the user can specify the number of oscillations which will be modeled. The 0 value is generally recommended but may be altered for the rare instances that a different choice would be more conservative or for special purposes.

<Show configuration>, ^RS:

Interprets the configuration string shown at the bottom of the interface screen. The other options are also summarized. An example configuration is shown in Figure 23.

<bEget configuration>, ^RE:

Copies the configuration string to subsequent cases. The number of cases involved is specified in the dialogue window.

```
                          PLUMES Configuration

A: Automatic ambient fill is on
T: Brooks equation input transmitted
N: The CORMIX flow categorization algorithm is inactive
O: UM far-field predictions begin at element overlap
   Farfield model initiation choices are:
   M: maximum rise; O: element overlap; P: pause criterion.
   Other criteria, such as surface interaction, will override these choices.

0: Brunt-Vaisala reversals determined by UM as 1 or 2
```

Figure 23. The Show configuration command window.

<esc>
The null command. Returns the interface level.

The Movement Commands Menu

The Movement Commands menu is shown in Figure 24. It can be accessed with <F1> followed by ^V or <V>. Once the commands are known, it is more convenient to use the commands given below. Note that even though they appear on a submenu, to use the movement commands from the interface level it is **NOT** necessary to first use the ^V key.

```
+) Movement commands )),
* A cell left          *
* S char left          *
* D char right         *
* F cell right <space> *
* E cell up            *
* X cell down          *
* go to next Case      *
* Jump cell blocks     *
* P (return last cell) *
* <esc>                *
* <bckspc> del left    *
* ^t del word right    *
* ^ql sorry key        *
* (more: see manual)   *
.))))))))))))))))))))))-
```

Figure 24. The Movement menu.

The movement keys given on the Movement Commands menu are augmented by other editing commands described in the next section: Other Useful Editing Commands. They are basic and useful and should be learned thoroughly.

<A cell left>, ^A:
In the title cell, ^A moves the cursor to the beginning of any word in which the cursor is located. If the cursor is at the beginning of the string, it moves the cursor to the [tot flow] cell.

In the other cells, ^A moves the cursor to the beginning of the number in a cell, or, to the previous cell if the cursor is already at the beginning.

<S char left>, ^S, or < 7 >:
Moves the cursor one character to the left of its present position. If it is already at the beginning of the number or string, it moves the cursor to the previous cell.

<D char right>, ^D, or < 6 >:
Moves the cursor one character to the right of its present position. If the cursor is at the end of the number or string, it moves the cursor to the next cell.

<F cell right>, ^F:
In the title cell, ^F moves the cursor to the end of any word in which the cursor is located. At the end of the title cell it moves the cursor to the [tot flow] cell. In all other cells, ^F moves the cursor to the right side of the value in cell or to the next cell if the cursor is already on the right side.

<Space bar> works normally in the title cell but moves the cursor to the next cell in the rest of the interface.

<E cell up>, ^E, or < 8 >:

Moves the cursor up one cell in the interface. If the cursor is in the uppermost row of cells, the cursor is moved to one line below the deepest defined line in the ambient block or to the bottom of the column of cells.

<X cell down>, ^X, or < 9 >:
Moves the cursor down one cell. If the cursor is in the row of cells in the ambient block one below the lowest defined depth, or is at the bottom of a column of cells, the cursor is moved to the top of the column of cells. Affected by the <Auto ambient> command.

<go to Case>, ^C:
Directs PLUMES to go to another case specified in response to a typeover prompt in the dialogue window. The next case is always offered as a default and can be accepted with <space bar> or <Enter>. Otherwise, the default may be overridden by typing any other number followed by <space bar> or <Enter>.

If the specified case number is one greater than the number of cases that currently exist in the file of cases, a new case, is appended and filled with the same information contained in the case from which the ^C command is issued. Any number less than one or greater than the number of cases plus one is ignored.

See the <Page Up> and <Page Down> commands below.

<Jump cell blocks>, ^J:
Moves the cursor into the next colored block of the interface. ^J is a fast way to move about in the interface and the only way to move the cursor into the [title] cell.

<P (return last cell)>, ^VP:
This command is useful after a variable is selected for deletion in the conflict resolution mode. When a deletion is made the cursor normally returns to the cell in which the cursor was located after the value that caused the conflict was entered. The ^VP command returns the cursor to the cell which was deleted. Also works after the ^J, ^E, and ^X commands. NOTE: Due to the presence of the ^P (cell precision) command on the main menu, this command can only be accessed by using the ^V prefix.

<esc>
The null command. Returns the interface level.

Mnemonics:
The Movement commands menu lists a few editing commands which also may be issued at the interface level. These are described in the next section.

Other Useful Editing Commands

The following commands perform useful editing functions in the interface. Many of the commands are similar to those in the WordStar (trademark) word processing program and in the Borland Pascal editor. Some common WordPerfect (trademark) commands are also used.

<space bar>, or <Enter>:
Moves the cursor to the next cell, except in the title cell, where it works normally.

<backspace>, or ^H:
Erases the character or digit to the left of the cursor.

<Delete>, or ^G:
Erases the character or digit under the cursor.

<End>
Directs PLUMES to go to the highest numbered case in the case file.

<Home>
Directs PLUMES to go to Case 1. To create new cases using an intermediate case as a template, use the ^C command.

<Page Down>:
Directs PLUMES to go to the previous case of the case file. When used in Case 1, the highest numbered case is brought into the interface.

<Page Up>:
Directs PLUMES to go to the next case of the case file. When it is the last case in the case file, a beep is issued to alert you to the fact that a new case will be created if the command is issued again. This is a fast way for browsing the case data file and for creating new cases using the last case as a template.

^T:
Erases the rest of the word or number to the right of the cursor.

^QD:
Moves the cursor to the right of the last character or digit in the cell.

^QY:
Erases everything in the cell to the right of the cursor, all of it.

^QL:
"Sorry-I-changed-it-command". Restores the original value of a cell providing the cursor has not left the cell. Exceptions to this rule make it necessary to retype data.

<~>:
May be used in many situations to dump whatever is on the screen to an ASCII file called DUMPALL. Subsequent uses of the command will cause the DUMPALL file to be appended so that occasional examination or deletion of the file may be appropriate. Intended for debugging and documentation purposes.

The Miscellany Menu

The Miscellany Menu (^Y) is shown in Figure 25.

```
+)) Miscellany menu ))),
* ambient column Fill  *
* Interpolate amb cell *
* Copy ambient line    *
* Delete ambient line  *
* Beget new cases      *
* cHeck consistency    *
* Notes                *
* clear Output cells   *
* Purge cases          *
* construct Udf file   *
* pauSe cell           *
* cormiX category      *
* Zap most variables   *
* <esc>                *
.)))))))))))))))))))))-
```

Figure 25. The Miscellany menu.

<ambient column Fill>, ^YF:
If variables in an ambient column are all the same, it is often useful to fill only the surface cell for that column and use the <space bar> to skip over successive cells in that column. After all the depths are entered (i.e. all the [depth] cells are filled with the appropriate depths), move to the surface cell in the empty column and issue the ^YF command. All the remaining cells in that column down to the deepest depth will be filled with the same value.

The <Auto ambient> command on the Configuration menu is useful for achieving these results on a continuous basis.

<Interpolate amb cell>, ^YI:
This command is used to place depth interpolated ambient values into intermediate empty cells in a given column in the ambient block. For example, similar to the ^YF command, you could specify a surface current of 0.10 m/sec and a bottom current of 0.20 m/sec. Then, from the cell below the empty cell containing 0.20, issue the ^YI command. The empty intermediate cells will be filled with depth interpolated values.

<Delete ambient line>, ^YD:
Used to delete the line in which the cursor is located from the ambient block.

<Copy ambient line>, ^YC:
Used to insert a copy of the line in the ambient block in which the cursor is located, i.e., between it and the next line in the ambient block.

<Beget new cases>, ^YB:
Used to copy the cell in which the cursor is located to the same cell in a specified number of subsequent cases. The number of cases involved is specified in a dialogue window which is provided.

<cHeck consistency>, ^YH:
Instructs PLUMES to evaluate all possible solutions for the cell from the set of equations which may be displayed with the ^L command. The results are compared and any difference greater than a tenth of one percent is reported in the dialogue line. Not all differences reported are cause for concern. In particular, very small values, which are for all practical purposes identical to zero, can occasionally differ by more than the criterion. Also, if the defining equation has more than one solution, as for example is the case when the horizontal velocity [hor vel] is computed from the total velocity [total vel] and the vertical velocity [ver vel], the signs of the reported values may differ. Nevertheless, any reported differences should be contemplated. See the Notes command below.

<Notes>, ^YN:
Reports the previous messages, up to 20, that have displayed in the dialogue window,

<clear Output cells>, ^YO:
Just as cells may be added to the list of variables to be printed or displayed by UM at run time, cells already on the list may be cleared using ^YO. The dialogue window gives a choice for clearing all cells from the table or for returning to the default list of variables. After the command is used the ^O command may be used to establish a different list.

<Purge case>, ^YP:
All cases after the one shown on the interface may be deleted from the case file. The command is especially useful when terminal cases have been added to the file inadvertently by the use of the < Page Up > command.

<construct Udf file>, ^YU:
Used to translate the cases specified in the dialogue window from and into the UDF format used in the 1985 plume models (Muellenhoff et al., 1985). See Appendix 5 for UDF.IN file format. This makes PLUMES operationally compatible with the earlier models. The intent is to support the 1985 models and users who may not have adopted the resident models. The interpreted cases are read from or are appended to an ASCII file called UDF.IN. When reading the UDF.IN file the Append option may be used to transmit some variables found in the interface but not in the UDF.IN file, for example, the farfield increment cell. In other words, the present case may be used as a template for variables not included in the UDF.IN file.

<pauSe cell>, ^YS:
Used to edit and set up the pause cell located near the lower right hand corner of the interface. After typing ^YS the dialogue line shown in Figure 26 is displayed. The cell is the only way to

```
Back, Inequalities, Output, Variables(space), or <esc>,
```

Figure 26. The pause cell dialogue window.

access selected model variables not present on the interface screen, viz. average dilution, **centerline concentration**, time, density difference, and horizontal distance. The program control function of the pause cell works in conjunction with the <Farfield start> command on the Configuration menu. (Other cells that can be controlled, via conditions given below, include [port dep], [plume dia], [effl sal], [effl temp], [horiz vel], [vertl vel], and [p amb den].) The capital letters in the window are highlighted; their functions are:

<Back> or <B>:
Moves backwards through the list of model variables, including those listed above.

<Inequalities> or <I>:
Selects the possible inequality conditions or criteria. The idea is to set up conditions under which UM will be forced to output data or terminate before initiations of the farfield algorithm. For example, if the pause cell is the horizontal distance (travelled) [hor dis] cell, with a numeric value of 10 m, the inequality >=, and the Farfield start character in the Configuration string is set to "P" for Pause criterion, then UM will output a dilution immediately after 10 m is reached and initiate the farfield algorithm. If the Configuration string is not set to the Pause criterion, then UM will simply output a value at that point and terminate. This is a convenient way to establish output at desired points (like the mixing zone boundary) or criteria. The inequalities include >=, <=, =.

<Output> or <O>:
Adds the variable to the output table (compare the ^O command).

<Variables> or <V> or <space bar>:
Moves forward through the list of variables.

<esc>
The null command. Returns the interface level.

<cormiX category>, ^YX:
Used to determine the CORMIX1 flow classification for the current values in the interface. The command is equivalent to setting the CORMIX program configuration to C for a single instance (see the ^RC command.) Also see Appendix 4.

<Zap most variables>, ^YZ:
Used to clear most of the variables on the interface screen. The cells not affected include the aspiration coefficient, the print frequency, the decay constant, and the farfield diffusion coefficient.

<esc>
The null command. Returns the interface level.

A TUTORIAL OF THE INTERFACE

EXAMPLE: PROPOSED SAND ISLAND WWTP EXPANSION

Introduction

This example is a step-by-step development, or tutorial, of the kind of problems encountered in applying 301(h) regulations. It is designed to make you familiar with the use of PLUMES and to give you a feel for its capabilities and limitations. Several figures are given along the way to allow you to compare your progress with a prepared example. These figures do not adequately convey what is a full **color** display on the computer monitor. Consequently, **the tutorial is most effective if it is used as a guide while filling out the PLUMES interface input form**.

The Sand Island example is intended to be realistic, not only as being representative of the problems encountered in practice but in terms of how analyses are not unique. In other words there is not a single right way, instead, an analysis is likely to be an evolutionary process. An examination of work and simulations already completed are likely to identify other factors that need to be considered. Thus, part of planning the analysis is to carefully examine modeling results already in hand to guide further changes which, fortunately, with PLUMES, are easily made. But, the greater flexibility available in PLUMES also requires vigilance on the part of the user because it is easy to overlook cells that, no longer standing out because they are filled, need however to be changed.

It is assumed that the installation procedures described briefly at the beginning of the previous chapter have been completed.

The problem described here is based on a proposal by the Sand Island Waste Water Treatment Plant (WWTP) of the City and County of Honolulu, Hawaii which seeks to increase its permitted wet-weather flow capacity from 102 to 130 MGD. An increase in the design capacity of 202 MGD is also under consideration.

What will be the effects of the proposed actions on initial and farfield dilution? How are bacterial, turbidity, and other contaminant levels likely to change? Is the new discharge likely to meet water quality standards under the proposed operating changes? How do new techniques compare to earlier analytical procedures? These are some of the questions addressed.

The problem involves a diffuser with 285 ports located on both sides of the diffuser. Over time, the landward ports have become clogged with sand so that the discussion changes between 285 and 142 ports, 24 foot spacing and 12 foot spacing, which is confusing. This poses the question: "How do you compare the performance of the diffuser, now clogged, with the previously unclogged diffuser?" Ultimate answers are not provided and this analysis is incomplete. In fact, **THIS EXAMPLE CONTAINS DELIBERATE MISTAKES**.

Analysis

The problem can be broken down into five different parts:

(1) Collect pertinent information.
(2) Input information into the PLUMES interface.
(3) Run the PLUMES initial dilution and farfield plume models.
(4) Analyze the model results and make adjustments, if necessary.
(5) Use the results in the decision making process.

STEP 1: Collect Pertinent Information

One way to get a feel for the information needed is to run PLUMES and work an example. The first time you do so you may be dismayed by the number of cells displayed by the interface. It may seem imposing at first but only some of the variables, which you may choose, need to be defined -- the interface automatically calculates the rest, as soon as sufficient data is provided. You are free to pass over cells for which you have no data, filling those for which data is available. The ^L, or <List equations>, command can help define the needed input.

When you create subsequent cases, the data contained in an existing case may be used as a template for the new case by using the ^C command to simply move from the case to be copied to the new case to be appended (which will have a number one greater than the number of cases). Minor changes may then be made very quickly to only the affected variables.

STEP 2: Input the Sand Island Information

It is assumed the necessary data needed for Sand Island have been acquired; the appropriate references are given. Begin by entering the main menu using <F1> and set up a file for the example by pressing <W>, the <get Work file> command, or, better, press ^W without first pressing <F1>. The dialogue window changes to request the work filename. Type in <Sandis.var> (which does not exist yet) followed by <space bar> or <enter>. Notice that the default filename can be overwritten without first deleting it. The .VAR filename extension is recommended because the <get Work file> command may be used to scan existing .VAR files in the current directory by simply using the <9> key.

It is worth noting that the default name given in the dialogue box can be edited. For example, pressing < 6 >, or some other editing key like ^QD (move to the last character), before you type an ordinary character, will move the cursor into the field of the cell where it may be edited by adding or deleting characters.

When you are done the monitor will look somewhat like Figure 27, without the 4.469 values or title. The other values are default values which may be accepted or rejected as appropriate.

To start, give this case, identified as Case 1 in the upper right hand corner, a descriptive title, e.g. "Sand Island validation". First, of course, you must move into the title cell. You could go to the Movement menu using the <F1> key but it is faster to use the "jump" command, ^J, several times until the cursor moves into the title cell. Go ahead and type in the title. Type <enter> (or <8>, <9>, ^J, or ^X) when you are finished, in all cases the cursor moves to the [tot flow] cell which is a good place to start filling out the rest of the interface.

```
Mar 15, 1994,  14:32:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of   1
Title   Sand Island validation                                        linear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    4.469         1     4.469      1000       0.0
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
                                                              0.10       500
port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
                0.0       1.0                 100
hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90    1000.0                      0.000453
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0
                                                             buoy flux puff-ther

                                                             jet-plume jet-cross

                                                             plu-cross jet-strat

                                                             plu-strat

                                                               hor dis>=

CORMIX1 flow category algorithm is turned off.
 4.469 m3/s, 102.0 MGD, 157.8 cfs.                       >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:NTNO0.  FILE: sandis.var;
```

Figure 27 The PLUMES interface with the dialogue line showing units conversions of the total flow cell.

The total flow corresponding to the current permit is 102 MGD. It is the appropriate value for the [tot flow] cell in which the cursor should now be located. However, the dialogue line informs you that the primary **units** in this cell are m3/s, or cubic meters per second, so a conversion is required. On the main menu we note there is a command called <units Konversion>. By toggling it (pressing ^K) we can change the input units to any that are shown on the dialogue line. Do so, then, when the dialogue line shows "MGD", enter 102 in the cell. Press the space bar to enter the value (in the process, moving the cursor to the next cell). Notice that, if you move the cursor back to the [tot flow] cell using ^A or <7>, the dialogue line will appear as shown at the bottom of Figure 27. In addition to showing the total flow in m^3/sec, MGD (million gallons per day), and cfs (cubic feet per second), the dialogue line also gives the recommended range of values for the cell, which, incidentally, is not enforced.

The cursor should now be in the [# ports] cell and the value shown in the [tot flow] cell should be 4.469. When the cursor was moved to the number of ports [# ports] cell, the third cell, labeled [port flow], acquired a white value equal to 4.469, even though we did not input a value

in this cell. This is an example of how the interface is event driven, i.e. an event, your pressing the space bar, automatically initiated an action. We will have more to say about this shortly.

The number of ports is 285, but they are not uniform and the diffuser has sections of different diameters. Strictly speaking, a hydraulic model is needed to properly analyze the effluent velocities from the ports, but we will assume that the flow is uniformly distributed. If the diffuser is well designed, the deviations from this assumption will not be too great. If there is doubt a program such as PLUMEHYD.EXE (Appendix 2) may be run to give better estimates of the port flow distribution. In that case the total flow may not be consistent with the port flow and we may need to do a piecewise analysis of the diffuser. Alternatively, some other more conservative assumptions could be made. To simplify the analysis we will assume uniformity.

Do not worry about what to do about the "1" that is already in the cell, just type 285. As explained previously, the "1" disappears when you begin to type. Again, there are a number of editing commands explained in the previous chapter which allow you to modify the information that is previously contained in the cell.

After typing in 285 use the space bar to move the cursor to the [port flow] cell: it has now changed from 4.469 to 0.01568. The new value in m^3/sec is consistent with the flow from 285 equal ports producing a total flow of 102 MGD (4.469 m^3/sec). The [port flow] cell value is **white** (when the cursor is not in the cell) instead of yellow to remind you that this is a **dependent variable** which you did not input but was calculated by PLUMES from information you did input. Which cells are independent and which cells are dependent depends entirely on how you fill in the interface, i.e. whichever variables are most compatible with the available information. This gives you flexibility to use the data you have, not data you wish you had.

Before going on, note also that the new value is expressed as 0.01568 and not 0.016 (three decimal places to the right of the period) as might have been expected based on the formatting pattern established in the total flow [tot flow] cell. PLUMES reports data to three or four significant digits and up to six are accessible with the <cell Precision> command.

The spacing is 7.315 m (24 ft). It is also noted that the ports are opposed so that there are really two ports per 24 ft section. This presents an interesting problem because, if the plumes from both sides merge, as they would in a crosscurrent or as they might even in the absence of current because they tend to attract each other by mutual suction, then this spacing is too large because this kind of merging is not modeled in the UM program, only side by side merging is. Thus, there is an intuitively appealing suggestion that we should use spacing of 12 instead of 24 feet. But for the moment we will ignore this complication. It will be easy to estimate its effect later when we develop additional cases. Input 7.315 or use the ^K command to input in feet.

In the case of Sand Island, we encounter another complication. Because the diffuser parallels the isobaths it acts as a barrier to sand moving seaward. This has apparently clogged the ports on one side and causes the port flow to double in the remaining ports. But, for now leave the spacing at 7.315.

It is important to note that with the spacing described in this way the farfield predictions will not be correct unless the Configuration menu is used to enable you to input the correct length of the wastefield and the end of initial dilution. The reason is that, by ignoring cross diffuser merging, we have described the diffuser as if all ports are on one side of the diffuser. Consequently, the initial wastefield width needed for the farfield algorithm will be overestimated by approximately a factor of two. More will be said about this subsequently.

It may seem that we are following a rather cavalier path in defining the problem. However, in practice, it is common to first estimate parameters and play around. In effect, this represents a screening analysis. If it is found that the initial dilution is close to being inadequate for meeting water quality standards, then the analysis can be refined. In fact, as will be seen, the interface is ideally suited for this purpose because it is easy to change values anywhere in the interface without starting over. Thus, there is no disadvantage to first scoping out the problem and becoming aware of some of the potential pitfalls in the analysis beforehand.

When you are finished with the [spacing] cell you could move to the salinity cell. But wait a minute, we have just made an important observation about spacing so let's jump (repeated ^J's) back to the title and reflect this fact there. This will give you a chance to practice your editing. In the title cell you could use the arrow keys to move to the end of the string, but, for touch typists, it is easier to use the control key movement cluster. A few ^F's get you to the right place. If there are several words to jump over, the ^QD command does the move in one step. Type in ": no blockage" or something like that. Then return to where you were using the movement commands.

The header of the next cell shows "effl sal" and, because the cursor is now in the brown block, you may infer, correctly, that this refers to effluent salinity. If you are unsure about the content of any cell however, the ^L command (<List equations> on the main menu) may be used to define the cell, as shown in Figure 28.

```
 Help for variable:  s =  effl sal  o/oo

    Effluent salinity.  Sea salt composition is assumed.

Equations and variable definitions:
 s   = sigmasal(t,den).
   den : plume density
   t   : plume temperature
   sigmasal: Newton approximation using the SigmaT function
   (if no solution to sigmasal then s is quasi-defined).


<key>
```

Figure 28. A <List equations> screen for the effluent salinity cell.

The information given, that s = sigmasal(t,den), is somewhat more cryptic than most cells.

It is an abbreviated way of showing that salinity is derived from a complicated function, in this case involving the Newton-Raphson method because the function cannot be solved analytically for salinity. Also, most cells have more than just one defining equation.

Information on the salinity of municipal effluent is not always available. We suspect that the effluent is largely fresh water and guess that it is close to 0.0. (If possible, this should be checked later.) The default is accepted by passing over the cell using the space bar and going to the effluent temperature cell [effl temp]. Being in Hawaii, the temperature is estimated to be about 25 C. As soon as both the salinity and temperature are specified, PLUMES calculates a value of -2.893 for plume density ([effl den] cell). This density is given in sigma-t units and translates to kg/m3 when 1000 is added. Thus, the approximated density of the effluent is 997.107 kg/m3. The conversion can be verified directly by taking an excursion to the [effl den] cell and consulting the dialogue line which gives the value in additional units. (Try the ^P command).

We can approximate for now the effluent salinity and temperature because the effluent is discharged to sea water with a much higher salinity. Thus, the greater part of the density difference, i.e. buoyancy, is due to salinity differences, and the temperature approximations are unlikely to affect the outcome by more than a few percent. However, in regulatory work you would try to define these variables more accurately. (See also the discussion in the Freshwater Discharges of Buoyant Plumes section of Chapter 1.)

The cursor should now be in the upper right corner of the interface in the Miscellaneous (gray) block of cells. Again using the <List equations> command, it is determined that the farfield increment cell [far inc] is the distance between points at which the farfield dilution estimates are reported during the simulation. Notice also that the header typeface is black, which means that cell input is not necessary to determine the initial dilution, (i.e. neither UM nor RSB require it for input). However, as we are interested in farfield bacterial concentration predictions, values for these should be established.

It is known that a surfing area is located within approximately 2000 m of the outfall and, therefore, this is considered to be an appropriate value to put in the farfield distance [far dis] cell. Since only the bacterial levels at this distance are of interest, the farfield increment, the [far inc] cell in which the cursor is presently located, can be rather large, 500 m will do. (An unnecessarily small value may give more output than you want causing previous information to scroll off the screen when RSB or UM are run, necessitating a dump to a disk file.) Enter this value and follow this by putting the value 2000 m in the [far dis] cell.

Now enter the plume depth measured from a standard datum such as mean lower low water (MLLW). (This is an UM program variable which, like a few others, is initialized by the interface.) In this case we know the depth to the center of the ports from which the plumes emanate to be 70.1 m. All ports are at essentially the same depth. The blue background before the first letter in [port dep] indicates the variable, (centerline) plume depth, will be an output variable when running UM. It can be turned on and off with the ^O command.

The next cell, [port dia], is the actual physical diameter of the port (as opposed to the vena contracta plume diameter, the minimum diameter of the plume, in the following [plume dia] cell). The Sand Island diffuser has five different diameters to choose from, so which one should be used? Technically, a diffuser hydraulics model (Appendix 2) could be used to provide estimates for port flow from each port. Experience shows, however, that varying port flow over a limited range does not affect initial dilution radically. Nevertheless, it would be wise, especially for beginners, to do a sensitivity analysis by changing some of the values somewhat. The interface is ideal for this kind of exploration. A conservative value is always appropriate if the screening test is ultimately passed. (See Chapter 1: Effect of Wastewater Flow on Dilution.)

For now, enter 8.5 cm. Notice that the possible input units are in meters, feet, and inches, not centimeters. This time the proper conversion is not available through the ^K command. It is assumed that you are familiar with the fact that 8.5 cm is equal to 0.085 m. Notice that the leading 0 does not have to be entered. Notice also that after inputting the diameter many cells are starting to fill up with white values[2].

Now keep moving the cursor until the cursor is on the [print frq] cell. The print frequency cell [print frq] simply determines how many model steps there are between outputs. Except when the time step becomes too large, UM is designed to double dilution every 100 program steps. Thus a [print frq] cell value of 100 will cause UM to output dilutions of 1, 2, 4, 8..., approximately. This can be adjusted to taste, we will accept the default value for the time being. It is not critical in any case because the model outputs at important milestones, e.g. the trapping level. The performance of RSB is not affected by this cell.

---

[2] The basic idea behind filling empty cells in the interface is this: PLUMES can calculate cell values from input you provide because it is event driven and because it normally has many ways to calculate each cell. To give an example, move the cursor to the [total vel] cell. You may have wondered why some cell labels are displayed against a checkered background which changes as you move from cell to cell. These checkered labels tell you which other variables (cells) serve as independent variables for the cell in which the cursor is located. For example, right now the [port flow] and [plume dia] labels should be on a checkered background. That means that if [port flow] and [plume dia] are defined (either white or yellow), [total vel] will be calculated by PLUMES, as it apparently has been. This is a basic characteristic of the PLUMES interface that makes it act like a specialized spreadsheet. Essentially, most cells have one or several equations associated with it (cf. Figure 19), just like spreadsheets, that allows unknown cells to be defined, providing the appropriate information is available.

But PLUMES provides more than the standard spreadsheet in this respect. If you will now push <F1> followed by <I> (or simply ^I at the interface level) for the <show Independents> command, you will see that other labels are now checkered: first [horiz vel] and [vertl vel], then [plume dia], [p amb den], [effl den], and [Froude #], etc.. Many cells have a multitude of ways of being calculated by PLUMES. The ^L command will reveal just how many there are and define them if the file EQNS resides in the current directory where it can be accessed by PLUMES. It is this ability of PLUMES to calculate variables in many different ways that helps assure that you will have to input only a minimum of information and that you do not have to be an expert and know how to provide specialized information. Your job is to keep finding cells that you know something about and fill them until the interface is completely defined. You can do this by moving directly to the cells you know, passing over the others. If at the end some cells remain unfilled, you will need to continue the process. Remember, cells with black lettering in their labels are not needed for initial dilution calculations, only for farfield estimates.

The port elevation cell [port elev] is used in calculating the CORMIX flow categories, and it also affects UM's prediction of when the plume hits bottom. Here we use the radius of the diffuser pipe, in this case enter 0.84 m.

Accept the default value in the vertical angle cell [ver angle] by skipping over it. A value of 0.0 indicates that the effluent is being discharged horizontally, which is the case with Sand Island and many modern diffusers. It should be becoming apparent that filling out the interface is not such a difficult task after all.

The contraction coefficient cell [cont coef] is normally used to compute the actual initial plume diameter by adjusting [port dia] on the basis of the differentiation between **bell shaped ports**, which have a coefficient approximately equal to 1.0, and **sharp-edged ports**, which have a value near 0.61. Sometimes this information is not provided in which case the value that yields the more conservative dilution could be used. Its value tends not to affect dilution very much.

If salinity and temperature are specified, as they are here, the [effl den] (effluent density) cell is calculated using the **nonlinear** equation of state found in Teeter and Baumgartner (1979). Computed values vary slightly from published values (see Table III in the next chapter). The equation of state used at **run time** in UM is indicated in the **linear/nonlinear window** below the case counter. In running UM, if suspended or dissolved substances factor prominently into determining density it may be better to use a linear equation of state, invoked by defining the density cells while leaving the temperature and salinity cells empty. Any such empty cells (providing, in the ambient block, the layer is defined) will cause the linear mode of UM to run.

Now move the cursor to the pollutant concentration [poll conc] cell. This cell is used to specify the concentration of a specific pollutant in the effluent and, in combination with the ambient concentration cell [amb conc], to help determine the **effective dilution** achieved by the diffuser (see Chapter 1: Dilution Factor, Effective Dilution Factor, and Relationship of Ambient Dilution Water to Plume Concentrations). For example, if the ambient concentration is everywhere zero then the effective dilution is identical to the effluent dilution. However, suppose we accept the default value of 100 (i.e. thinking in terms of percentage) given in the [poll conc] cell and all the ambient concentration cells have a concentration of 1.0. Then, no matter how great the volume dilution is, the effective dilution can never exceed 100.

Any **consistent units of concentration** may be used, which means that the units in the pollutant and ambient concentration cells must match. We will use a value of 6.1×10^8 (colonies)/100ml for the bacterial concentration. In PLUMES format, **scientific notation is input in "e" format**, for example as 6.1e8. Note again, that to replace the default value we simply start typing in the value of 6.1e8 and <space bar> when done.

The cursor should now be on the decay cell [decay]. This is the simple first order decay constant, *k*, used in the equation

$$c \;'\; c_o e^{\&kt} \qquad \textbf{(18)}$$

where c is the concentration time t after a concentration of c_o is measured. For convenience, the primary unit is inverse days. Often, however, decay is expressed in terms of T90 values, which specifies how much time is required for 90 percent of the pollutant to decay, or how much time is required for 90 % of the bacteria to die. The T90 time must be input in hours; for Sand Island we use 1 hr. Thus, after one hour of exposure to daylight in surface waters, 90 % of the bacteria have died. This unit is available by using the <units Konversion> command; when t90hr is indicated in the dialogue window enter the value 1.

As you move to the next cell you will notice that the space bar movement command bypasses the densimetric Froude number [Froude #] and Roberts Froude number [Roberts F] cells; the red block parameters are normally of interest only to researchers and designers. (When it is convenient to use them the ^J command may be used to get into this block.) These numbers will be calculated by the interface when all necessary input is entered.

The cursor should be in the horizontal diffuser angle cell [hor angle]. The outfall structure variables, effluent characteristics, and miscellaneous blocks are complete. The interface screen should now look like Figure 29.

```
 Mar 15, 1994,  14:36:40  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of   1
 Title   Sand Island validation: no blockage                          linear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
     4.469       285   0.01568     7.315       0.0        25       500      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      70.1     0.085   0.08500     2.763     2.763     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
      0.84       0.0       1.0    -2.893     6.1e8     55.26
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90     7.315                        0.000453
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0
                                                                buoy flux puff-ther

                                                                jet-plume jet-cross

                                                                plu-cross jet-strat

                                                                plu-strat

                                                                  hor dis>=

CORMIX1 flow category algorithm is turned off.
 90 deg                                                         45 to 135 deg range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: sandis.var;
```

Figure 29 A partially completed interface.

The cursor is now in the green ambient block, specifically, in the horizontal diffuser angle cell. An angle of 90 degrees (the default value) indicates that the current is perpendicular to the axis of the diffuser, i.e. it is flowing across the pipe and parallel (co-flowing) to the effluent plume. Notice that if 45 degrees were entered the value in the following reduced spacing cell [red space] would change from 7.315 m (the physical port spacing) to 5.172 m, the geometrically

projected spacing. **In UM, the effect of changing the direction of the current simply changes the reduced spacing**. The justification for this procedure is derived from Roberts (1977) and is valid over angles ranging from 45 to 135 degrees. While 90 degrees is the desired angle for now you may change it temporarily to see how it works. Values of 0 to 44 and 36 to 180 degrees, which are outside the range shown in the dialogue window, would produce reduced spacings of 0 to 5.1 m and should not be used for UM (but are appropriate for RSB). Similarly, **values of 181 to 360 produce negative reduced spacings and should not be used**.

Now skip the reduced spacing cell [red space] and move to the port ambient density [p amb den] cell. Notice that it is not one of the cells preferred for input (it has a white header) and we will not enter a value into this cell, even though we could, or into the following port ambient current [p current] cell. Both cells will be calculated by the interface when the ambient depth, density (or temperature and salinity), and current are completed[3].

Now move to the farfield diffusion coefficient cell [far dif] and use the ^L command to get an explanation of this parameter. While the value of the coefficient is not known accurately, it is considered to have the properties of a universal constant. The value, 0.000453, used in this chapter corresponds closely to the 0.01 $cm^{2/3}$/sec found in Fischer et al. (1979), however, a more conservative one, 0.0003, has been adopted as a default value in PLUMES.

The next cell is the farfield velocity [far vel]. The cell label is black, to indicate it is not required for initial dilution estimates. However, it is our goal to estimate farfield dispersion in order to determine maximum bacterial levels in areas where water contact activities occur. Although the dilution of contaminants in the near field would be enhanced by greater current speeds we recognize that high current speed will also result in shorter travel times for the diluted wastes that are carried to the protected zone, thus resulting in less die-off of bacteria. However, the current speed should be realistic and take into consideration not only consistency with the near field current but also factors such as tidal reversals and the likelihood that high currents will persist for long periods of time. In the case of Sand Island, a current of 15 cm/sec is used

---

[3]. This is a good place to point out something you may have already noticed, some of the labels have yellow letters (yellow lettering on a colored field like the [tot flow] cell) while others have white ones (white lettering like the port ambient density [p amb den] cell). In general, the yellow labels mark the variables that are recommended for input, in a sense, they are **preferred variables**. There are a variety of reasons why they are preferred which are rather technical and have to do with the math of the equations. For example, the program may need additional information about the sign of a calculated number if one of the secondary variables is input (e.g. if it is a solution of a square root). **There is even a possibility of inconsistencies** in the input (refer to the manual for an explanation). The miscellanY submenu has a <cHeck consistency> command that can be issued when it is suspected that there is an inconsistency. Normally, inconsistencies will not develop unless the user overrides a cell containing a white (not to be confused with the header lettering color described above) numeric dependent value with a yellow independent input value, a topic that has not been covered yet. Even under these circumstances, inconsistencies (or conflicts) will not usually arise. Also, to avoid alarm, in some cases the <cHeck consistency> command will report values of the same magnitude but different sign; this does not necessarily indicate the case is inconsistent. Finally, the check is based on a comparison of values of the same parameter calculated from each of the different equations that can be seen when issuing the ^L command. Sometimes it will report two very small values, both essentially equal to zero, which nevertheless differ by more than the fractional criterion.

corresponding to a travel time to affected areas 2000 m away of 3.7 hrs. Input 0.15 m/sec.

The cursor is now in the main ambient block [depth]. This is where information on various layers of the ambient receiving water is input. The first depth cell [depth] should normally contain the default value of 0.0 m (water surface), so move to the ambient current [current] cell of the surface layer. We will input depth, salinity, and temperature data shown in Figure 30.

```
 Mar 15, 1994,  14:38:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of   1
 Title   Sand Island validation: no blockage                          nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
     4.469       285   0.01568     7.315       0.0        25       500      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      70.1     0.085   0.08500     2.763     2.763     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
      0.84       0.0       1.0    -2.893     6.1e8     55.26     18.40 1.759E-12
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90     7.315     24.080.00001000  0.000453      0.15    2763000.00004871
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0      1e-5     22.99     34.99     26.18         0   0.01217    0.2653
     30.48      1e-5     23.18     35.00     25.60         0 buoy flux puff-ther
     45.72      1e-5     23.40     35.02     24.95         0 0.0005686     35.61
     60.96      1e-5     23.49     35.00     24.60         0 jet-plume jet-cross
     76.20      1e-5     24.47     35.02     21.22         0     1.473     20820
                                                            plu-cross jet-strat
                                                            4.159E+12     4.136
                                                            plu-strat
                                                                6.933
                                                              hor dis>=

CORMIX1 flow category algorithm is turned off.
  deg C,  deg F                                          -2.0 to 50 deg C range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: sandis.var;
```

Figure 30 Completed interface.

Zero current is often chosen to estimate minimum dilution, which we input in the surface ambient current [current] cell. Note that upon moving to the next cell, the 0 is replaced by a small, near-zero value of 1e-5, which is the e-form scientific notation for 0.00001 m/s. This is done to avoid a mathematical singularity elsewhere in the interface[4]. The value of 1e-5 is practically equivalent to zero but can be input as a smaller value still if necessary.

Note: Other quasi-defined cells can still be generated, if they are, usually the last cell entered caused the condition and can be changed to resolve it. In the case of the [Stratif #] cell,

[4]. Originally a 0.0 value was allowed but resulted in the creation of **quasi-defined cells** (identified by the background color of the cell turning cyan) which made this capability inconvenient. For example, a zero current throughout the ambient block would make it impossible to define a value for the effluent to current ratio cell [K:vel/cur] because the ratio would involve a division by zero. Thus, a quasi-defined cell is one which would normally be defined (all the independent variables that are needed exist), however a singularity (division by zero, negative square root, etc.) keeps that from happening. This is now avoided.

a non-zero density gradient in the ambient density cells will keep it from being quasi-defined.

To establish the minimum dilution it is necessary to also use the maximum density gradient. The appropriate values, as shown in Figure 30 in terms of the depth and density columns, are established by filling in the salinity and temperature columns for the depths shown.

For now, go to the surface ambient salinity cell [salinity], and then the surface ambient temperature cell [temp] and type in the appropriate values shown in the figure. As soon as you do, and follow it with <space bar>, the ambient density [density] value at the surface of 22.99 sigma-t units is computed. The cursor should now be in the ambient concentration [amb conc] cell. Here it is safe to input 0.0 since we expect the receiving water to be generally very pristine, the ambient currents carry the effluent out of the region of the diffuser, and, most importantly, the die-off is generally sufficiently rapid that even recirculated water is likely to contain negligible bacterial concentrations, but that should not generally be assumed. If background were specified the analysis would be correspondingly more conservative because the pollutant concentrations are assumed to be horizontally homogeneous, i.e. constant, even though in the case of bacteria they would be expected to decrease away from the source.

The cursor should now be in the next depth cell [depth]. Since data are given at 100 feet and every 50 feet thereafter, use the ^K command to bring up the ft units in the dialogue line and enter 100 ft. Move to the salinity and temperature cells and continue to fill in the ambient block as shown (the remaining depths are 150, 200, and 250). Because the Configuration string shows a leading "A" the auto-ambient mode is on, which means that default values are taken from the line above. Thus, none of the ambient current speeds or ambient concentrations below the surface need to be typed.

As the last cell in the ambient temperature [temp] column was filled the remaining red cells were automatically calculated by PLUMES and also filled in. The stratification parameter [Stratif #] characterizes the degree to which the ambient is stratified between the surface and seabed when a linear approximation is appropriate. Some technical references (e.g. Fisher et al., 1979) use the linear approach in estimating dilution factors and trapping levels. Like the Froude number, the stratification number is also used to determine similitude between prototype and hydraulic model representations of plume behavior. While useful especially for laboratory experiments, most environmental problems involve complex nonlinear density profiles. The RSB and UM models calculate plume variables, such as dilution and rise, based on the density gradients established by the inputted ambient salinities, temperatures, or densities, rather than the overall average represented by the stratification parameter[5]. You can demonstrate that the stratification parameter does not change when intermediate lines of ambient data are added, deleted, or changed, as long as the data that determine the average parameters are not changed. However, by running successive cases you will see that dilutions and geometric variables calculated by RSB and UM do change appropriately.

---

[5]. Actually, the RSB model uses a stepwise series of linear gradients. It starts with an overall gradient and steps down until the dilution is no longer reduced by more than an arbitrary small amount.

STEP 3: Run Initial Dilution Models

The fact that all the cells (except for the elective Pause cell which is presently showing the horizontal distance [hor dis] cell, its default value) are filled is a sign that the plume model can now be run. Issue the ^U, or <run Um program>, command. The dialogue line will then query "Go to case (<space> for default): 1" offering the current case in the dialogue window. Since we still have only one case we can simply use the space bar to accept the default value. A second query asks "Write to ("prn" for printer, "console", or disk file name):" with a default value of "console". Accepting the default with a <space bar> routes the output to the monitor. The result is shown in Figure 31. Note the use of the nonlinear equation of state is indicated.

```
UM INITIAL DILUTION SIMULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                            m
     70.10   0.08500 610000000     1.000     0.000
     67.27     1.822  18800000     31.18     4.417
     61.20     3.682   6751000     84.58     6.463 -> trap level
     54.65     7.502   3744000     144.2     8.460 -> merging
     53.04     10.75   3406000     153.5     9.365 -> begin overlap
Farfield calculations based on Brooks (1960), see guide for details:
Farfield dispersion based on wastefield width of       2088m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                             m        sec   hrs
    420200     153.6    420200     153.6     500.0      3271   0.9
     49130     155.9     49430     154.9      1000      6604   1.8
      5594     162.6      5723     158.8      1500      9938   2.8
     626.7     172.3     656.8     164.2      2000     13270   3.7
==============================================================================

 <key>
```

Figure 31 UM simulation of the first Sand Island case. Note that the initial wastefield width of 2088m is too large by a factor of two and the farfield predictions should be ignored.

The trapping level dilution is 84.58 which corresponds almost exactly to the dilution found by UMERGE (84.48) and UPLUME (Muellenhoff et al., 1985), and the earlier reported value of 84. Experience shows that under a large range of conditions (without current) UPLUME and UMERGE agree very closely (Baumgartner et al., 1986). Therefore, it is not surprising that we obtain close agreement with UM. It gives us some confidence in the new methodology. Nevertheless, this degree of agreement should not be expected in general. For one thing, in comparing UM and UMERGE, the definition of the aspiration velocity has been simplified which can cause small differences depending on the relative importance of forced and aspiration entrainment. Also, some of the input was approximated and the values are subject to some adjustment. Later, you can make some of these adjustments.

The farfield bacteria concentration based on the open water diffusion equation described in the final chapter — Farfield Algorithm — which uses the less conservative eddy diffusivity factor appropriate to coastal waters (the 4/3 power law), is 626.7, above the water quality standard of 400 colonies/100ml. However, this estimate may be too liberal, in other words, since the wastefield is deeply submerged the survival of the bacteria may be much higher. As a result of this run we could now adjust the T90 time to a value more appropriate for a submerged flow field, such as 10 hours. We would then see a bacterial concentration 1.5×10^6 colonies per 100 ml.

The message "plume element overlap", which is discussed further in the sections on model theory, means that dilution predictions beyond this point would degrade increasingly if UM (not the farfield algorithm) were continued to be used. It may not be significant if dilution increases little in the overlapped region, which can be established by running the simulation to maximum rise using the ^R command and comparing dilution at the beginning and end of overlap.

The UM simulation can be interrupted at any time, execution is then suspended until another keypress restarts or terminates it. After it is finished running, any key will reestablish the input screen, i.e. the interface. The same procedure can be used to run the program again. If we override the word "console" with "prn" (do not enter the quotation marks) on the dialogue line the output will go to the printer (be sure that it is properly connected). Given any other name, PLUMES will attempt to send the output to a disk file (created or appended). Notice that the output contains a copy of the interface screen so that there is an exact record of the input.

As has been indicated, the farfield predictions shown in Figure 31 are not correct because the length of the wastefield is overestimated owing to the assumption that all ports are on one side of the diffuser and are spaced 7.315 m apart. The farfield simulation could be "corrected" without changing the near-field predictions by accessing the Configuration menu (^R) and toggling the <Brooks eqn input> option. The Configuration string will then change from, for example, "A**T**NO0" to "A**R**NO0", where the R stands for "reset" the farfield algorithm initial conditions. Then run UM or RSB as you normally would. After the initial dilution phase is completed PLUMES will prompt "Input wastefield width:" in the dialogue window. Enter an approximate width of 1040 m to override the default value of 2088. PLUMES then prompts "Input starting longitudinal coordinate", i.e., the horizontal travel distance. Here we will accept 9.36 m which is the horizontal distance between the source and the end of the initial dilution zone.

The results are shown in Figure 32. As was anticipated, since small plumes disperse relatively faster than large ones, the farfield concentration is now lower: 536.9. We hasten to add however that this underpredicts farfield concentration because the effect of cross diffuser merging is ignored. At least we have had the opportunity to demonstrate the Configuration menu, and, in any case, we now feel more certain that the 400 colonies/100ml standard will be exceeded. A better estimate of farfield concentration awaits a more complete analysis.

```
UM INITIAL DILUTION SIMULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                            m
     70.10   0.08500 610000000     1.000     0.000
     67.27     1.822  18800000     31.18     4.417
     61.20     3.682   6751000     84.58     6.463 -> trap level
     54.65     7.502   3744000     144.2     8.460 -> merging
     53.04     10.75   3406000     153.5     9.365 -> begin overlap
Farfield calculations based on Brooks (1960), see guide for details:
Input starting longitudinal coordinate:
Farfield dispersion based on wastefield width of       1040m

   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                               m        sec   hrs
    418200     154.4    419100     154.0     500.0      3271   0.9
     46750     164.0     48000     159.6      1000      6604   1.8
      5033     181.1      5387     169.0      1500      9938   2.8
     536.9     201.8     602.7     179.4      2000     13270   3.7
==============================================================================

 <key>
```

Figure 32 Using the Configuration menu to gain control over farfield input and output.

Go ahead and change the Configuration string back to "ATNO0" and run RSB by using the ^B command. The results are given in Figure 33. **For those who also run the non-PLUMES version of RSB, it is important to note that for equivalence the PLUMES RSB version must use a spacing value half as large as the original model since the latter assumes two ports per spacing distance while PLUMES RSB assumes only one.** This is done to be consistent with the UM convention.

Notice that RSB does not report a trapping level or intermediate dilution. However, we may compare the average volume flux dilutions at the plume element overlap level: they are 153.6 and 185.8 for UM and RSB respectively. The corresponding wastefield thicknesses are 10.75 (see [plume dia]) and 12.8 meters respectively, varying by a similar amount. Finally, the respective centerline rises are 17.06 and 11.4 meters.

Once again, if the analysis allows the luxury, it is convincing to present the results of the most conservative conditions likely to be encountered for the variables even if they are unlikely to occur simultaneously.

(Note that if the UM simulated plume is allowed to develop to maximum rise, which is possible when the Configuration string is changed to, for example, "ATNM0" ("M" is maximum rise), the corresponding farfield dilution, diameter, and rise are 156.2, 16.5, and 17.23 respectively. This is characteristic of the overlap problem under which plume diameter is overestimated, which, if prolonged, feeds back and increases the initial dilution. Frick, Baumgartner, and Fox (1994) show this problem is shared by Lagrangian and Eulerian integral flux plume models generally, due to inadequacies of the standard round plume assumption. It is unimportant in this case, the dilution increasing from only 153 to 156 in the overlapped region.)

```
                                  RSB
                 Written by Philip J. W. Roberts (12/12/89)
                   (Adapted by Walter E. Frick (1/12/92))

 Case:  1: Sand Island validation: no blockage

 Lengthscale ratios are: s/lb =   3.35 lm/lb =   0.20
 Froude number, u3/b =            0.00
 Jet Froude number, Fj =         18.6

 Rise height to top of wastefield, ze =  17.1
 Wastefield submergence below surface =  53.0
 Wastefield thickness, he =              12.8 m
 Height to level of cmax, zm =           11.4 m
 Length of initial mixing region, xi =    8.7 m

 Minimum dilution,       Sm =   161.6
 Flux-average dilution, Sfa =   185.8 ( 1.15 x Sm)
 Results extrapolated beyond their experimental values, may be unreliable
 Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed

<key> for farfield prediction


Farfield calculations based on Brooks (1960), see guide for details:
Farfield dispersion based on wastefield width of       2085m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                             m         sec   hrs
    403900     185.9    404000     185.9     500.0      3275   0.9
     47210     188.7     47500     187.5      1000      6608   1.8
      5369     196.8      5496     192.2      1500      9942   2.8
     600.6     208.6     630.2     198.8      2000     13280   3.7
Farfield result will not reflect decay in the near-field.  <key>
```

Figure 33 The RSB simulation of the first Sand Island case. (Note the excessive estimate of the wastefield width.)

PLUMES links the same Brooks farfield model to RSB as it does to UM. It may seem odd then that RSB predicts a farfield concentration almost equal to that of UM (600.6 vs. 626.7) even though the dilution is substantially higher (208.6 vs. 172.3). One reason is the small T90 time: in UM the decay mechanism is functional from discharge, while the pollutant is assumed to be conservative (non-decaying) in the initial dilution region in RSB.

As was suggested previously, it is perhaps appropriate to consider a weakly stratified case, as shown in Figure 34, in order to simulate a surfacing waste field that might impact recreational waters. Notice that this case is Case 2, as is shown in the upper right corner of Figure 34. To create a new case use the ^C command, <go to next Case> on the Movement menu. The new case will use the information contained in the present case from which the ^C command is given as a template. Once in the new case, it may be edited. In Figure 34, some of the ambient data has been changed: the case title, one line of ambient has been removed using the ^YD command, and changes shown in **bold**.

```
Mar 15, 1994,  14:44:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   2 of   2
Title   Sand Island validation, no blockage, min strat.              nonlinear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    4.469       285   0.01568     7.315       0.0        25       500      2000
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
     70.1     0.085   0.08500     2.763     2.763     0.000      0.10       500
port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
     0.84       0.0       1.0    -2.893     6.1e8     55.26     18.68 1.759E-12
hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     7.315     23.290.00001000  0.000453      0.15    2763000.00001395
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0      1e-5     22.99     34.99     26.18         0  0.006417    0.2576
       30      1e-5     23.23     35.11     25.71         0 buoy flux puff-ther
       61      1e-5     23.31     35.16     25.56         0 0.0005686     35.96
       76      1e-5     23.28     35.15     25.64         0 jet-plume jet-cross
                                                                1.494     20820
                                                            plu-cross jet-strat
                                                            4.039E+12     5.696
                                                            plu-strat
                                                                11.12
                                                              hor dis>=

CORMIX1 flow category algorithm is turned off.
                                                             0.0 to any  range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: sandis.var;
```

Figure 34 Case 2: a weakly stratified Sand Island case.

As before, you can now run UM and RSB, the results are given in Figure 35. Again, the predicted UM and RSB dilutions compare well, being 601.6 and 686.3 respectively. This time the UM plume diameter and the RSB wastefield thickness, which are not totally comparable quantities, also agree closely, being 37.57 and 36.1 meters respectively. The message warning **plume element overlap**, indicates upstream intrusion of the wastefield is possible (Frick et al., 1989). The rises are considerably different, being 50.53 (70.10 - 19.57) and 32.3 meters respectively. The UM farfield concentration is now 134.2 colonies/100ml, which is much less than the previous farfield concentration and would meet the water quality standard of 400 colonies/100ml.

STEP 4: Analyze the Model Results and Make Adjustments

In the previous section the RSB, UM, and historical model results were compared. Now we will delve into the implications of some of the findings and question some of the assumptions that were made. In doing so, we will change the program configuration to make it possible to find the CORMIX flow categories for the cases in question. We will also illustrate the **PLUMES conflict resolution capability**.

From the standpoint of assumptions made earlier, in Sand Island Case 3 we will first examine the implications of sand blockage of half of the diffuser ports. In Case 4 the focus shifts to the sensitivity of the models to the magnitude of the decay coefficient, to other assumptions and input data. Finally, in Case 5, we examine the effect of current on predictions.

```
UM INITIAL DILUTION SIMULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                            m
     70.10   0.08500 610000000     1.000     0.000
     67.28     1.810  18800000     31.21     4.432
     44.72     7.382   1603000     331.5     8.008< merging
     29.51     11.73    936100     520.1     8.868< trap level
     19.57     37.57    727000     601.6     9.652< begin overlap
Farfield calculations based on Brooks (1960), see guide for details:
Farfield dispersion based on wastefield width of       2115m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                                m        sec   hrs
     89800     602.0     89810     601.9     500.0      3269   0.9
     10510     610.5     10570     606.9      1000      6602   1.8
      1197     636.2      1224     621.8      1500      9936   2.8
     134.2     673.9     140.5     642.9      2000     13270   3.7
==============================================================================

 <key>


                                  RSB
                 Written by Philip J. W. Roberts (12/12/89)
                   (Adapted by Walter E. Frick (1/12/92))

 Case:  2: Sand Island validation, no blockage, min strat.

 Lengthscale ratios are: s/lb =   0.92 lm/lb =   0.06
 Froude number, u3/b =            0.00
 Jet Froude number, Fj =         18.9

 Rise height to top of wastefield, ze =  48.2
 Wastefield submergence below surface =  21.9
 Wastefield thickness, he =              36.1 m
 Height to level of cmax, zm =           32.3 m
 Length of initial mixing region, xi =   32.6 m

 Minimum dilution,       Sm =   596.8
 Flux-average dilution, Sfa =   686.3 ( 1.15 x Sm)
 Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed

<key> for farfield prediction
```

Figure 35 UM and RSB predictions for Sand Island Case 2.

Instead of using the ^C command, in going from one case to the next it is easier to use the <Page Up> key. Use it to create Case 3. Now make the changes indicated in Figure 36 to the ambient block (remember to delete the middle lines using ^YD), the title, and the [# ports] cell. To change the PLUMES configuration use the ^R command to obtain the Configuration menu, then toggle the CORMIX flow categorization feature — simply press <C>. Notice that the configuration string at the bottom of the interface changes from AT**N**O0 to AT**C**O0 after which the flow category is given above the dialogue line: "CORMIX1 one port flow s5 unattached".

```
 Mar 15, 1994,  14:46:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   3 of   3
 Title   Sand Island validation, blockage, min strat.                nonlinear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    4.469       142   0.03147     7.315       0.0        25       500      2000
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
     70.1     0.085   0.08500     5.546     5.546     0.000      0.10       500
port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
     0.84       0.0       1.0    -2.893     6.1e8     55.26     37.50 9.028E-13
hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     7.315     23.270.00001000  0.000453      0.15    554600 4.089E-06
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0      1e-5     23.19     35.13     25.90         0  0.003473    0.2574
        76      1e-5     23.28     35.15     25.64         0 buoy flux puff-ther
                                                              0.001107     72.19
                                                            jet-plume jet-cross
                                                                3.001     41780
                                                            plu-cross jet-strat
                                                            8.100E+12     10.97
                                                            plu-strat
                                                                20.97
                                                              hor dis>=

CORMIX1 one port flow s5 unattached.  Use UM to overlap point. (See manual)
 0                                                            0.0 to any  range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: sandis.var;
```

Figure 36 Sand Island blocked ports case.

The PLUMES CORMIX classification algorithm is presently limited to single ports, thus the classification applies only to the unmerged region of the plume. Also, CORMIX is limited to predicting plume behavior in, at most, two layer systems. Consequently, the interface will not predict the flow category unless there are at least two and not more than three lines of ambient input information. This is one reason why the middle lines in the ambient block in Figure 34 have been deleted. (Also, the surface salinity and temperature cells have been arbitrarily adjusted to give about the same density gradient found between the 30 and 76 m depths, ignoring the measured values at 61 m.) In this case this is not a significant simplification, especially since the original density structure is not entirely self-consistent as is evidenced by the unstable layer in the third line of ambient stratification in Figure 34 (denser fluid of 23.31 sigma-t units would appear to lie over less dense fluid of 23.28 sigma-t units). This could be the result of measurement anomalies or a real transient condition.

Run Case 3 — Figure 37. The initial dilutions do not change very much: 601.6 to 577.1 and 686.3 to 658.7 for UM and RSB respectively. The farfield concentrations also change little: from 134.2 to 124.8 and 184.0 to 174.0 for UM and RSB respectively. The changes would be greater except for the fact that the surface is reached in Figure 37. Under these conditions involving light currents, the two models, very different in formulation, are in close agreement.

While you are still in Case 3, use the <Page Up> command to create Case 4. Earlier it was assumed that the effluent temperature was 25 C, its more "correct" value is 25.1 C. While this is a trivial change, go ahead and enter it anyway. Also, an effluent of 0.99979 gm/cc is reported; do not enter it just yet. While the differences are seemingly trivial, it does provide an opportunity to demonstrate the conflict resolution capability.

```
UM INITIAL DILUTION SIMULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                            m
     70.10   0.08500 610000000     1.000     0.000
     68.53     2.388  18860000     31.21     5.957
     49.04     7.377   2578000     211.2     13.38< merging
     2.752     19.19    790700     561.3     17.97< trap level
    0.1349     20.25    758700     577.1     18.17< surface hit
Farfield calculations based on Brooks (1960), see guide for details:
Farfield dispersion based on wastefield width of       1052m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                                m        sec   hrs
     96780     579.9     96960     578.8     500.0      3212   0.9
     10840     614.9     11120     599.2      1000      6546   1.8
      1169     678.0      1249     633.6      1500      9879   2.7
     124.8     754.9     139.8     672.4      2000     13210   3.7
==============================================================================


 <key>

                                  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:  2: Sand Island validation: blockage, min strat.

Lengthscale ratios are: s/lb =   0.59 lm/lb =   0.09
Froude number, u3/b =            0.00
Jet Froude number, Fj =         38.0

Rise height to top of wastefield, ze =  70.1 m
Wastefield submergence below surface =   0.0 m    PLUME SURFACES
Wastefield thickness, he =              52.6 m
Height to level of cmax, zm =           47.0 m
Length of initial mixing region, xi =   50.0 m

Minimum dilution,       Sm =   572.8
Flux-average dilution, Sfa =   658.7 ( 1.15 x Sm)
Roberts Fr. # < 0.1 (aspiration dominated), no avg. flux dilution formed

<key> for farfield prediction

FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of       1039m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                                m        sec   hrs
    135500     661.1    135600     660.2     500.0      3000   0.8
     15190     699.1     15570     682.3      1000      6333   1.8
      1634     770.7      1746     721.5      1500      9667   2.7
     174.0     858.7     195.0     766.1      2000     13000   3.6
Farfield result will not reflect decay in the near-field.  <key>
```

Figure 37 UM and RSB predictions for Case 3.

By now you are familiar with the fact that PLUMES differentiates between independent (yellow) variables, or values, that you provide (or accept by default) and dependent (white) variables that PLUMES can create on its own from the information you type into the spreadsheet interface. You may have wondered, "What would happen if I move to a cell which contains a white value and I input a new value, thus overriding the old value?" This is the primary reason why other programs do not allow the input of redundant variables. The danger is that you will either create an inconsistency or, as it is called in mathematics, overspecify the system. PLUMES has the capability to resolve many of these conflicts.

Go ahead and move the cursor in the effluent density [effl den] cell and, ignoring the dependent value it contains, use the ^K command to obtain the units of gm/cm3 and enter 0.99997 kg/m^3.

As soon as you are finished entering the data the background in the effluent salinity and temperature cells ([effl sal] and [effl temp]), the plume (port) depth cell [port dep] and the brown effluent plume density [effl den] cells acquire a magenta background color and the 70.1 value in [port dep] should begin to blink. PLUMES has detected the conflict that your overriding of the density value has caused. You are now confined to the conflict resolution mode until you complete the actions shown in the dialogue window. The <space bar> will move you from cell to cell, showing its location by blinking the value in each in turn. You must determine which of the conflicting independent variables you wish to delete and then do so. That is the only normal way to leave the mode. In this case, move the cursor to the [effl sal] and press <D> or the delete key. Immediately, PLUMES replaces it with the value of 3.600 o/oo.

This new value has interesting implications. The question might be asked whether the effluent is indeed so saline, or is it more likely that suspended or other dissolved contaminants contribute to the density or is it a case of analytical measurement errors? This question will not be resolved here but may be important to pursue if the reduction in dilution caused by reduced buoyancy results in a standards violation. In any case, by running UM you find that the farfield bacterial count has been raised only a few percent and is still below the critical value.

Now we will create Case 5 to provide another variation of Case 2, the case with minimum stratification and no blockage. Use ^C and <2> to return to Case 2 followed by ^C and <5> to establish the new case. Our main objective is to analyze the effect of current, but first we will look at another bacterial contaminant that is regulated, Enterococcus, which is found in the effluent at 6.3×10^6 colonies/100ml. When you make just this change in the [poll conc] cell and run UM and RSB you see that UM provides a farfield dilution of 673.9 which is exactly the same as Case 2 and a plume concentration of 1.386 which is 1/96.6 of 139, the concentration found with Case 2. Of course this is the same fraction as 6.3×10^6 is of 6.1×10^8.

RSB provides a greater farfield dilution (993.9) than UM because the initial dilution is higher. However, the 1.901 colonies/100ml is greater than the UM concentration because UM

includes die-off in the initial dilution region while RSB does so only in the farfield. However, both RSB and UM plume concentrations are proportional to the effluent concentrations.

Both RSB and UM are now in agreement: the discharge will meet the Enterococcus water quality criterion of 7 colonies/100ml, predicting 1.901 and 1.386 colonies/100ml respectively. However, predicted concentrations are very sensitive to the value of the decay constant. For example, if the T90 time for Enterococcus is 1 hour and 15 minutes, rather than one hour, an increase of only 25%, the Enterococcus bacteria concentration predicted by UM increases more than sixfold, to 8.044 colonies/100ml, a value close to the numerical value of the Enterococcus standard. The corresponding RSB concentration is 10.18.

Before wrapping this example up, we will make one more change. It may be argued that it is unrealistic to subject the plume to zero current in the initial dilution (or rise) region and then assume that the subsequent current is 15 cm/sec. We will now examine the effect of current on predictions of the two models.

From Case 3 create Case 6 using the ^C command. Add to the title the word "current". Move to the ambient current cell [current]. Now type .1, i.e. 10 cm/sec, over each of the currents. Also, change the concentration in the [poll conc] cell to 6.3e6. The interface for Case 6 should agree with Figure 38.

The predictions for both UM and RSB are shown in Figure 39. The UM average dilutions at the end of initial mixing (overlap is no longer a problem) and at 2000 meters are substantially higher than RSB, 1667 compared to 1111.8 and 2131.3 versus 1400.9. The UM farfield Enterococcus concentration is disproportionally lower than the RSB value, 0.5343 compared to 2.144 colonies/100ml, reflecting again the treatment of die-off in the initial dilution phase by UM but not by RSB. Since the initial dilution region is 275 m long, the effluent takes the better part of an hour to traverse this distance. Nevertheless, both RSB and UM predict that the standard would be met under these conditions. However, at 1500 m the models would be in disagreement on the standard being met.

Some of the differences in average dilutions can be attributed to the fact that RSB uses a constant peak-to-mean ratio of 1.15. The average flux dilution calculation of 1440.7 also given in Figure 39 suggests a higher ratio would agree more closely with the average flux dilution calculation and with UM. It is difficult to describe the relationship between average and centerline values based on empirical measurements because it is necessary to define the plume boundary. Thus, it is possible that the RSB average predictions are overly conservative.

All along we have been finessing the issue of port blockage and using the spacing on one side of the diffuser (half the number of ports) versus using half the spacing (all ports). Of course, PLUMES can be easily set up to do either. When the number of ports in Case 6 is restored to 285 and the spacing is reduced to 3.858 m (12ft) the initial dilution for UM increases from 1667 to 1774, a relatively small change. Increased dilution from more ports more than offsets decreases due to smaller spacing. For RSB it increases comparably from 1111.8 to

1268.9. Neither change is really significant, although it may be in other circumstances. If the most conservative analysis still shows the standards will be met, the "right" answer is really irrelevant. However, if standards are not met then refinements are in order.

```
 Mar 15, 1994,  14:47:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   6 of   6
 Title   Sand Island validation: blockage, min strat., current        nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
     4.469       142   0.03147     7.315         0         25       500      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      70.1     0.085   0.08500     5.546     5.546     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
      0.84       0.0       1.0    -2.893     6.3e6     55.26     37.50    0.9028
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90     7.315     23.27    0.1000  0.000453      0.15     55.46 4.089E-06
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0       0.1     23.19     35.13     25.90         0  0.003473    0.2574
        76       0.1     23.28     35.15     25.64         0 buoy flux puff-ther
                                                              0.001107     3.351
                                                            jet-plume jet-cross
                                                                3.001     4.178
                                                            plu-cross jet-strat
                                                                8.100     10.97
                                                            plu-strat
                                                                20.97
                                                              hor dis>=

CORMIX1 one port flow s4 attached.  a1. Use UM. (See manual)
 76 m, 249.3 ft                                          0.0 to ~200 m range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: sandis.var;
```

Figure 38 Case 6, with current.

STEP 5. Using the Results in the Decision Making Process.

As we said it might, the analysis evolved along several paths and examined several issues. Yet, the higher flow cases are still not analyzed and the analysis remains incomplete. Completing the job is left an as exercise. However, given that the data was reliable and appropriate, that our conclusions about the proper use of UM and RSB are correct, and that this is the only contaminant of concern, it seems that the proposed plant expansion should meet the state's water quality criterion for Enterococcus. Thus, even doubling the flow rate would allow the standard to be met according to the UM predictions.

But how good are the input data? In the case of the decay constant, we have observed extreme sensitivity of the bacterial concentration to minor changes in the decay constant. Bacterial survival in ocean water is known to depend strongly on solar insolation, protozoan predation, and other factors. We also saw that dilutions and concentrations were sensitive to ambient current speeds and ambient density, and, in this case, less sensitive to port spacing.

With these considerations in mind, it is important for the analyst to obtain the best data possible and to encourage regulatory agencies to acquire environmental data over a wide range of conditions. Even then, it is apparent that judgment is also likely to play a role in the decision making processes.

```
UM INITIAL DILUTION SIMULATION (nonlinear mode)
plume dep plume dia poll conc  dilution   hor dis
         m         m                            m
     70.10   0.08500   6300000     1.000     0.000
     69.22     2.082    195300     31.21     5.830
     62.52     7.347     28050     208.3     16.46< merging
     42.47     34.54      4950     997.8     45.46
     35.52     48.89      3433      1335     57.70< trap level
     30.02     64.53      2546      1667     70.17< surface hit
Farfield calculations based on Brooks (1960), see guide for details:
Farfield dispersion based on wastefield width of       1096m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                               m        sec   hrs
     406.3    1670.4     406.7    1669.0     500.0      2866   0.8
     45.97    1753.4     46.91    1717.4      1000      6199   1.7
     4.987    1921.2     5.285    1810.3      1500      9532   2.6
    0.5343    2131.3    0.5924    1917.9      2000     12870   3.6
==============================================================================

 <key>

                                  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:  6: Sand Island validation: blockage, min strat., current

 Lengthscale ratios are: s/lb =   0.59 lm/lb =   0.09
 Froude number, u3/b =            0.91
 Jet Froude number, Fj =         38.0

 Rise height to top of wastefield, ze =  70.1 m
 Wastefield submergence below surface =   0.0 m    PLUME SURFACES
 Wastefield thickness, he =              62.4 m
 Height to level of cmax, zm =           47.0 m
 Length of initial mixing region, xi =  206.2 m

 Minimum dilution,       Sm =   966.8
 Flux-average dilution, Sfa =  1111.8 ( 1.15 x Sm)
 Wastefield width:    1031.50m   Avg. flux dilution (width*he*u/Q):     1440.7


<key> for farfield prediction

FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of       1039m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                               m        sec   hrs
      1618    1112.4      1618    1112.4     500.0      1959   0.5
     185.4    1151.7     188.0    1135.4      1000      5292   1.5
     20.11    1259.2     21.18    1195.6      1500      8625   2.4
     2.144    1400.9     2.367    1269.1      2000     11960   3.3
Farfield result will not reflect decay in the near-field.  <key>
```

Figure 39 UM and RSB predictions for Case 6.

EXAMPLE: CORMIX1 COMPARISON, DENSITY, AND STABILITY

INTRODUCTION

Beginning in 1973, the U.S. EPA sponsored research which ultimately led to a succinct, untuned statement of forced entrainment, the Projected Area Entrainment (PAE) hypothesis (Frick and Winiarski, 1975; Winiarski and Frick, 1976, 1978; Teeter and Baumgartner, 1979; Frick, 1984; Frick, Baumgartner, and Fox, 1994). Models using PAE, all currently expressed in the Lagrangian formulation, include OUTPLM (Teeter and Baumgartner, 1979), UMERGE (Muellenhoff et al., 1985), UM, and JETLAG (Lee and Cheung, 1990). Sometimes criticized, the work was recently verified and justified by Lee and Cheung (1990) and Cheung (1991). Cheung (1991) shows that JETLAG, a three-dimensional plume model, clearly outperforms the highly regarded Chu (1975) and Schatzmann (1979) models in predicting trajectory and dilution constants in asymptotic flow regimes. It also indicates the correct power law dependence of the trajectory in different flow regimes. Frick, Baumgartner, and Fox (1994) demonstrate the similarity between UM and JETLAG for two-dimensional flow, showing that Cheung's conclusions concerning JETLAG apply to UM as well.

Nevertheless, while it should be possible to apply the PAE hypothesis to plume behavior in general, the EPA UM model is presently limited to simple merging geometries and surface interaction phenomena. Thus, it performs best when plumes are discharged in deep water. It is also a two-dimensional model, though the merging version is pseudo-three-dimensional and an experimental single-port three-dimensional vector version comparable to JETLAG exists.

The RSB model overcomes some of these limitations, which also played a role in EPA's decision to develop the EPA CORMIX models, or expert systems (summarized by Jirka and Hinton, 1992). CORMIX stands for CORnell MIXing zone models. The idea was to exploit accumulated laboratory and field experience to compile a set of methods and empirical models to bridge the gaps evident in theoretical modeling. The Cornell initiative resulted in the development of CORMIX1, CORMIX2, and CORMIX3 for the analysis of submerged single port discharges, submerged diffusers, and surface discharges, respectively. About 80 different diffuser and ambient profile combinations, or **flow classifications** are represented.

But, while theoretical models are subject to assumptions, their behavior is fairly predictable when those assumptions are met. On the other hand, empirical models are most effective when prototype and model variables and conditions match closely. When they do not the predictions can degrade substantially. This is a real, if fine, distinction. In other words, it is often difficult to extrapolate to conditions which were not included in the experimental design on which the models are based. Since it is often not clear to the user when extrapolation occurs, this can be a real problem. The example in this chapter demonstrates some of the pitfalls.

An example comparing the UM and CORMIX models is presented to give you an appreciation

of how PLUMES may be used to assess the appropriate uses for CORMIX, RSB, and UM. At the same time it will help you understand the differences between the plume models, their strengths and weaknesses. The example chosen is from Appendix B of Jirka and Hinton (1992), in which a full statement of the problem and a description of the CORMIX1 solution is found.

In addition to the references to CORMIX, this example provides an opportunity to explore the very important roles of density and stability in plume behavior and modeling. They are the sources of some of the pitfalls alluded to above. It also addresses the relationship between average and centerline plume properties.

PROBLEM

A manufacturing plant is discharging effluent into a reservoir. The effluent of 3.5 MGD contains chlorides at a concentration of 3500 ppm (3.5 o/oo) and is released at a temperature of 20 C. The reservoir is large and deep, a cross section is shown in Figure 40(a). The discharge is at a depth of 29.9 m, 0.6 m off the bottom, and is directed upward at an angle of 10 degrees, whose horizontal projection is perpendicular to the current. The port diameter is 25.4 cm. In summer, the temperature profile (CORMIX approximation) of the lake is 29 C at the surface and 28.1, 19.1, and 11 C at depths of 15.5, 15.5, and 35 m respectively as shown in Figure 40(b). The current in the bottom layer is small: 0.015 m/s.

The maximum allowable concentration is 1200 ppm of chloride and the allowable continuous concentration is 600 ppm. The mixing zone boundary is 60 m away from the port. CORMIX1 calculates an effluent density of 998.3872 kg/m^3 and an ambient density of 999.6476 kg/m^3.

Using a layer boundary depth of 15.5 m, CORMIX predicts the flow class S3 for this example. No bottom attachment is indicated. The dilution at the boundary of the specified regulatory mixing zone is predicted to be 11.9 at a depth of 27.5 m. This is a centerline dilution — the average dilution would be significantly greater. The dilution is sufficient to meet both the maximum and continuous criteria.

Because the plume is expected to trap in the stable bottom layer, we expect the PLUMES UM model to simulate this case well, even though some of the underlying assumptions are not met. RSB, as a multiple port diffuser model, is not applicable. If issued, the RSB command will cause the message "Use RSB for multiple port diffusers" to appear in the dialogue window.

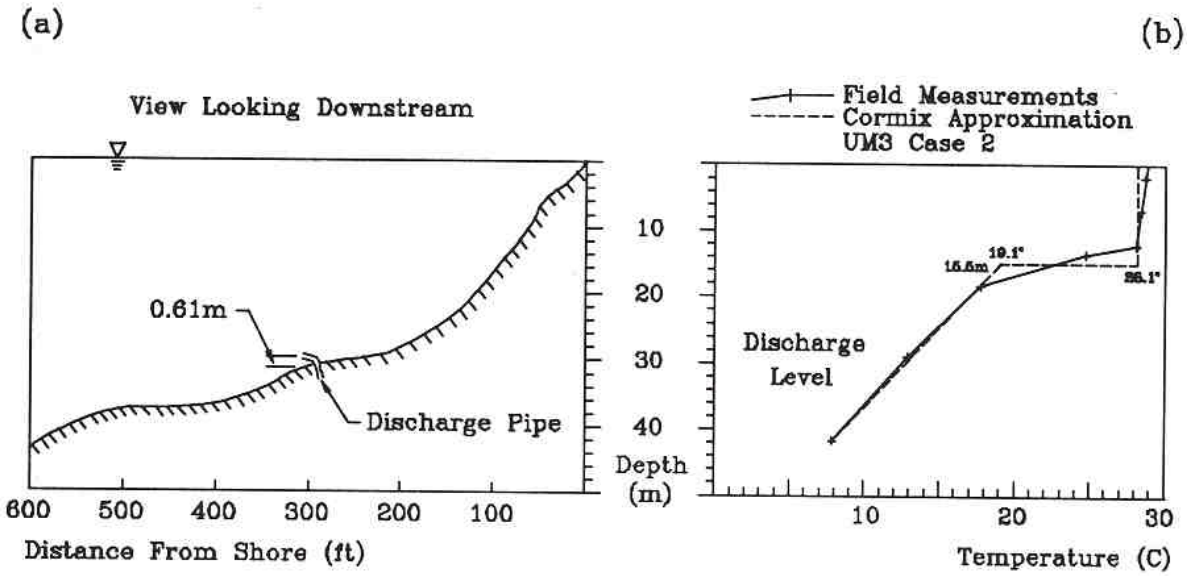

Figure 40. (a) Reservoir cross-section. (b) Temperature profile.

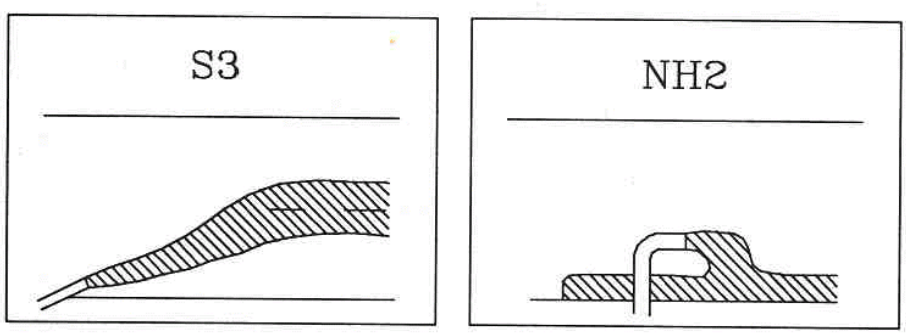

Figure 41. Schematics of flow classifications S3 and NH2 (Hinton and Jirka, 1992).

ANALYSIS

General Considerations

To begin this exploration of the relationship of the UM model to CORMIX and the issues of density, stability, and plume profiles, start PLUMES and type in the data as shown in Figure 42. (Since the PLUMES interpolation capability will be demonstrated, leave the blank cells in the ambient block as shown. Since the Configuration string shows that the auto ambient option is on, which will normally provide a default value for these cells, you can turn it off.

```
Mar 11, 1994,  15:28:16  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of   1
Title   CORMIX1 example, H&J 1992                                      linear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
   0.1533         1    0.1533      1000       3.5        20        20        60
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
     29.9    0.2540    0.2540     3.026     2.980    0.5255      0.10       500
port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
      0.6        10       1.0    0.9296      3500         0
hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90    1000.0             0.01500  0.000453     0.015     201.8
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0     0.015    -3.993         0      29.0         0
     12.5     0.015    -3.733         0      28.1         0 buoy flux puff-ther
     18.0     0.015    -1.250         0      17.5         0
     29.9     0.015                                        0 jet-plume jet-cross
     35.0     0.015   -0.3299         0        11         0               45.41
                                                            plu-cross jet-strat

                                                            plu-strat

                                                              hor dis>=

CORMIX1 algorithm limited to three lines of ambient
                                                             0.0 to any  range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: cormix1.var;
```

Figure 42. First draft input for the CORMIX1 example.

Alternatively, you could move around the cells or delete the default values using ^T.)

Several assumptions and statements concerning the input should be clarified: **The default port spacing [spacing] of 1000 m is acceptable. It means that merging will not occur because the plumes will never grow that large and thus UM will run as a point source model**. Also, as a first cut, the effluent salinity cell is input as 3.5 o/oo (3500 ppm) even though, since the effluent is neither fresh nor sea water, the PLUMES equation of state is not valid for accurately estimating the density of the effluent. The ^K (units conversion) command has been used to convert units in several cells, e.g. to input 3.5 MGD in the total flow cell. For purposes of demonstration, the ambient depth of 29.9 m has been entered into the ambient block while the density, salinity, and temperature cells have been left blank.

It is assumed the effluent is co-flowing, i.e. discharged in the direction of the current, even though it contradicts the actual geometric flow configuration. This is necessary because for single ports UM is a two-dimensional model. A horizontal angle [hor angle] of 90 degrees indicates the plume will be modeled as a co-flowing case. It is a justifiable assumption because the current is small. Furthermore, it is a conservative assumption because entrainment will be underestimated and, therefore, dilution will be less than it would be otherwise. This is due to the fact that the plume will project less area to the current and therefore forced entrainment will be reduced. Thus, a solution combining near and far field solutions may be patched together. CORMIX1 works in a somewhat similar fashion, patching together different modules valid in different parts of the plume's trajectory.

```
                              PLUMES Configuration

 A: Automatic ambient fill is on
 R: Brooks equation input deleted
 C: The CORMIX flow categorization algorithm is inactive
 O: UM farfield predictions begin at element overlap
    Farfield model initiation choices are:
    M: maximum rise; O: element overlap; P: pause criterion.
    Other criteria, such as surface interaction, will override these choices.

 0: Brunt-Vaisala reversals determined by UM as 1 or 2
 ...
   <key>
```

Figure 43. The PLUMES configuration.

Before proceeding, it is good practice to assure that the model configuration options are set appropriately. Use the <Show configuration> command, ^RS, to show the current settings (Figure 43). It shows that the CORMIX1 classification algorithm is currently inactive. Since we want to illustrate the association between PLUMES and CORMIX, use the <Cormix1 categories> command, or <C>, to activate the option. The third letter in the configuration string at the bottom of the screen will change from "N" to "C" (e.g., ATNO0 to ATCO0). The new configuration string is shown in Figure 44.

To establish the proper, interpolated temperature at the 29.9 m depth in the ambient block,

```
 Mar 11, 1994,  15:32:37  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   1 of   1
 Title   CORMIX1 example, H&J 1992                                     nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    0.1533         1    0.1533      1000       3.5        20        20        60
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      29.9    0.2540    0.2540     3.026     2.980    0.5255      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
       0.6        10       1.0    0.9296      3500         0    -49.73     1.510
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    1000.0   -0.5584   0.01500  0.000453     0.015     201.8  -0.01961
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0     0.015    -3.993         0      29.0         0   0.03357  -0.01458
      12.5     0.015    -3.733         0      28.1         0 buoy flux puff-ther
      18.0     0.015    -1.250         0      17.5         0-2.235E-06     18.59
      29.9     0.015   -0.5584      0.00      13.0         0 jet-plume jet-cross
      35.0     0.015   -0.3299         0        11         0     11.89     45.41
                                                              plu-cross jet-strat
                                                                  662.4     4.504
                                                              plu-strat
                                                                  2.772
                                                                hor dis>=

CORMIX1 algorithm limited to three lines of ambient
  o/oo                                                 0.0 to ~200 o/oo range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: cormix1.var;
```

Figure 44. Interface with CORMIX flow category and interpolated temperature.

put the cursor in the temperature cell at 35 m depth. Since the automatic ambient fill option is on you may have to use the ^T command to keep the 29.9 m temperature cell empty after the cursor is moved through it. From the 35 m temperature cell issue the command ^YI; the correct **interpolated** temperature, 13.0 C, appears immediately as shown in Figure 44. The same could be done for the salinity cell although it will be easier to simply move the cursor through the cell (or input 0 if the automatic ambient fill option is off). The ambient density will be calculated automatically upon moving from the salinity cell. While density issues will be discussed further, it is worth noting here that interpolating temperature and salinity value, will not result in the same density as interpolating on density directly. The interpolated values are also shown in Figure 44. The inclusion of the 29.9 m ambient line is not a requirement.

Notice that the **CORMIX window** near the bottom of the screen states: "CORMIX1 algorithm limited to three lines of ambient". This is a limitation of the PLUMES interface which does not yet implement the full CORMIX classification algorithm. (CORMIX provides also for two layers with a discontinuity, requiring four lines of ambient data. Also, the abridged version that is implemented has not been reviewed by authors of the CORMIX models.) In some cases it is possible to circumvent this limitation. For example, if the plume remains in the bottom layer the

```
plume dep plume dia poll conc  dilution   hor dis
          m         m                            m
     29.90    0.2540      3500     1.000     0.000
     28.89     3.240     267.5     13.10     7.496 -> bottom hit
     28.82     4.045     212.8     16.47     9.574 -> bottom hit
 -> local maximum rise or fall
     30.37     7.460     109.4     32.05     19.00 -> bottom hit
     30.51     7.654     106.4     32.95     19.51 -> trap level -> bottom hi
     31.66     10.39     77.88     45.01     26.31 -> bottom hit
 -> local maximum rise or fall -> begin overlap
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      10.39m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                             m        sec   hrs
     48.38      72.4     59.93      58.5     40.00     912.4   0.3
     24.09     145.3     43.24      81.0     60.00      2246   0.6
==============================================================================

 <key>

 Use RSB for multiple port diffusers  <key>

 <key>
```

Figure 45. UM and RSB output for the draft case (Case 1).

details of the ambient temperature near the surface will be superfluous, making it possible to simplify the ambient profile in order to obtain the CORMIX flow class. (In other cases, the one or two layer approximation used in CORMIX may be inadequate.) Thus UM may be used to predict the rise of the plume which, after the fact, shows that the simplification is appropriate (i.e. the rise is limited to the bottom layer). The predictions are given in Figure 45.

UM predicts a plume concentration of 212.8 at maximum rise at a downstream distance of 9.574 m and a depth of 28.82 m. This is clearly in the bottom stratified layer and within the specified mixing zone of 60 m. Thus, the simplification of the ambient data to two lines of data, as is done in Case 2 (which is developed in Figure 48), is appropriate. Consistent with the predictive strategy for negatively buoyant plumes indicated by the configuration string, the UM prediction continues past the point of maximum rise. **With the <Reversals set> option set to 0, UM determines the number of reversals, i.e. levels of maximum rise and fall, to be two if the effluent is negatively buoyant.** The average concentration at maximum fall is 77.88.

UM may also be used to estimate plume centerline concentrations. For this purpose there is a centerline concentration [CL conc] cell which does not normally appear on the interface, because, unlike the average properties which are fundamental model variables, it is an approximated value. It can be added by manipulating the Pause Cell in the lower right hand corner of the interface. To get the centerline concentration into the Pause Cell use the <pauSe

Back, Inequalities, Output, Variables (or <space>), or <esc>

Figure 46. The Pause cell dialogue window.

cell> command, ^YS, on the Miscellany menu. When you do the dialogue window shown in Figure 46 appears. Press space bar to move through the list of available cells until the centerline concentration [CL conc] cell appears. If you go too fast and pass it you can return to it by pressing <B>, then press <O> to put it on the output table. The left byte of the cell turns blue to indicate the variable will be output. It is worthwhile becoming familiar with this procedure.

Run UM again. The results are shown in Figure 47. We see that the maximum rise centerline and average concentrations are 424.7 and 212.8 ppm respectively. At maximum fall, the corresponding concentrations are 164.6 and 77.88 ppm. Note that the ratio of the centerline to average concentration is not constant but increases from 1.0 at the source to 2.1 (164.6/77.88) at the end of the initial dilution zone. This is a typical range although its theoretical limit for single round plumes is 3.89. All concentrations are well below the 600 ppm standard.

The farfield concentrations are centerline concentrations. However, with merged plumes, between the near and farfield, the concept of pollutant profiles shifts its orientation from vertical to horizontal. Thus, since the initial wastefield is assumed to be well mixed, there is a region in which the horizontal Gaussian profile is established whose length is difficult to determine.

If we were confident about the assumptions the analysis would be complete; after all, the standards are met under relatively conservative conditions (e.g. at the first maximum rise for a co-flowing plume). The same basic conclusion that the criteria will be met has been reached by

```
 plume dep plume dia poll conc  dilution   CL conc   hor dis
         m         m                                      m
     29.90    0.2540      3500     1.000      3500     0.000
     28.89     3.240     267.5     13.10     529.8     7.496 -> bottom hit
     28.82     4.045     212.8     16.47     424.7     9.574 -> bottom hit
 -> local maximum rise or fall
     30.37     7.460     109.4     32.05     225.6     19.00 -> bottom hit
     30.51     7.654     106.4     32.95     219.8     19.51 -> trap level
 -> bottom hit
     31.66     10.39     77.88     45.01     164.6     26.31 -> bottom hit
 -> local maximum rise or fall -> begin overlap
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      10.39m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                               m        sec   hrs
     48.38      72.4     59.93      58.5     40.00     912.4   0.3
     24.09     145.3     43.24      81.0     60.00      2246   0.6
================================================================================

<key>
```

Figure 47. UM output with centerline concentrations.

the PLUMES and CORMIX1 analyses. However, it is instructive to continue with the analysis, especially as it serves the purpose of further illustrating the subtleties of the modeling process.

Ambient Profile Simplification

If the assumption that the effluent brine density obeys the PLUMES equation of state were valid, there would be no reason to continue the analysis. However, since one is buoyant (rises) while the other is negatively buoyant (sinks), it is clear that CORMIX uses another relationship and therefore the assumption is questionable. Further examination shows that the effluent density calculated by CORMIX1 corresponds closely to fresh water. Of course, the freshwater assumption is also tenuous because chloride is a major constituent of sea water and the effluent should probably exhibit a greater density. In any case, it is sobering to see how little it takes to switch from one flow pattern shown in Figure 41 (S3) to another (NH2). Thus, **understanding the role that density plays in plume behavior and ambient stability is very important**.

Continue with the analysis by forming a new case, Case 2, using the ^C command or <Page Up> key. Then, delete the three intermediate lines from the ambient block using the ^YD command. Finally, move to the surface ambient temperature cell and type in 25.5 (the extension of the bottom temperature gradient shown as a dotted line in Figure 40). When you are done the interface screen should look like the upper part of Figure 48.

PLUMES predicts a negatively buoyant flow classification type: NH3 with [bottom] attachment a5 (see Doneker and Jirka, 1990 for schematic descriptions of these classes). That the plume is negatively buoyant is also apparent from the fact that the effluent density (0.9296

```
Mar 11, 1994,  15:29: 9  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   2 of   6
 Title   CORMIX1 example, H&J 1992, reduced ambient lines             nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    0.1533         1    0.1533      1000       3.5        20        20        60
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      29.9    0.2540    0.2540     3.025     2.979    0.5254      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
       0.6        10       1.0    0.9296      3500         0    -47.19     1.360
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    1000.0   -0.7222   0.01500  0.000453     0.015     201.7  -0.01183
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0     0.015    -3.022         0      25.5         0   0.02748  -0.01618
      35.0     0.015   -0.3299         0        11         0 buoy flux puff-ther
                                                              -2.481E-06     17.95
                                                               jet-plume jet-cross
                                                                   11.28     45.40
                                                               plu-cross jet-strat
                                                                   735.1     4.979
                                                               plu-strat
                                                                   3.307
                                                                 CL conc>=

CORMIX1 one port flow nh3 attached.  a5. Use CORMIX. (See manual)
 0.1533 m3/s, 3.499 MGD, 5.414 cfs.                       >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: CORMIX1.VAR;

UM INITIAL DILUTION CALCULATION (non-linear mode)
 plume dep plume dia poll conc  dilution   CL conc   hor dis
         m         m                                       m
     29.90    0.2540      3500     1.000      3500     0.000
     28.90     3.219     269.3     13.01     533.4     7.440 -> bottom hit
     28.83     4.019     214.3     16.36     427.5     9.505 -> bottom hit
 -> local maximum rise or fall
     30.38     7.467     109.4     32.05     225.6     19.00 -> bottom hit
     30.42     7.515     108.6     32.27     224.1     19.13 -> trap level
 -> bottom hit
     31.53     10.19     79.52     44.08     167.8     25.81 -> bottom hit
 -> local maximum rise or fall -> begin overlap
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      10.19m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                                m         sec   hrs
     47.97      73.0     60.29      58.1     40.00     945.8   0.3
     23.97     146.1     43.66      80.2     60.00      2279   0.6
==============================================================================

 <key>
```

Figure 48. Simplified Case 1 input to enable the CORMIX flow classification algorithm in PLUMES.

sigma-t) in the brown block is greater than the ambient density (-0.7222 sigma-t) in the green block and the Froude # is negative. The NH3 is a classification similar to the NH2 classification given if Figure 41. It differs significantly in character from the S3 classification.

It is gratifying that the overall flow characterization is essentially equivalent to the one analyzed in Case 1, as it should be since the plume is negatively buoyant. Specific numerical differences with the previous case may be attributed to small inaccuracies in specifying the surface temperature, which was estimated graphically.

```
Mar 11, 1994,  15:29:10  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   3 of   3
 Title   CORMIX1 example, H&J 1992, effl den = 998.3872               nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    0.1533         1    0.1533      1000    0.1573        20        20        60
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      29.9    0.2540    0.2540     3.025     2.979    0.5254      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
       0.6        10       1.0    -1.613      3500         0     64.17     2.516
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    1000.0   -0.7222   0.01500  0.000453     0.015     201.7   0.02193
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0     0.015    -3.022         0      25.5         0   0.02748  0.008750
      35.0     0.015   -0.3299         0        11         0 buoy flux puff-ther
                                                               1.341E-06     22.03
                                                               jet-plume jet-cross
                                                                   15.35     45.40
                                                               plu-cross jet-strat
                                                                   397.5     4.979
                                                               plu-strat
                                                                   2.836
                                                                 CL conc>=

CORMIX1 one port flow s3 unattached.  Use UM. (See manual)
 11 deg C, 51.80 deg F                                    -2.0 to 50 deg C range
Help: F1.  Quit: <esc>.  Configuration:ATCO0.  FILE: cormix1.var;

 plume dep plume dia poll conc  dilution   CL conc   hor dis
         m         m                                     m
     29.90    0.2540      3500     1.000      3500     0.000
     28.19     3.897     218.8     15.98     436.1     9.160 -> trap level
     27.03     6.973     119.7     29.21     245.4     17.06 -> bottom hit
     27.00     7.494     110.9     31.53     228.5     18.44 -> bottom hit
-> local maximum rise or fall
Farfield calculations based on Brooks (1960), see guide for details:
Farfield dispersion based on wastefield width of      7.494m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                               m         sec   hrs
     110.6      31.6     110.7      31.6     20.00     103.7   0.0
     42.26      82.8     67.54      51.8     40.00      1437   0.4
     22.25     157.3     51.39      68.1     60.00      2770   0.8
==============================================================================
 <key>
```

Figure 49. The interface screen after correction of CORMIX effluent density, with output.

For the sake of comparison, we will attempt to correct the discrepancy between the two models by revising the assumption that the discharged chloride brine has the same equation of state as that built into the interface. To do so, make a new case, Case 3. Then move the cursor to the effluent plume density [effl den] cell, invoke the ^K command, and input the effluent density in kg/m^3 given in the CORMIX1 analysis: 998.3872. After attempting to move from the cell, the conflict resolution mode will trap the overspecification. Press <space bar> to move to the effluent salinity cell and delete its value. The interface screen should now look like that in Figure 49. The effluent salinity now indicates 0.1573 o/oo which supports the conclusion that the density of fresh water is used in the CORMIX example with chloride being treated as a noncontributing component to density. With this assumption, the flow classification now agrees with the CORMIX1 prediction — both are S3, with no bottom attachment in the initial dilution

region.

The corresponding simulation is also shown in Figure 49. The predicted dilution is now 31.53 at the end of the initial dilution zone, i.e. at maximum rise. This is almost twice large as the dilution found in Case 1 and consequently, if the density assumption were valid, which it is not, the criterion for chloride will be easily met. (Note the inverse relationship between concentrations and dilutions.) Consistent with the fact that the plume is now said to be buoyant (-1.613 sigma-t < -0.7222 sigma-t), the farfield model begins at maximum rise and the advisory message about growth and aspiration entrainment may be ignored.

Density: The Linear and Nonlinear Forms of UM

The CORMIX equation of state applies only to fresh water. For sea water, the user is required to input density values directly. The PLUMES equation applies strictly only to both fresh and sea water. However, there is another option in UM — a linear form of the equation of state. In this form, as in the CORMIX sea water equation, the density is assumed to be linear function, i.e. to have a constant coefficient of bulk expansion. Essentially the density is a weighted average of the densities of the plume and ambient fluids. It is a useful approximation in many cases where the nonlinear form is inappropriate. However, it does not account for non-linearities and is totally inadequate for predicting nascent density effects.

The linear equation of state is invoked simply by entering densities instead of salinity and temperature, which are left undefined. In this mode the complex equation of state built into PLUMES is ignored in favor of the simple linear equation of state. To illustrate, create Case 4 pressing the <Page Up> key in Case 3. Then delete ambient temperatures and salinities and override the values in the ambient density cells. See Figure 50 and note the linear designation.

In this case the differences with the previous run in Case 3 are relatively small. The predicted dilution at maximum rise for the linear form is 29.02 compared to 31.53 for the nonlinear. The differences in rise are correspondingly small: 2.63 m (29.90 - 27.27) for the linear form compared to 2.90 m (29.90 - 27.00) for the nonlinear form.

While the linear form is appropriate here, **in most cases involving fresh or sea water, without significant dissolved or suspended species, it is best to use the nonlinear form of UM**, i.e. to specify salinity and temperature rather than only density as input. It is recommended because the equation of state of water, especially fresh, cold water, is significantly nonlinear. For plumes discharged to very cold, fresh water, the linear form of the model can lead to significant errors in the predictions, in extreme cases predicting monotonically rising plumes where, in fact, real plumes will rise briefly before sinking to the bottom (Frick and Winiarski, 1978). This is the nascent density effect described in the first chapter.

To illustrate this very interesting behavior, consider the case of a highly buoyant plume discharged to near freezing, fresh water. This is a common occurence in cold climates with thermal discharges to fresh water bodies. From Case 4 press <Page up> to create Case 5. Now change the temperatures and configuration as shown in Figure 51. Then, after you are finished,

run this **nonlinear** form of UM. The predicted plume reaches a false trapping level at the 29.46 m level and, expending its vertical momentum, rises to a depth of 28.37 m. At this point the plume is, and remains, negatively buoyant and, therefore, descends back to the bottom.

```
Mar 13, 1994,  16:14: 4  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   5 of   6
 Title   CORMIX1 example, nonlinear mode, very cold ambient            nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    0.1533         1    0.1533      1000         0        40        20        60
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      29.9    0.2540    0.2540     3.025     2.979    0.5254      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
       0.6        10       1.0    -7.724      3500         0     21.86    0.2919
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    1000.0  -0.09290   0.01500  0.000453     0.015     201.7 6.449E-08
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0     0.015  -0.09295         0         0         0 0.0001378   0.07542
      35.0     0.015  -0.09289         0     0.001         0 buoy flux puff-ther
                                                      0.00001156     10.74
                                                       jet-plume jet-cross
                                                           5.227     45.40
                                                       plu-cross jet-strat
                                                            3426     70.29
                                                       plu-strat
                                                           257.7
                                                         CL conc>=

CORMIX1 one port flow h4-0 unattached.  Use UM until near surface. (See manual)
0.1533 m3/s, 3.499 MGD, 5.414 cfs.                      >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:ATCO2.  FILE: CORMIX1.VAR;

UM INITIAL DILUTION SIMULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   CL conc   hor dis
         m         m                                      m
     29.90    0.2540      3500     1.000      3500     0.000
     29.46     1.237     705.8     4.921      1372     2.441 -> trap level
     28.42     4.187     204.1     17.02     407.8     9.886 -> bottom hit
     28.37     4.850     175.2     19.82     352.3     11.61 -> bottom hit
-> local maximum rise or fall
     29.60     7.355     109.4     31.75     225.4     19.00 -> bottom hit
     35.12     9.726     70.19     49.48     149.6     27.68 -> bottom hit
Leaving defined depth range
==============================================================================
 <key>
```

Figure 50. Discharge of a highly buoyant plume to very cold water; nonlinear form of UM. With output.

The reason for this behavior is due to the fact that fresh water has its maximum density around 4C. Initially the plume is very buoyant (-7.724 sigma-t < 0.09290 sigma-t), but, as the plume ascends in the water column, it rapidly cools through entrainment and becomes more dense than the ambient fluid as the average density of the plume element approaches 4 C. At that temperature it is considerably more dense than its surroundings which has a temperature somewhere between 0 and 4 C at this point. Consequently, the upward ascent of the plume is first inhibited and finally reversed due to the negative buoyancy.

```
Mar 13, 1994,  16:14: 4  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   5 of   6
 Title   CORMIX1 example, nonlinear mode, very cold ambient            nonlinear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
    0.1533         1    0.1533      1000         0        40        20        60
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
      29.9    0.2540    0.2540     3.025     2.979    0.5254      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
       0.6        10       1.0    -7.724      3500         0     21.86    0.2919
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    1000.0  -0.09290   0.01500  0.000453     0.015     201.7 6.449E-08
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
       0.0     0.015  -0.09295         0         0         0 0.0001378   0.07542
      35.0     0.015  -0.09289         0     0.001         0 buoy flux puff-ther
                                                      0.00001156     10.74
                                                       jet-plume jet-cross
                                                           5.227     45.40
                                                       plu-cross jet-strat
                                                            3426     70.29
                                                       plu-strat
                                                           257.7
                                                         CL conc>=

CORMIX1 one port flow h4-0 unattached.  Use UM until near surface. (See manual)
0.1533 m3/s, 3.499 MGD, 5.414 cfs.                      >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:ATCO2.  FILE: CORMIX1.VAR;

UM INITIAL DILUTION SIMULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   CL conc   hor dis
         m         m                                      m
     29.90    0.2540      3500     1.000      3500     0.000
     29.46     1.237     705.8     4.921      1372     2.441 -> trap level
     28.42     4.187     204.1     17.02     407.8     9.886 -> bottom hit
     28.37     4.850     175.2     19.82     352.3     11.61 -> bottom hit
-> local maximum rise or fall
     29.60     7.355     109.4     31.75     225.4     19.00 -> bottom hit
     35.12     9.726     70.19     49.48     149.6     27.68 -> bottom hit
Leaving defined depth range
==============================================================================
 <key>
```

Figure 51. Discharge of a highly buoyant plume to very cold water; nonlinear form of UM. With output.

To compare this simulation to one with the linear model, form Case 6 starting from Case 5 and override all the dependent (white) densities with equivalent independent densities. First erase any salinity or temperature values. (Or, if the conflict resolution capability is used, the ^QD command is handy for moving to the end of the cell where you can add an extra zero to the replacement string so that PLUMES knows that the densities are to become independent). When you are done the interface should look like that in Figure 52.

In this, a case superficially identical to Case 5, the plume rises to the surface. Clearly it is important to be aware of these extreme differences in model behavior. They are not both right. Depending on the analysis, in one case one would conclude that benthic organisms will be affected, in the other, surface organisms. Thus, whenever the data are available and suspended and dissolved, foreign solids are not an important factor, the nonlinear equation of state should be considered.

```
  Mar 13, 1994,  16:14: 5  ERL-N PROGRAM PLUMES, Ed 3, 3/11/94  Case:   6 of   6
  Title   CORMIX1 example, linear mode, very cold ambient                linear
   tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
     0.1533         1    0.1533      1000                              20        60
   port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
       29.9    0.2540    0.2540     3.025     2.979    0.5254      0.10       500
  port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
        0.6        10       1.0    -7.724      3500         0     21.86    0.2919
  hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
         90    1000.0  -0.09290   0.01500  0.000453     0.015     201.7 5.706E-08
      depth   current   density  salinity      temp  amb conc  N (freq) red grav.
        0.0     0.015  -0.09295                              0 0.0001297   0.07542
       35.0     0.015  -0.09289                              0 buoy flux puff-ther
                                                               0.00001156     10.74
                                                                jet-plume jet-cross
                                                                    5.227     45.40
                                                                plu-cross jet-strat
                                                                     3426     72.47
                                                                plu-strat
                                                                    269.9
                                                                  CL conc>=
 CORMIX1 one port flow h4-0 unattached.  Use UM until near surface. (See manual)
 0.1533 m3/s, 3.499 MGD, 5.414 cfs.
Help: F1.  Quit: <esc>.  Configuration:ATCO2.  FILE: cormix1.var;
 Mar 13, 1994,  16:16: 4  ERL-N PROGRAM
 UM INITIAL DILUTION SIMULATION (linear mode)
  plume dep plume dia poll conc  dilution   CL conc   hor dis
          m         m                                      m
      29.90    0.2540      3500     1.000      3500     0.000
      20.93     5.665     109.4     31.76     225.4     14.08
      1.529     10.48     38.14     91.08     86.82     22.36 -> surface hit
 Farfield calculations based on Brooks (1960), see guide for details:
 Farfield dispersion based on wastefield width of      10.48m
    --4/3 Power Law--   -Const Eddy Diff-
       conc  dilution      conc  dilution  distance         Time
                                               m        sec   hrs
      20.28     171.9     27.17     128.1     40.00      1176   0.3
      10.73     325.5     20.36     171.2     60.00      2510   0.7
 ==============================================================================
   <key>
```

Figure 52. Discharge of a highly buoyant plume to very cold water; linear form of UM. With output.

Some densities, including ones pertinent to this problem, are compared in Table III.

Table III. PLUMES and CORMIX1 densities compared with published values (Weast, 1977).

Temperature (C)	Salinity	Densities (kg/m^3) UM	CORMIX1	Weast
0.0	0.0	998.267		999.842
4.0	0.0	998.691		999.975
13.0	0.0	999.442	999.648	999.380
28.1	0.0	996.267	996.341	996.208
20.0	0.0	998.267		998.207
20.0	34.84	1024.66		1024.5
20.0	79.69	1060.04		1058.5

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.

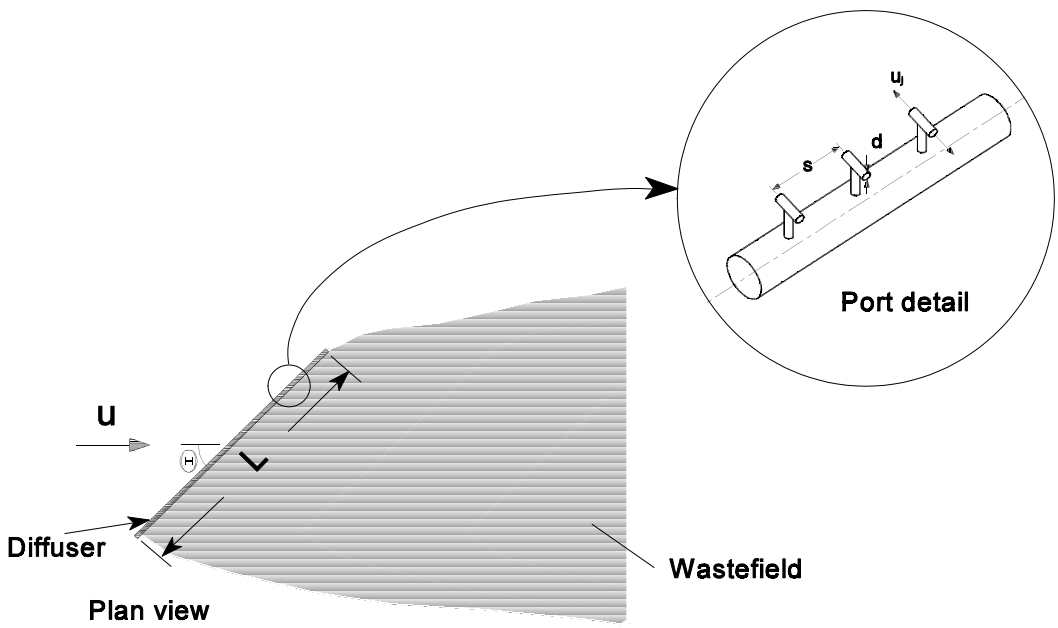

Figure 53. Diffuser configuration considered by RSB.

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

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.

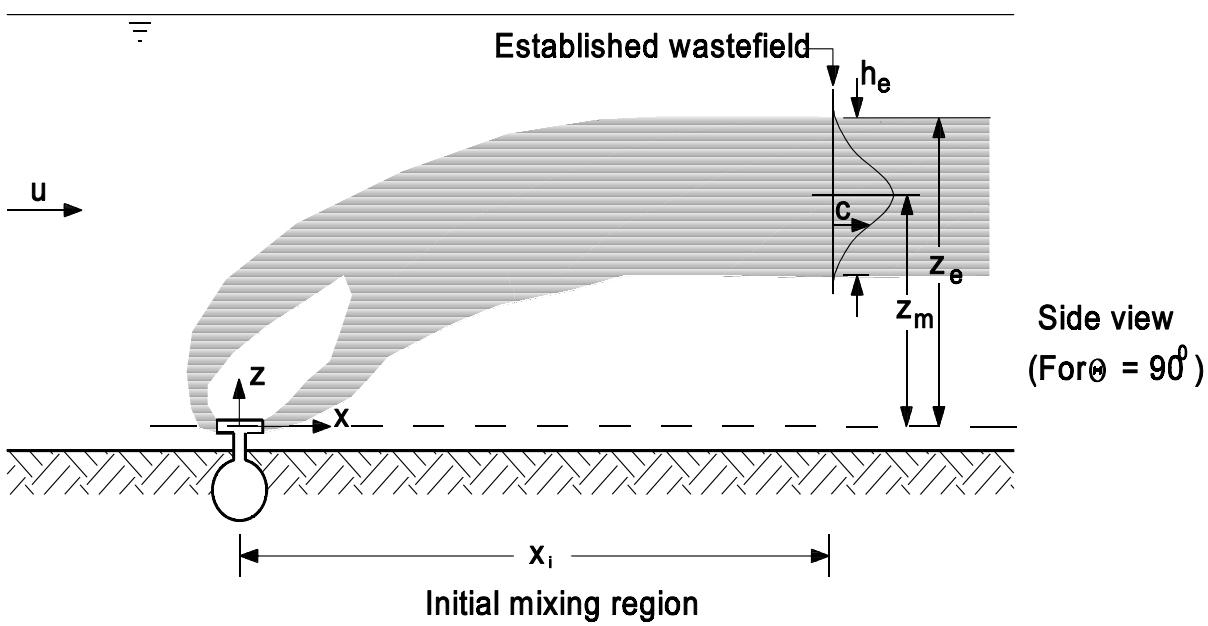

Figure 54. Definition of Wastefield Geometry.

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:

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

where Q is the total discharge, L the diffuser length, u_j the jet exit velocity, and $g_o' = g(\rho_a - \rho_o)/\rho_a$ is the reduced gravitational acceleration due, g is the acceleration due to gravity, ρ_a is the ambient density at the level of the ports and ρ_o 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}:

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

We define three length scales:

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

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:

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

Which, by means of dimensional analysis, becomes:

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

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

ports. The corresponding normalized expression for dilution is:

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

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 Θ. For a line diffuser $0 < \Theta < 90^o$. Tests were run with $\Theta = 90^o$ (diffuser oriented perpendicular to the current), 45°, and 0° (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):

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

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.

$$L = s\left(\frac{n}{2} - 1\right) \tag{26}$$

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, ρ_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 σ_t-units per meter. Taking the strongest stratification (0.025 σ_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.

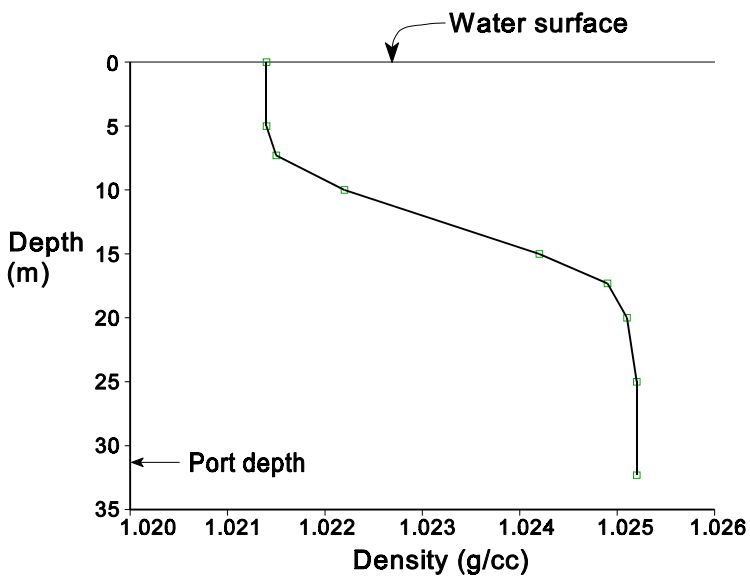

Figure 59. Density Profile used in Non-Linear Example.

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.

```
 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 m^3/s), 620 mgd (27.16 m^3/s), and 1270 mgd (55.63 m^3/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.

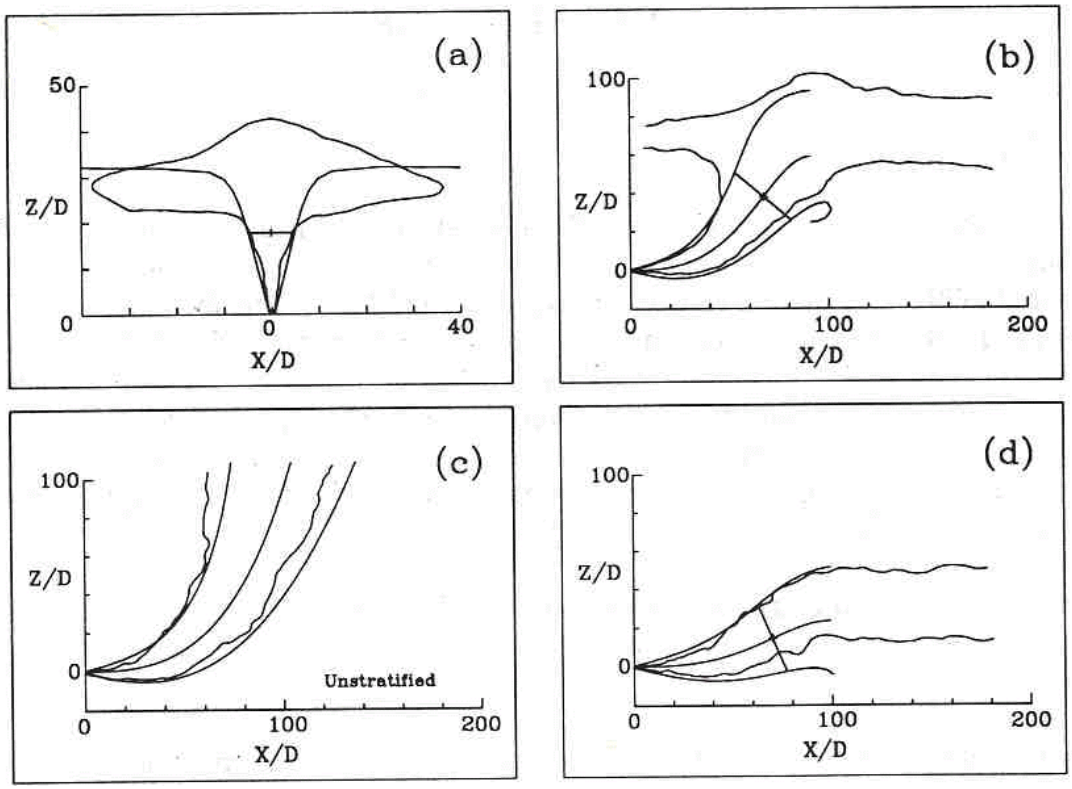

Figure 62. UM centerline and boundary predictions in stagnant ambient compared to Fan (1967). (a) Jet No. 10, (b) Jet No. 16, (c) Jet No. 22, unstratified, and (d) Jet No. 32.

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

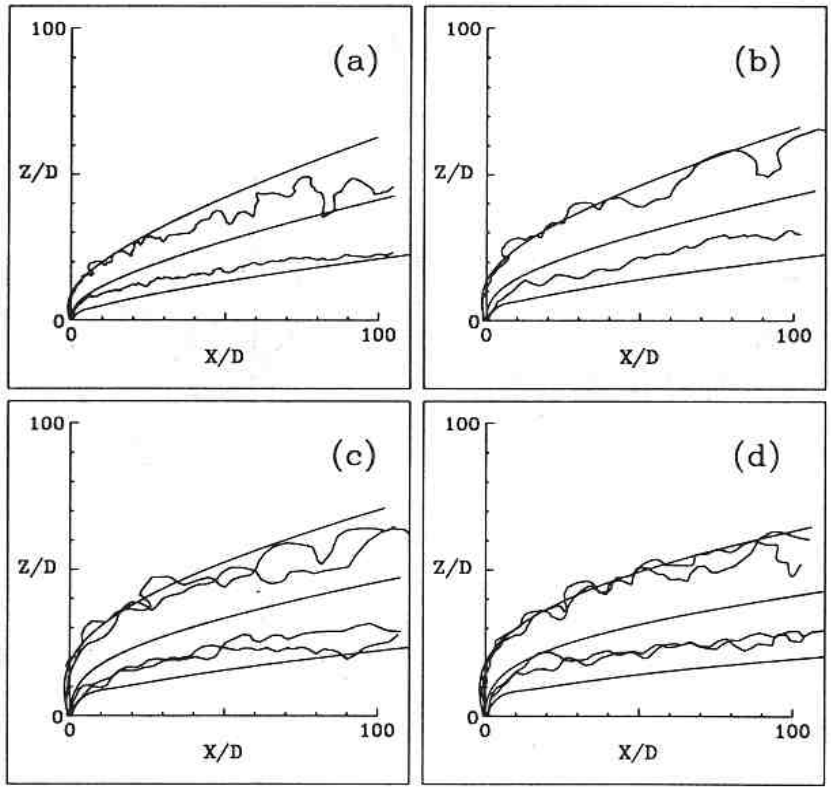

Figure 63. Plume trajectory, the element at three stages of development, and selected plume variables.

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.

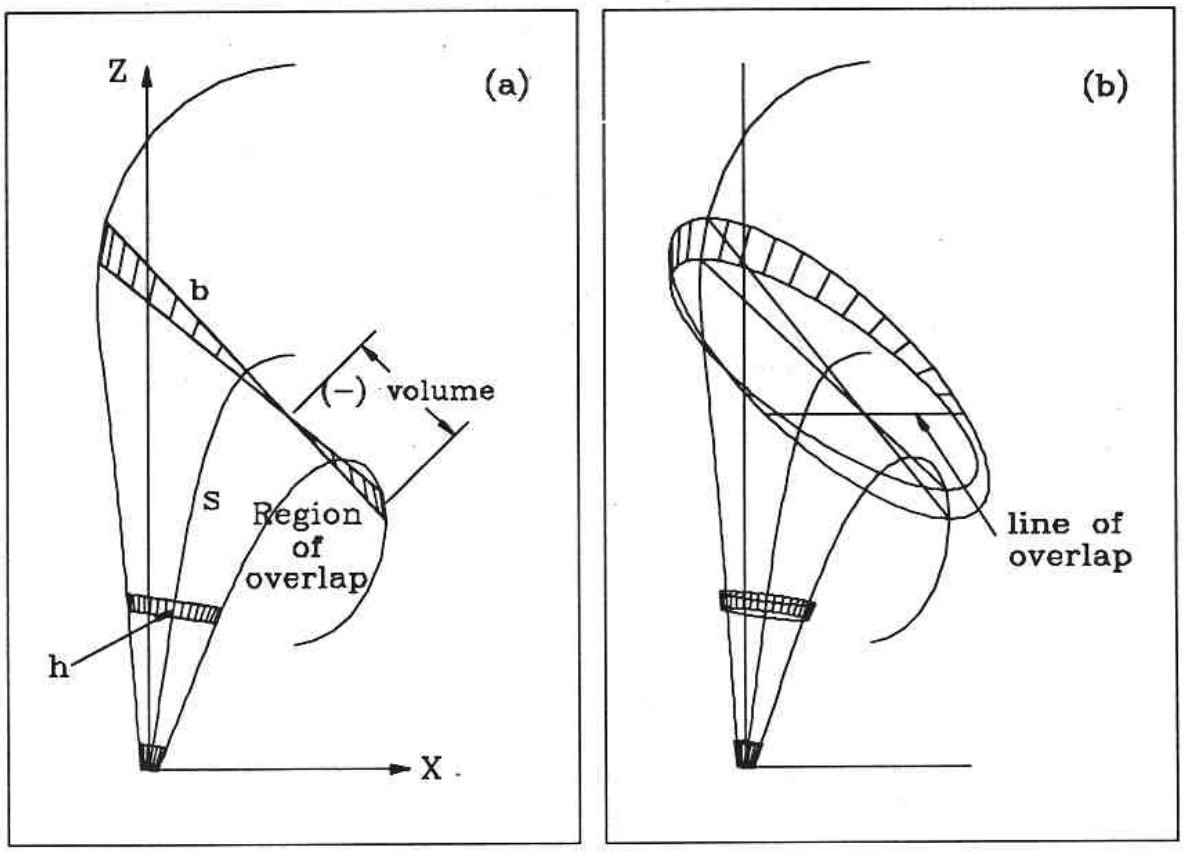

Figure 64. UM predictions in flowing ambient compared to Fan (1967). (a) F_j=10, k=8, (b) F_j=20, k=12, (d) F_j=40, k=16, and (d) F_j=80, k=16.

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 not 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.

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

$$\frac{dm}{dt} = \rho_a A_p u \qquad \textbf{(27)}$$

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 ρ_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

$$\frac{dm}{dt} = -\rho_a \, \underline{A}_p \cdot \underline{U} \qquad \textbf{(28)}$$

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.

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.,

$$\Delta h \;\; ' \;\; \Delta*\underline{V}* \;\; \delta t \qquad \textbf{(29)}$$

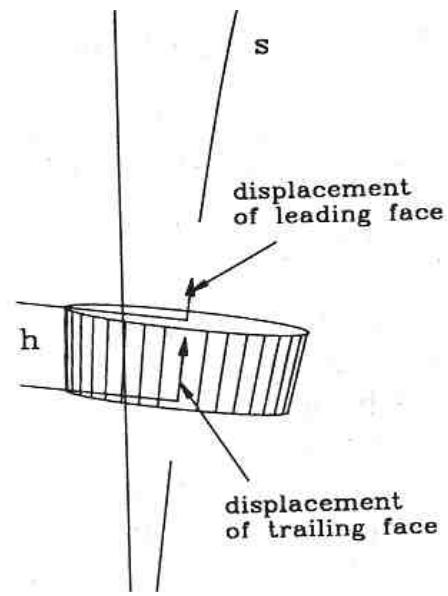

Figure 65. Convergence of element faces due to differences in face velocities.

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

$$\int_{h_o}^{h} dh \;\; ' \;\; \delta t \int_{u_{so}}^{u_s} du_s \qquad \textbf{(30)}$$

where u_s = $*\underline{V}*$ and u_{so} = $*\underline{V}_o*$. Equation 30 can be integrated to yield

$$h \;\&\; h_o \;\; ' \;\; (u_s \;\&\; u_{so})\delta t \qquad \textbf{(31)}$$

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

$$\frac{h}{h_o} \;\; ' \;\; \frac{u_s}{u_{so}} \qquad \textbf{(32)}$$

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

$$\frac{dm}{dt} = -\rho\, \underline{A}_p \cdot \underline{U} + \rho A_T\, v_t \qquad \textbf{(33)}$$

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, α:

$$v_T = \alpha * \underline{V} * \qquad \textbf{(34)}$$

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

$$A_T = 2\pi b h \qquad \textbf{(35)}$$

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

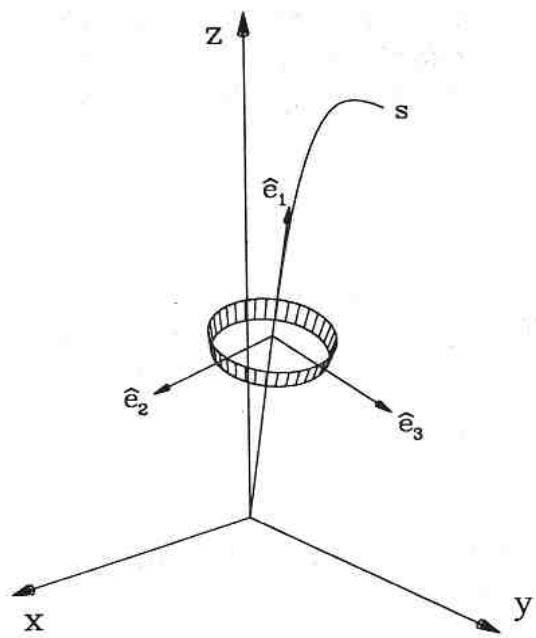

Figure 66. The local coordinate system.

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

$$\underline{U} = u_1\hat{e}_1 + u_2\hat{e}_2 + u_3\hat{e}_3 \qquad \textbf{(36)}$$

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 $\hat{e}_2$:

$$\hat{e}_3 = \hat{e}_1 \times \hat{e}_2 \qquad \textbf{(37)}$$

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

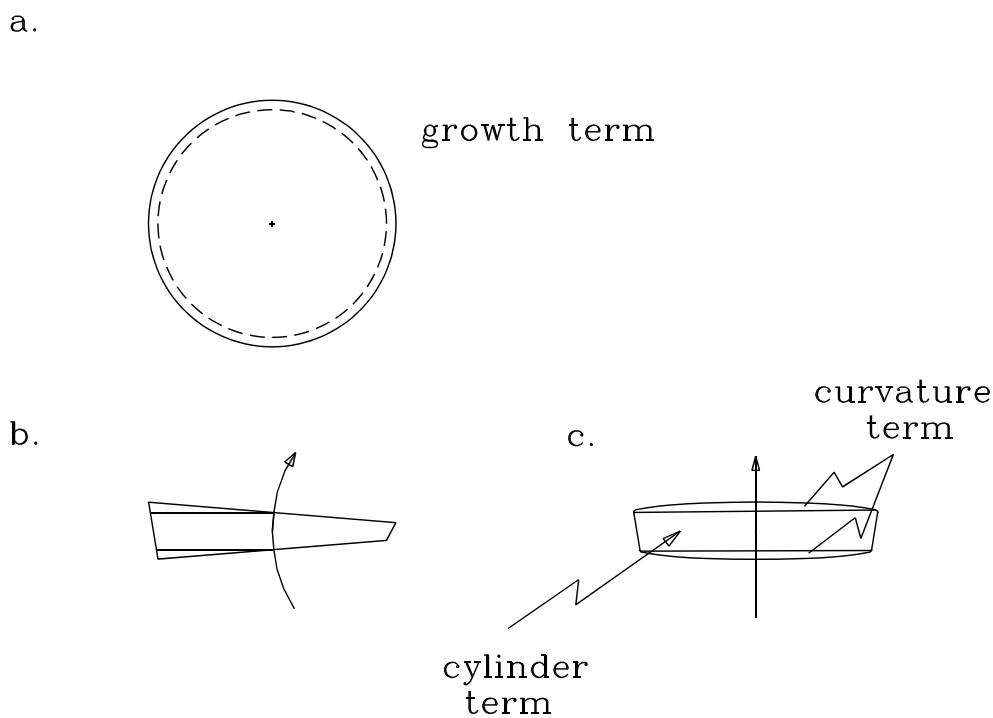

Figure 67. The projected area entrainment components: a) the growth area, b) side view of the element, and c) the cylinder and curvature area.

$$A_1 \;'\; \pi b \;\Delta b \qquad \textbf{(38)}$$

where $\hat{I}b$ 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

$$\Delta b \;'\; \frac{\mathrm{M}b}{\mathrm{M}s} h \qquad \textbf{(39)}$$

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

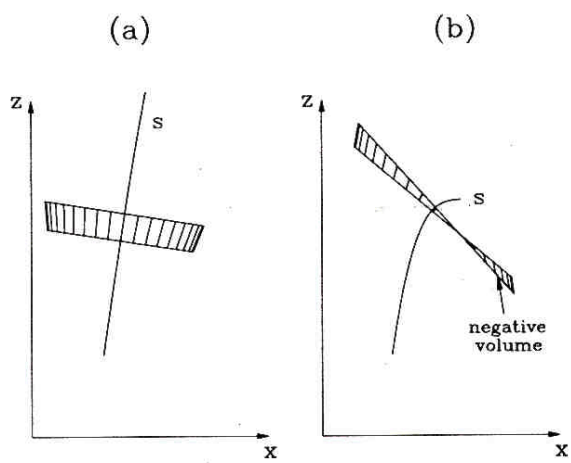

Figure 68. a) The plume element in a region of weak trajectory curvature and b) strong trajectory curvature (showing overlap).

is given in Figure 68.

The curvature component of the projected area is

$$A_{cur} = -\frac{\pi}{2} b^2 \frac{\partial\theta}{\partial s} h \qquad \textbf{(41)}$$

where θ is the elevation angle of s. This area can be positive or negative depending of the sign of $\partial\theta/\partial s$ 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

$$\frac{d m \underline{V}}{dt} = \underline{U}\frac{dm}{dt} - m\frac{(\rho_a - \rho)}{\rho}\underline{g} \qquad \textbf{(42)}$$

where m is the mass of the plume element ($m = \rho\pi b^2 h$), ρ_a and ρ are the ambient and average element densities respectively, and $\underline{g}$ 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

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

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,

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

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

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

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.

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

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, $((\rho_a-\rho)/\rho)g$, 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

$$\frac{d\underline{R}}{dt} = \underline{V} \tag{47}$$

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

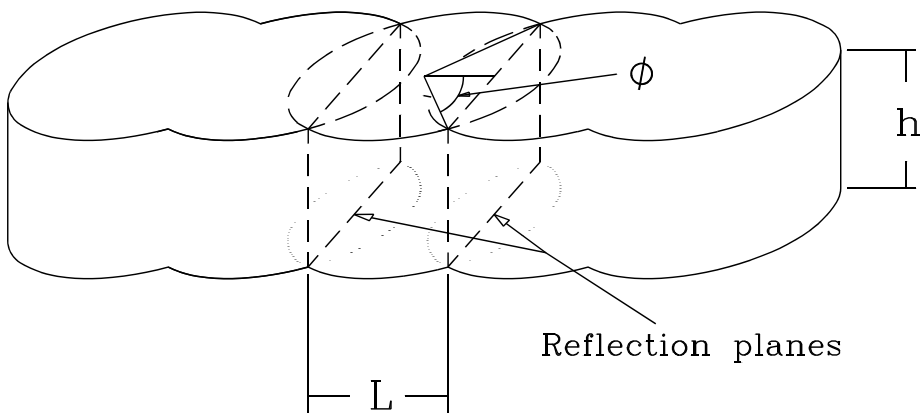

Figure 69. Merging geometry and reflection planes.

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

$$a_T = \frac{\pi - 2\varphi}{\pi} \qquad \textbf{(51)}$$

where

$$\varphi = \arctan\sqrt{\frac{4b^2 - L^2}{L^2}} \tag{52}$$

where φ 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 ψ where ψ 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

$$a_{cur} = 1 - \frac{2\varphi}{\pi} + \frac{\sin 2\varphi}{\pi} \tag{54}$$

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

$$\pi b_r^2 = \pi b^2\left(1 - \frac{2\varphi}{\pi}\right) + 2b^2 \sin\varphi \cos\varphi \tag{55}$$

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

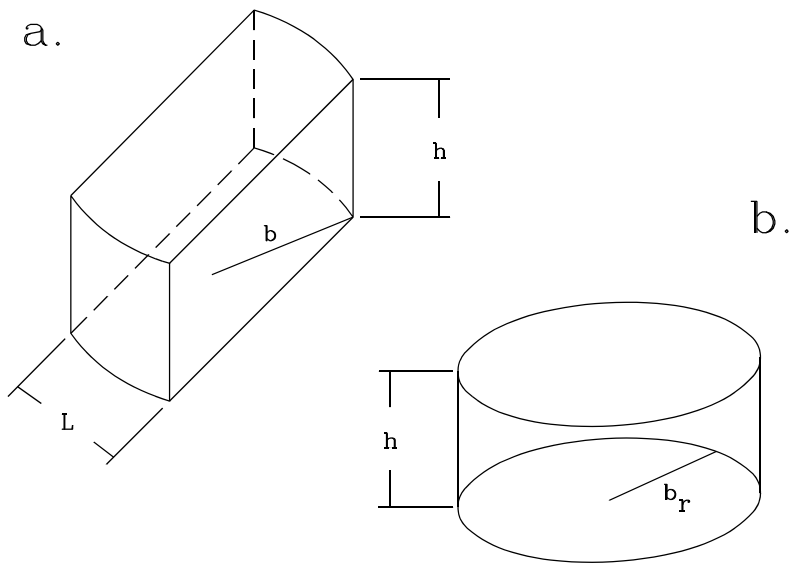

Figure 70. Derivation of dimensions under merging: a) the merged element with volume confined between reflection planes, and b) the corresponding unmerged element of equal volume.

$$b = \frac{\pi b_r}{\pi - 2\varphi + 2\sin\varphi\cos\varphi} \qquad \textbf{(56)}$$

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

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

where Φ 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 Φ 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

$$C_{avg} = \frac{\int_A C v\, dA}{\int_A v\, dA} \qquad \textbf{(58)}$$

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}

$$\frac{C_{\max}}{C_{avg}} = \frac{C_{\max} \int_A v\, dA}{\int_A C v\, dA} \qquad \textbf{(59)}$$

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

$$\frac{C_{\max}}{C_{avg}} = \frac{C_{\max} \int_A dA}{\int_A C\, dA} \qquad \textbf{(60)}$$

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

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

$$\frac{S_m q N}{b^{2/3}} = 1.08 F^{1/6} \qquad \textbf{(61)}$$

$$N = \left(-\frac{g}{\rho_a}\frac{d\rho}{dz}\right)^{1/2} \qquad \textbf{(62)}$$

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

$$\frac{z_e}{l_b} = 1.86 F^{-1/6} \qquad \textbf{(63)}$$

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

$$l_b = \frac{b^{1/3}}{N} \qquad \textbf{(64)}$$

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

$$S_m \approx \frac{1.08}{1.86}\frac{Lz_e u}{Q} \qquad \textbf{(65)}$$

The quantity $Lz_e u$ 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

$$S = \frac{S_a}{erf\left(\sqrt{\frac{b^2}{16\alpha\, b^{4/3} t}}\right)} \qquad \textbf{(66)}$$

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), α 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 α (in Equation 66) and ε_o (in Equation 17) is simply

$$\alpha = \varepsilon_o / b^{4/3} \qquad \textbf{(67)}$$

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

$$\alpha = 4/900^{4/3} = 0.00046\ m^{2/3}/\text{sec} \qquad \textbf{(68)}$$

The value for α 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:

$$S = \frac{S_a}{erf\left(\sqrt{\frac{1.5}{\left(1 + 8\alpha b^{4/3}\frac{t}{b^2}\right)^3 - 1}}\right)} \qquad \textbf{(69)}$$

For coastal areas of known high energy dissipation features, or in many geographical areas at certain times of the year, α may have a value as high as 0.0005 m$^{2/3}$/sec. In less turbulent situations α 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 α yield the most conservative estimates of farfield dilution.

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

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

where N is the number of ports, s_{eff} is the effective spacing (spacing multiplied by sinψ), 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

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

where $\hat{I}m$ 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

$$m_{p\,t+\Delta t} = m_{pt}e^{-k\Delta t} + \Delta m\,\chi_a e^{-k\,t} \qquad \textbf{(72)}$$

where m_p is the total mass of pollutant in the plume element, k is the first order decay constant, χ_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:

$$\bar{\chi} = \frac{\chi_o m_p}{S m_o} \tag{73}$$

where χ with the bar is the average pollutant concentration in the element and χ_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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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

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 / Effluent Types	Stratification			Current		Other sources, decay	BCs	Intrusion	VSW
	none	1,2	3+	2-D	3-D				
Buoyant discharges: sewage, industrial waste especially to saline waters	*C* U	*C* U	U	*C* U	*C* u	*C* (decay) U	*C* u	*C* u	u
Slightly buoyant discharges, signif. momentum: thermal discharges	*C* U	*C* U	U	*C* U	*C* u	*C* (decay) U	*C* u	*C* u	u
Dense discharges: light brine, R.O. discharge, industrial waste	*C* U	*C* U	U	*C* U	*C* u	*C* (decay) U	*C* u	*C* 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.

```
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 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.

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.

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
}
```

```
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;
```

```
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);
```

```
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,
```

```
    '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      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   Specific    Coeff     Pipe      Port      Port      Port
number   energy       cd    velocity  velocity discharge  Froude #
           (m)              (m/sec)   (m/sec)  (m^3/sec)

     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   Specific    Coeff     Pipe      Port      Port      Port
number   energy       cd    velocity  velocity discharge  Froude #
           (m)              (m/sec)   (m/sec)  (m^3/sec)

     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

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.

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 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

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

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 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
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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.