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# TECHNICAL GUIDANCE MANUAL FOR PERFORMING WASTE LOAD ALLOCATIONS

## BOOK III: ESTUARIES

## PART 3: Use of Mixing Zone Models in Estuarine Waste Load Allocations


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# 1. Introduction

## 1.1 Initial Mixing in Estuaries and Coastal Waters

The discharge of waste water into an estuary or coastal water body can be considered from two vantage points regarding its impact on ambient water quality.

On a larger scale, or system wide context, care must be taken that water quality conditions that protect designated beneficial uses are achieved. This is the realm of the general waste load allocation (WLA) procedures and models as discussed in the first two parts of this manual. As noted, an additional benefit of a technically sound WLA is that excessive degrees of treatment which are neither necessary nor productive of corresponding improvements in water quality for the whole water body, or at least major sections thereof, can be avoided.

On a local scale, or in the immediate discharge vicinity, additional precautions must be taken to insure that high initial pollutant concentrations are minimized and constrained to small zones, areas or volumes. The definition of these zones, commonly referred to as "mixing zones", is embodied in United States water quality regulations, on the Federal and/or State level. The mixing zone is a legally defined spatial quantity - with certain size and shape characteristics - that allows for initial mixing of the discharge. More recent regulations on discharges of toxic substances define an additional subregion -labeled herein the "toxic dilution zone" - within the usual mixing zone. The intent of those regulations is to require rapid mixing of toxic releases to limit the exposure of aqueous flora and fauna to elevated concentrations. The detailed prediction of pollutant concentrations and water quality constituents in the initial mixing phase of a wastewater discharge is the realm of mixing zone models. This is the subject of this part of the manual. Mixing zone models are intended to document for any given combination of discharge and environmental conditions the size and shape of legally defined "mixing zones", and for toxic substances, of embedded "toxic dilution zones", and the levels of pollutant concentration within these zones and at their edge.

There may be a great diversity in the types of initial mixing processes for wastewater discharge. First, the size and flow characteristics of estuaries or coastal water can vary widely: the water body may be deep or shallow, stagnant or flowing, and may exhibit ambient density stratification of various degrees. Secondly, the discharge type and configuration can be highly variable: the flow may contain various pollutants ranging from conventional to toxic substances, vary greatly in magnitude ranging from low flowrate for a small sewage treatment plant to the substantial cooling water flow for a large steam-electric power plant, issue with high or low velocity, be denser or lighter than the ambient, be located near shore or far offshore, and exhibit various geometric details ranging from single port submerged discharges to multiport submerged diffusers to surface discharges.

Given this diversity of both discharge and ambient environmental conditions, there are a large number of possible flow patterns which will develop as the discharge waste stream mixes in the ambient water. These flow patterns will determine the configuration, size, and intensity of the mixing process, and any impact of the discharge on the water body surface, bottom, shoreline, or other areas. This, in turn, requires that engineering analyses, in the form of mixing zone models, be robust, adaptable and reliable under a wide spectrum of flow conditions.

## 1.2 Mixing Zone Requirements: Legal Background

### *1.2.1 Pollutant Types*

The Clean Water Act of 1977 defines five general categories of pollutants. i) conventional, ii) nonconventional, iii) toxics, iv) heat, and v) dredge and fill spoil. The Act distinguishes between new and existing sources for setting effluent standards. Table 1-1 lists examples of the first three pollutant categories.

Pollutants designated as "conventional" would be "generally those pollutants that are naturally occurring, biodegradable, oxygen demanding materials and solids. In addition, compounds which are not toxic and which are similar in characteristics to naturally occurring, biodegradable substances are to be designated as conventional pollutants for the purposes of the provision". Pollutants designated as "nonconventional" would be "those which are not toxic or conventional" (Congressional Research Service, 1977).

### *1.2.2 Mixing Zone Definitions*

The mixing zone is defined as an "allocated impact zone" where numeric water quality criteria can be exceeded as long as acutely toxic conditions are prevented. A mixing zone can be thought of as a limited area or volume where the initial dilution of a discharge occurs (USEPA, 1984a). Water quality standards apply at the boundary of the mixing zone, not within the mixing zone itself. USEPA and its predecessor agen-

Table 1-1. **Examples of Conventional, Nonconventional, and Toxic Pollutants [USEPA 1984]**

| Conventional | Nonconventional | Toxic |
|---|---|---|
| biochemical oxygen demand (BOD) | chemical oxygen demand (COD) | chloroform/lead |
| pH | flouride | flourene |
| total suspended solids (TSS) | aluminum | nickel |
| fecal coliform bacteria | sulfide | selenium |
| oils and grease | ammonia | benzidine |

cies have published numerous documents giving guidance for determining mixing zones. Guidance published by USEPA in Water Quality Standards Handbook (1984) supersedes these sources.

In setting requirements for mixing zones, USEPA (1984a) requires that "the area or volume of an individual zone or group of zones be limited to an area or volume as small as practicable that will not interfere with the designated uses or with the established community of aquatic life in the segment for which the uses are designated," and the shape be "a simple configuration that is easy to locate in the body of water and avoids impingement on biologically important areas," and "shore hugging plumes should be avoided."

The USEPA rules for mixing zones recognize the State has discretion whether or not to adopt a mixing zone and to specify its dimensions. USEPA allows the use of a mixing zone in permit applications except where one is prohibited in State regulations. A review of individual State mixing zone policies shows that 48 out of 50 States (the exceptions are Arizona and Pennsylvania) make use of a mixing zone in some form (USEPA, 1984a, 1985). State regulations dealing with streams or rivers generally limit mixing zone widths or cross-sectional areas, and allow lengths to be determined on a case-by-case basis.

In the case of lakes, estuaries and coastal waters, some states specify the surface area that can be affected by the discharge. (The surface area limitation usually includes the underlying water column and benthic area.) If no specific mixing zone dimensions are given the actual shape and size can be determined on a case-by-case basis.

Special mixing zone definitions have been developed for the discharge of municipal wastewater into the coastal ocean, as regulated under Section 301(h) of the Clean Water Act (USEPA, 1982). For those discharges the mixing zone was labeled as the "zone of initial dilution" in which rapid mixing of the waste stream (usually the rising buoyant fresh water plume within the ambient saline water) takes place. USEPA (1982) requires that the "zone of initial dilution" be a regularly shaped area (e.g. circular or rectangular) surrounding the discharge structure (e.g. submerged pipe or diffuser line) that encompasses the regions of high (exceeding standards) pollutant concentrations under design conditions. In practice, limiting boundaries defined by dimensions equal to the water depth measured horizontally from any point of the discharge structure are accepted by the USEPA provided they do not violate other mixing zone restrictions (USEPA, 1982).

### *1.2.3 Special Mixing Zone Requirements for Toxic Substances*

USEPA maintains two water quality criteria for the allowable concentration of toxic substances: a criterion maximum concentration (CMC) to protect against acute or lethal effects; and a criterion continuous concentration (CCC) to protect against chronic effects (USEPA, 1985). The less restrictive criterion, the CCC, must be met at the edge of the same regulatory mixing zone specified for conventional and nonconventional discharges.

In order to prevent lethal concentrations of toxics in the regulatory mixing zone, the restrictive CMC criterion must be met within a short distance from the outfall or in the pipe itself. If dilution of the toxic discharge in the ambient environment is allowed, this requirement, which will be defined here as a toxic dilution zone (TDZ), is usually more restrictive than the legal mixing zone for conventional and nonconventional pollutants. USEPA (1985) recommends a minimum exit velocity of 3 meters per second (10 feet per second), in order to provide sufficiently rapid mixing that will minimize organism exposure time to toxic material. In addition, the outfall design must also meet the following geometric restrictions for a TDZ:

- The CMC must be met within 10% of the distance from the edge of the outfall structure to the edge of the regulatory mixing zone in any spatial direction.
- The CMC must be met within a distance of 50 times the discharge length scale in any spatial direction. The discharge length scale is defined as the square-root of the cross-sectional area of any discharge outlet. This restriction is intended to ensure a dilution factor of at least 10 within this distance under all possible circumstances, including situations of severe bottom interaction and surface interaction.
- The CMC must be met within a distance of 5 times the local water depth in any horizontal direction.

The local water depth is defined as the natural water depth (existing prior to the installation of the discharge outlet) prevailing under mixing zone design condition (e.g. low flow for rivers). This restriction will prevent locating the discharge in very shallow environments or very close to shore, which would result in significant surface and bottom concentrations. (USEPA, 1985)

## 1.3 Summary

The following two sections of Part III of this manual deal with the background and the application of predictive models for mixing zone analysis that address the various legal requirements as outlined above.

Section 2 first gives an overview of the important physical processes that govern the hydrodynamic mixing of aqueous discharges. Those processes are divided into near-field processes (influenced directly by the discharge geometry and dynamics and, to some extent, controllable through appropriate design choices) and into far-field processes (influenced primarily by the existing environmental conditions). It is shown that legal mixing zone requirements can encompass, in general, processes in both near-field and far-field. Then the mathematical background and formulations for different mixing zone models are reviewed. For practical routine applications, these models fall into two classes: (i) jet integral models that are applicable only to a sub-set of near-field processes including submerged buoyant jets without any boundary (surface or bottom) interaction, and (ii) a mixing zone expert system, CORMIX, that addresses both near-field and far-field processes under a variety of discharge and ambient conditions.

Section 3 illustrates the application of jet integral models and of the expert system CORMIX. Typical data requirements for the implementation of these models are discussed. Four case studies are presented in order to demonstrate the capabilities and/or limitations of individual models.

## 1.4 References

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USEPA. 1982. Revised Section 301 (h) Technical Support Document. EPA 430/9-82-011, Washington, DC.

USEPA. 1984a. Water Quality Standards Handbook,". Office of Water Regulations and Standards, Washington, DC.

USEPA. 1984b. Technical Guidance Manual for the Regulations Promulgated Pursuant to Section 301 (g) of the Clean Water Act of 1977 (Draft)", Washington, DC, August.

USEPA. 1985. Technical Support Document for Water Quality-based Toxics Control. Office of Water, Washington, DC, September.

# 2. Physical Processes and Modeling Methodologies

## 2.1 Ambient and Discharge Conditions

The mixing behavior of any wastewater discharge is governed by the interplay of ambient conditions in the receiving water body and by the discharge characteristics.

The ambient conditions in an estuary or coastal water body are described by geometric parameters - such as plan shape of the estuary, vertical cross-sections, and bathymetry, especially in the discharge vicinity and by its dynamic characteristics. The latter are given by the velocity and density distribution in the estuary, again primarily in the discharge vicinity.

Many estuaries are highly energetic water bodies and their velocity field with its vertical and temporal variability may be influenced by many factors. Usually the most significant velocity component is controlled by tidal influences, but freshwater inflows, wind-driven currents and wave-induced currents may also play important roles and, in some cases, may even dominate the flow. Furthermore the mean velocity field is often superposed by secondary currents due to topographic effects or due to baroclinic influences giving rise to complicated three-dimensional flow fields.

The density distribution in estuaries is usually strongly coupled with the velocity field. Density differences are mostly caused by the freshwater inflow and lighter, less saline, water tends to overflow the more saline ocean water. Estuaries are sometimes classified on the basis of their density structure into well-stratified, partially-stratified and vertically mixed estuaries (Fischer et al., 1979). Well stratified estuaries, usually those with weak tidal effects, exhibit a two-layer structure with an upper predominantly fresh water layer flowing over a lower saline layer (the so-called salt wedge). The dominant vertical velocity distribution in that instance is a seaward flow in the upper layer and a reversed landward flow in the lower layer. The other end of the spectrum is given by vertically well mixed estuaries with strong tidal energetics leading to nearly complete vertical mixing although density gradients may still exist in the horizontal direction (i.e. along the axis of the estuary or tidal bay).

Clearly, a major feature of estuarine ambient conditions is their time variability. For tidally controlled currents this is given by a time scale equal to the tidal period. Other time scales, usually also of the order of several hours, describe wind driven currents and seiche motions. However, the time scale for initial mixing processes of effluent discharges is usually much shorter (of the order of minutes to tens of minutes) so that it usually suffices to analyse certain flow and density conditions under a steady-state assumption. The consideration of tidal reversals and potential pollutant accumulation is discussed further below (section 2.6).

The discharge conditions relate to the geometric and flux characteristics of the submerged outfall installation. For a single port discharge the port diameter, its elevation above the bottom and its orientation provide the geometry; for multiport diffuser installations the arrangement of the individual ports along the diffuser line, the orientation of the diffuser line and construction details represent additional geometric features. The flux characteristics are given by the discharge flow rate from the port, by its momentum flux and by its buoyancy flux. The buoyancy represents the relative density difference between discharge and ambient that, upon multiplication with the gravitational acceleration, is a measure of the tendency for the effluent flow to rise (for positive buoyancy) or to fall (for negative buoyancy).

## 2.2 Hydrodynamic Mixing Processes

The hydrodynamics of an effluent continuously discharging into a receiving body of water can be conceptualized as a mixing process occurring in two separate regions. In the first region, the initial jet characteristics of momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing. This region will be referred to as the "near-field", and encompasses the buoyant jet subsurface flow and any surface or bottom interaction, or in the case of a stratified ambient, terminal layer interaction. In this region, designers of the outfall can usually affect the initial mixing characteristics through appropriate manipulation of design variables.

As the turbulent plume travels further away from the source, the source characteristics become less important. Conditions existing in the ambient environment will control trajectory and dilution of the turbulent plume through buoyant spreading motions and passive diffusion due to ambient turbulence. This region will be referred to here as the "far-field".

It is stressed at this point that the distinction between near-field and far-field is made purely on hydrodynamic grounds. It is unrelated to any legal mixing zone definitions that address prescribed water quality standards as discussed in Section 1.2.2. In many practical cases the legal mixing zone may, in fact, include near-field hydrodynamic mixing processes. But that does not have to be so: For example, buoyant jet mixing in a

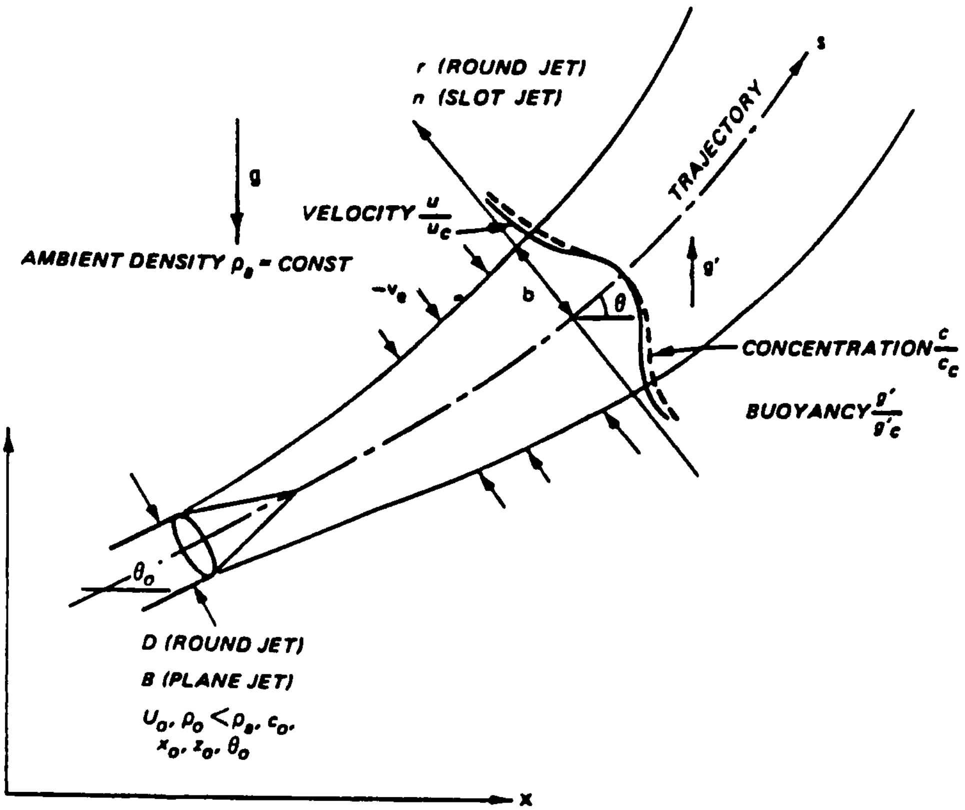


**Figure 2-1. Round Buoyant Jet In Stagnant Uniform-Density Environment.**

deep environment with crossflow may extend far beyond a legal mixing zone that is defined by a horizontal length equal to the water depth on the basis of section 301(h) of the Clean Water Act (USEPA, 1982). As a counter-example, a small source in a strong crossflow may rapidly enter the passive far-field diffusion region (in form of a bottom attached plume) well before the edge of a legal mixing zone! Thus, in principle, the whole gamut of mixing processes, ranging from the near-field to the far-field, must be considered for individual mixing zone analyses.

## 2.2.1 Near-Field Processes

### 2.2.1.1 Buoyant Jet Mixing

The effluent flow from a submerged discharge port provides a velocity discontinuity between the discharged fluid and the ambient fluid causing an intense shearing action. The shearing flow breaks rapidly down into a turbulent motion. The width of the zone of high turbulence intensity increases in the direction of the flow by incorporating ("entraining") more of the outside, less turbulent fluid into this zone. In this manner, any internal concentrations (e.g. of fluid momentum or of pollutants) become diluted by the entrainment of ambient water. Inversely, one can speak of the fact that both fluid momentum and pollutants become gradually diffused into the ambient field.

The initial velocity discontinuity may arise in different fashions. In a "pure jet" (also called "momentum jet" or "non-buoyant jet"), the initial momentum flux in the form of a high-velocity injection causes the turbulent mixing. In a "pure plume," the initial buoyancy flux leads to local vertical accelerations which then lead to turbulent mixing. In the general case of a "buoyant jet" (also called a "forced plume"), a combination of initial momentum flux and buoyancy flux is responsible.

Thus, buoyant jets are characterized by a narrow turbulent fluid zone in which vigorous mixing takes place. Furthermore, depending on discharge orientation and the direction of buoyant acceleration, generally curved trajectories are established in a stagnant uniform-density environment (see Figure 2-1).

Buoyant jet mixing is further affected by ambient currents and density stratification. The role of ambient currents is to gradually deflect the buoyant jet into the current direction and to induce additional mixing. The role of ambient stratification is to counteract the vertical acceleration within the buoyant jet leading ultimately

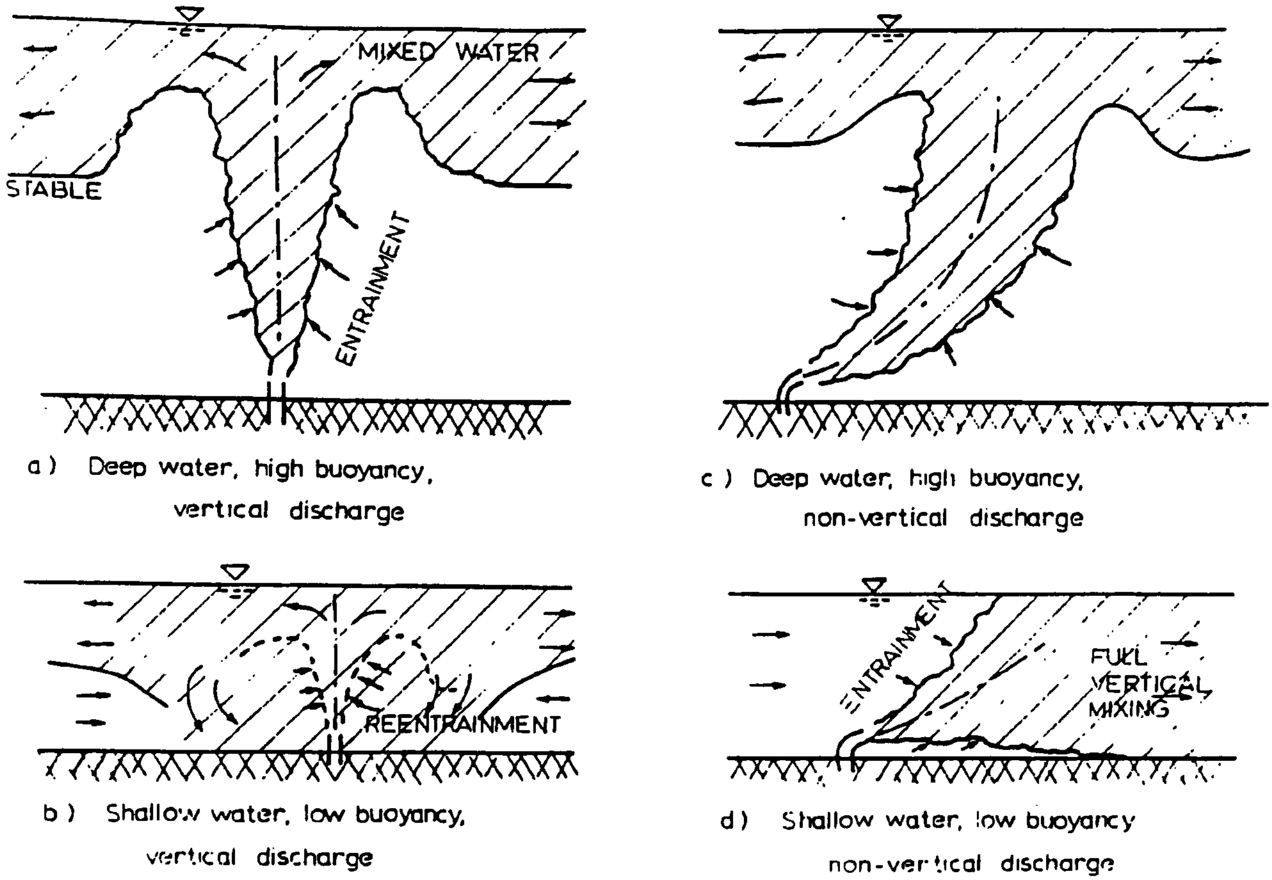


**Figure 2-2. Stable or Unstable Near-Field Flows Produced by Submerged Buoyant Discharges.**

to trapping of the flow at a certain level (trapping level or terminal level).

### 2.2.1.2 Boundary Interaction Processes and Near-Field Stability

Ambient water bodies always have vertical boundaries: these are the water surface and the bottom, but in addition "internal boundaries" may exist in the form of layers of rapid density change (pycnoclines). Depending on the dynamic and geometric characteristics of the discharge flow, a variety of interaction phenomena can occur at such boundaries. Furthermore, in the case of a continuously (e.g. linearly) stratified ambient where flow trapping may occur, other interaction phenomena may take place.

In essence, these interaction processes provide a transition between the buoyant jet mixing process in the near-field, and between buoyant spreading and passive diffusion in the far-field.

Interaction processes can be (i) gradual and mild or (ii) abrupt leading to vigorous transition and mixing processes. (i) If a buoyant jet is bent-over by the cross-flow it will gradually approach the surface, bottom or terminal level and will undergo a smooth transition with little additional mixing.

(ii) If a jet is impinging normally, or near-normally, on a boundary, it will rapidly spread in all directions (see Figure 2-2). Different possibilities exist at that point: (a) If the flow has sufficient buoyancy it will ultimately form a stable layer at the surface (Figure 2-2a,c). In the presence of weak ambient flow this will lead to an upstream intrusion against the ambient current. (b) If the buoyancy of the effluent flow is weak or its momentum very high, unstable recirculation phenomena can occur in the discharge vicinity (see Figure 2-2b,d). This local recirculation leads to re-entrainment of already mixed water back into the buoyant jet region. Thus, simple buoyant jet analyses no longer suffice to predict these phenomena.

The aspect of <u>near-field stability</u>, i.e. the distinction into stable or unstable conditions, is a key feature of pollution analyses. "Stable discharge" conditions, usually occurring for a combination of strong buoyancy, weak momentum and deep water, are often referred as "deep

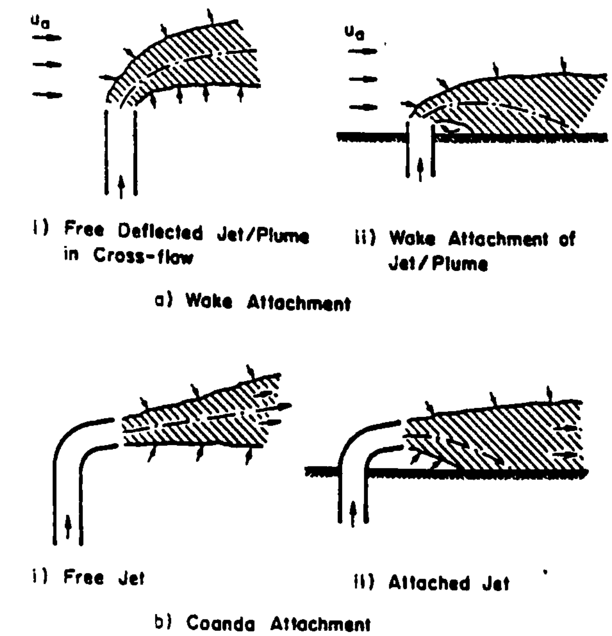


**Figure 2-3. Bottom Attachment Processes for Submerged Discharges.**

water" conditions. "Unstable discharge" conditions, on the other had, may be considered synonymous to "shallow water" conditions. Further detail on discharge stability can be found in Jirka (1982 a,b) and Holley and Jirka (1986).

Yet another type of interaction process concerns submerged buoyant jets discharging in the vicinity of the water bottom into a stagnant or crossflowing ambient. Two types of dynamic interaction processes can occur that lead to rapid attachment of the effluent plume to the water bottom (see Figure 2-3). These may be wake attachment forced by the crossflow or Coanda attachment (due to low pressure effects) forced by the entrainment demand of the effluent jet itself. In either case the assumption of free buoyant jets is invalidated and other analyses have to be pursued for these bottom-attached flows.

#### 2.2.1.3 Multiport Diffuser Induced Flows in Shallow Water (Intermediate-Field)

Some multiport diffuser installations represent large sources of momentum, while their buoyancy effects may be relatively weak. Therefore these diffusers will have an unstable near-field with shallow water conditions. This is characteristic, for example, for cooling water diffusers from thermal power plants. For certain diffuser geometries (i.e. the unidirectional and the staged diffuser types; see Section 2.3) strong motions can be induced in the shallow water environment in the form of vertically mixed currents that laterally entrain ambient water and may extend over long distances before they re-stratify or dissipate their momentum. In a sense, these "diffuser plumes" extend beyond the strict near-field (of the order of the water depth) and are sometimes referred to as the "intermediate-field" (Jirka, 1982b).

### 2.2.2 *Far-Field Processes*

In the context of this report, far-field mixing processes are characterized by the longitudinal advection of the mixed effluent by the ambient current velocity.

#### 2.2.2.1 Buoyant Spreading Processes

Buoyant spreading processes are defined as the horizontally transverse spreading of the mixed effluent flow while it is being advected downstream by the ambient current. Such spreading processes arise due to the buoyant forces caused by the density difference of the mixed flow relative to the ambient density. If the discharge is nonbuoyant, or weakly buoyant, and the ambient is unstratified, there is no buoyant spreading region in the far-field, only a passive diffusion region.

Depending on the type of near-field flow and ambient stratification several types of buoyant spreading may occur: (i) spreading at the water surface, (ii) spreading at the bottom, (iii) spreading at a sharp internal interface (pycnocline) with a density jump, or (iv) spreading at the terminal level in continuously (e.g. linearly) stratified ambient fluid.

As an example, the definition diagram and structure of surface buoyant spreading processes in unstratified crossflow is shown in Figure 2-4. The laterally spread-

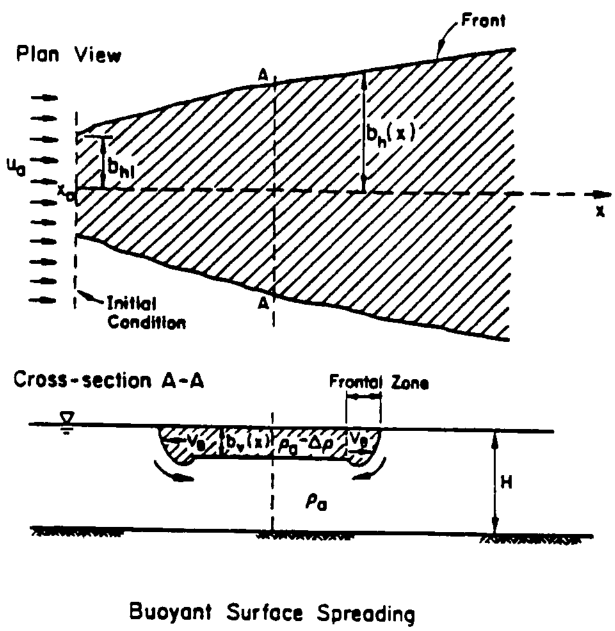


**Figure 2-4. Buoyant Spreading Processes in the Far-Field (Example: Surface Spreading).**

ing flow behaves like a density current and entrains some ambient fluid in the "head region" of the current. The mixing rate is usually relatively small. Furthermore, the flow may interact with a nearby bank or shoreline (not shown in the figure). The layer thickness may decrease during this phase.

Depending on source and ambient characteristics, buoyant spreading processes can be effective transport mechanisms that can quickly spread a mixed effluent laterally over large distances in the transverse direction. This can be particularly pronounced in cases of strong ambient stratification in which the effluent at the terminal level that may initially be of considerable vertical thickness collapses into a thin but very wide layer unless this is prevented by lateral boundaries.

#### 2.2.2.2 Passive Ambient Diffusion Processes

The existing turbulence in the ambient environment becomes the dominating mixing mechanism at sufficiently large distances from the discharge point. The intensity of this passive diffusion process depends upon the geometry of the ambient shear flow as well as any existing stratification. In general, the passively diffusing flow is growing in width and in thickness (see Figure 2-5). Furthermore, it may interact with the channel bottom and/or banks.

The strength of the ambient diffusion mechanism depends on a number of factors relating mainly to the geometry of the ambient shear flow and the ambient stratification. In the context of classical diffusion theory (i.e. gradient diffusion, see Fischer et al., 1979) diffusion processes in bounded flows (e.g. rivers or narrow estuaries) can be described by constant diffusivities in the vertical and horizontal direction that depend on turbulent intensity and on channel depth or width as the length scales. On the other hand, wide "unbounded" channels or open coastal areas are characterized by plume size dependent diffusivities leading to accelerating plume growth described, for example, by the "4/3 law" of diffusion. In the presence of a stable ambient stratification the vertical diffusive mixing is generally strongly damped.

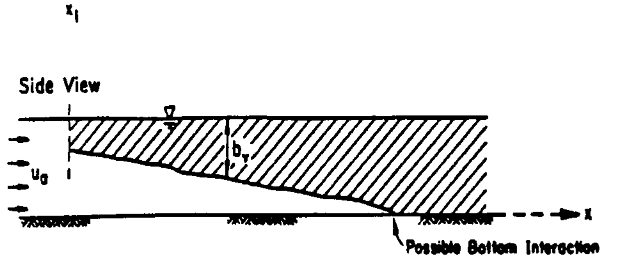


**Figure 2-5. Passive Ambient Diffusion Processes.**

## 2.3 Mathematical Predictive Models

### 2.3.1 *Modeling Methodology*

In principle, one can conceive of two approaches to the prediction of effluent discharges in the water environment: complete models or zone models.

(i) Complete models: These are three-dimensional numerical models that directly solve a finite difference or finite element approximation for the full dynamic and mass conservation equations with various assumptions for the turbulent shear and mass transport terms. In principle, with the advent of powerful computing facilities, even on the desktop, such a complete modeling approach that encompasses the entire fluid domain of interest with all individual mixing processes appears feasible. However, successful applications to date have been limited. Apparent reasons for the present shortcomings include (1) lack of fully workable turbulence closure techniques under the influence of buoyancy while considering the full range of jet-induced geophysical turbulence; (2) the difficult trade-off of modeling a large enough domain while providing sufficient resolution in a three-dimensional model (computer capacity and costs); and (3) the unknown nature of the open fluid boundary conditions which need to be specified as part of the elliptic equation system. These boundaries may, in general, contain a combination of stratified inflow and outflow that is inherently difficult to specify. For these reasons, complete numerical models are usually not used in routine mixing zone analyses of effluent discharges and this is expected to remain so for at least the next decade.

(ii) Zone Models: Instead of attempting to integrate the general governing equations over the whole region of interest it is frequently useful to divide the region into several zones with distinct behavior (such as individual mixing processes in the near-field and in the far-field). Within these zones it is then possible to simplify the governing equations by dropping unimportant terms. This gives a considerable advantage in the mathematical treatment and improved accuracy in the solution. However, a challenge remains because the solutions are restricted to specific zones. Thus, criteria need to be established for a meaningful division of the whole region into zones, and to provide transition conditions between zones.

Current practice in pollution analyses relies on zone models. Such models that deal with individual flow processes are described in the specialized research literature as well as in several monographs (e.g. Fischer et al., 1979, Holley and Jirka, 1986). However, a problem arises because there is limited guidance to the model user on the limits of applicability of each model, and on how to combine the individual models for an overall prediction of the entire flow process. The use of an integrated expert system framework (see below) promises to alleviate this problem.

An important group of zone models are the so-called buoyant jet integral models that are limited to the buoyant jet mixing process as described in Section 2.2.1.1 without attention to any problems of boundary interaction and near-field instability. Several of such integral model formulations are available as computer programs. Whenever their applicability has been ascertained, these models have been found through numerous data-model comparisons to be reliable and accurate. Jet integral models will be reviewed in Section 2.4.

An integrated framework of zone models for all important near-field and far-field mixing processes that effect effluent mixing has recently been developed. This framework is in the form of an expert system that classifies each discharge/ambient condition as to which flow processes are important and provides a prediction through a sequence of zone models with appropriate transition conditions. The zone modeling expert system methodology CORMIX (Doneker and Jirka, 1990; Akar and Jirka, 1991) is discussed in Sections 2.5 and 2.6.

### 2.3.2. *Zone Model Schematizations of Discharge and Ambient Conditions*

All zone models require some schematization of the complex and arbitrary ambient and discharge conditions that may prevail at any discharge site. These simplifications are needed to conform to the requirements of the individual models.

A schematic definition diagram for a single port discharge is given in Figure 2-6. The bottom is assumed to be flat (constant depth) while any banks (if considered in the analysis) are assumed to be vertical.

A corresponding diagram for multiport diffusers is provided in Figure 2-7. Of particular interest for this case is the alignment angle $\gamma$ between the crossflow direction and the diffuser axis, the orientation angle $\beta$ between the individual port axes and the diffuser line, and the vertical angle $\theta$ between port axis and the horizontal plane. Three major diffuser types have evolved in actual design practice and can be characterized by these angles (see Figure 2-8).

In the unidirectional diffuser, all the ports point in the same direction perpendicular to the diffuser axis ($\beta$=90°). In the staged diffuser, all ports point along the diffuser line ($\beta$ = 0°). In the alternating diffuser, the ports are arranged in an alternating fashion and point in opposite directions ($\beta$=± 90°). The undirectional and the staged diffusers possess a net horizontal momentum input with a tendency to induce currents within the ambient water body. The alternating diffuser has a zero net horizontal momentum, and a lesser tendency to generate currents and circulations.

Of course, there are variations on the basic theme for each of the three diffuser types. Some of these design possibilities are shown in Figure 2-8. There may be double or triple nozzle arrangements (with a small internal angle) for both unidirectional or staged diffusers, and the port orientation angle $\beta$ may differ somewhat from the nominal value, 90° or 0°, respectively. Or, in case of the alternating diffuser, there may be multiple port assemblies for each riser with several ports arranged in a circular fashion. Furthermore, alternating diffusers for thermal discharges in shallow water may have a variable port orientation along the diffuser axis to control instabilities and horizontal circulations (for details, see Jirka, 1982b). Another special case of

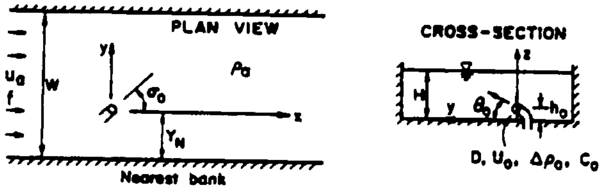


**Figure 2-6. Schematics of Single Port Discharge Geometry in Ambient Channel with Rectangular Cross -Section (Width W May Be Finite or Unlimited).**

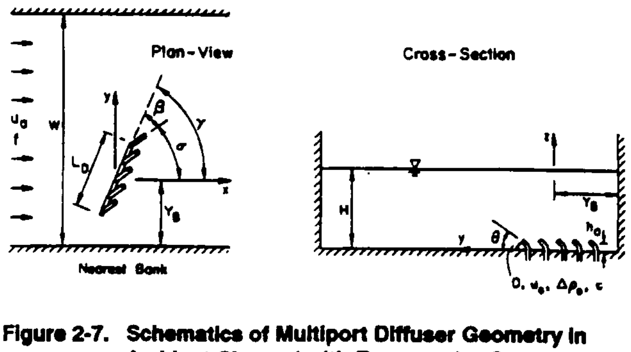


**Figure 2-7. Schematics of Multiport Diffuser Geometry in Ambient Channel with Rectangular Cross - Section (Width W May Be Finite or Unlimited).**

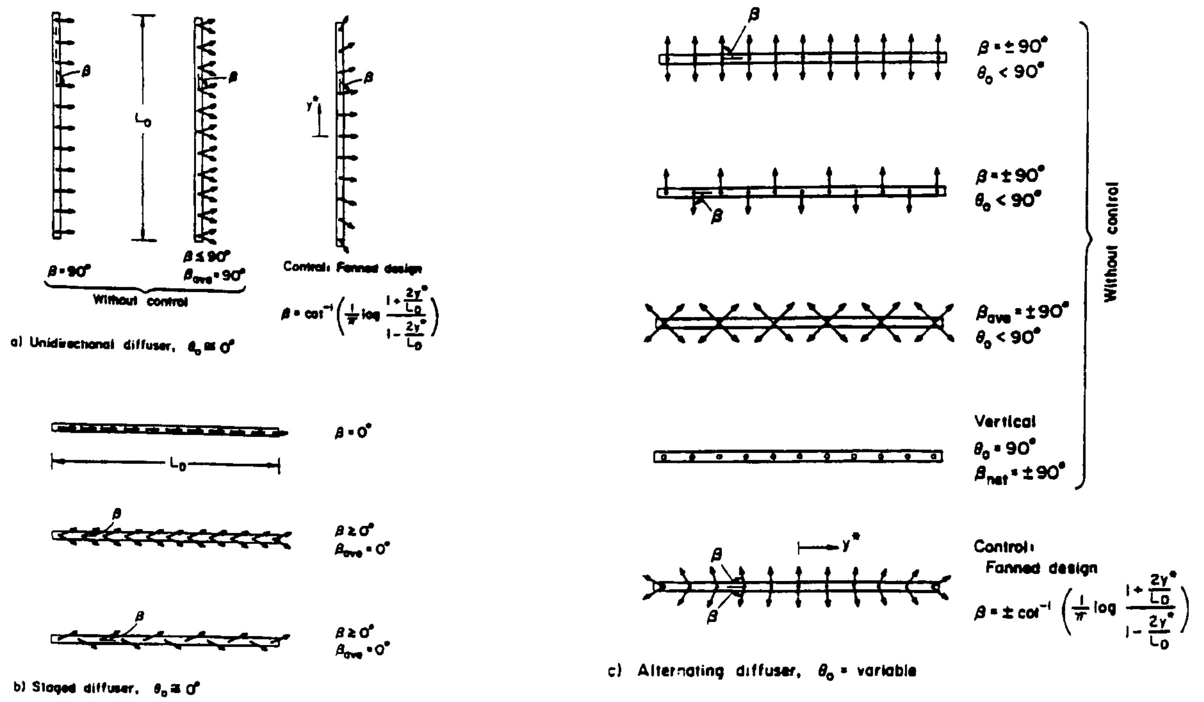


**Figure 2-8. Schematic Plan Views of Three Major Diffuser Types. a) Unidirectional Diffuser, b) Staged Diffuser, c) Alternating Diffuser. Any of Those Differusers May Have a Variable Alignment $\gamma$ Relative to the Ambient Current.**

an alternating diffuser is given by a vertical discharge from all ports.

Any diffuser can be deployed with arbitrary alignment $\gamma$. However, the two major arrangements are the perpendicular alignment ($\gamma \approx 90^{\circ}$) and the parallel alignment ($\gamma \approx 0^{\circ}$).

## 2.4 Buoyant Jet Integral Models

### 2.4.1 *Basic Elements: Stagnant Unstratified Ambient*

The narrow elongated shape of the turbulent zone within a buoyant jet (see Figure 2-1) suggests boundary-layer type simplifications to the equations of fluid motion and mass transport. The equations may be further simplified by integrating across the local jet cross-section thereby yielding a one-dimensional equation set for the actual three-dimensional problem. This is the essence of jet integral models which solve the equation set with a simple integration scheme marching forward along the trajectory.

The integral method is demonstrated in the following for a round buoyant jet issuing into a stagnant unstratified ambient (Figure 2-1). The jet-trajectory is assumed to lie within an x-z coordinate system. Local integration across the buoyant jet gives the following flux (integral) quantities:

Volume flux: $$Q = 2\pi \int_0^{\infty} u\, r\, dr = 2\pi I_1 u_c b^2 \qquad (1)$$

Momentum flux (kinematic):
$$M = 2\pi \int_0^{\infty} u^2 r\, dr = 2\pi I_2 u_c^2 b^2 \qquad (2)$$

Scalar (pollutant) mass flux:
$$Q_c = 2\pi \int_0^{\infty} u\, c\, r\, dr = 2\pi I_3 u_c c_c b^2 \qquad (3)$$

Buoyancy flux:
$$J = 2\pi \int_0^{\infty} u\, g'\, r\, dr = 2\pi I_3 u_c g'_c b^2 \qquad (4)$$

in which u = mean velocity in the trajectory direction, r = transverse coordinate from local jet centerline, c = mean concentration, and $g'$ = mean buoyant acceleration relative to the outside fluid where

$$g' = \frac{\rho_a - \rho}{\rho_a} g \qquad (5)$$

$\rho$ = local density, $\rho_a$ = ambient density, and g = gravitational acceleration. In the rightmost integrated quantities, the subscript c indicates centerline values, and the width b is a measure of the width of the jet (see below). The profile constants $I_1, I_2, I_3$, are simple numerical values that depend on the chosen profile shape and on the width definition (see Holley and Jirka, 1986). Frequently, a bell-shaped Gaussian profile is chosen and the width b is conveniently defined by the "1/e width" where the local quantities are 1/e = 37% of the centerline value.

When the conservation laws are applied to these four flux quantities using a control volume of differential length ds where s = axial direction along trajectory the following differential equations arise:

$$\text{Volume flux conservation: } \frac{dQ}{ds} = 2\pi\, \alpha\, u_c\, b \qquad (6)$$

i.e. the volume flux (discharge) increases due to entrainment along the jet periphery.

Axial momentum flux conservation:

$$\frac{dM}{ds} = 2\pi\, I_4\, g_c'\, b^2 \sin\theta \qquad (7)$$

i.e., only the sin $\theta$ component of buoyancy produces acceleration in the axial direction, in which $\theta$ = local vertical angle.

Horizontal momentum flux conservation:

$$\frac{d}{ds}(M \cos\theta) = 0 \qquad (8)$$

i.e., no acceleration in the horizontal direction.

$$\text{Scalar flux conservation: } \frac{dQ_c}{ds} = 0 \qquad (9)$$

$$\text{Buoyancy flux conservation: } \frac{dJ}{ds} = 0 \qquad (10)$$

i.e. in the uniform ambient environment both fluxes stay constant.

In addition, it is necessary to relate the local coordinate system (s,$\theta$) to the fixed global one (x,z)

$$\frac{dx}{ds} = \cos\,\theta \qquad (11)$$

$$\frac{dz}{ds} = \sin\,\theta \qquad (12)$$

This system of seven ordinary differential equations is fully specified by seven initial conditions at s = 0. These are the initial bulk fluxes $M_o$, $J_o$, $Q_o$, and $Q_{co}$ (alternatively,given by $U_o$ , $g_o' = g\,(\rho_a - \rho_o)/\rho_a$ , $c_o$ , and $D$ ) and the geometry $x_o$, $z_o$, and $\theta_o$.

Solution of this ordinary differential equation system by any chosen numerical method yields the seven local buoyant jet measures. These are M, J, Q, and $Q_c$ (or alternatively, the related variables $u_c$, $g_c'$, $c_c$ and b) and the trajectory measures x, z, and $\theta$. The local bulk (flux-averaged) dilution is then given by the ratio $Q/Q_o$ and the local centerline (minimum) dilution by the ratio $c_o/c_c$.

Two fundamental difficulties exist in the jet integral method:

(i) The closure problem: Entrainment and mixing of ambient fluid is a turbulent flow phenomenon. The volume flux conservation, Equation 6, presupposes that the mean entrainment velocity $v_e$ (see Figure 2-1) is linearly related to the centerline velocity, $v_e = \alpha\, u_c$, where $\alpha$ = entrainment coefficient. Inspection of data on buoyant jets that undergo a transition from initial jet-like (momentum-dominated) to final plume-like (buoyancy-dominated) behavior shows that $\alpha$ is quite variable. In some integral models a geometric equation is used instead of Equation 6, namely

$$\text{Jet spreading: } \frac{db}{ds} = k \qquad (6a)$$

In which k = spreading coefficient with somewhat less variability between the jet-like and plume-like stages. The actual choice of the appropriate equation, Eqs. 6 or 6a, and the specification of the coefficient that may be a function of local flow conditions is generally referred to as the "closure problem". The closure is made differently in the various integral models. A more detailed discussion is given by Holley and Jirka (1986).

(ii) The zone of flow establishment: The above equation set is, strictly speaking, not valid in a short initial zone of flow establishment in which a gradual adjustment between the efflux profile (approximately uniform) to the final bell-shaped profile takes place. Since this zone is short ( $\approx 5D$ to 10D, where D = diameter of the discharge port) no major error is introduced if it is simply neglected. This is the case in some integral models. Alternately, some models include an adjustment via a virtual origin or others perform a detailed, though approximate, analysis of this zone.

The derivation of integral jet equations for the slot buoyant jet (see the alternative source conditions indicated in Figure 2-1) is quite analogous to the round jet. It is omitted here for brevity (see Holley and Jirka, 1986). The slot buoyant jet is an important element of the analysis of subsurface multiport diffuser plumes that are formed after merging of the individual round jets.

### 2.4.2 *Extensions to Flowing Stratified Ambients*

The advantage of jet integral models is their ready extension to more complex environmental conditions, such as ambient stratification and crossflow.

If the receiving water is stratified with a stable density gradient ($d\rho_a/dz < 0$, i.e. the ambient density $= \rho_a(z)$ decreases upward), then the buoyancy flux is not conserved along an upward jet trajectory but is constantly decreasing. Eventually the buoyant jet will reach, and may even overshoot, its terminal level $z_t$ at which the local internal jet density is equal to the

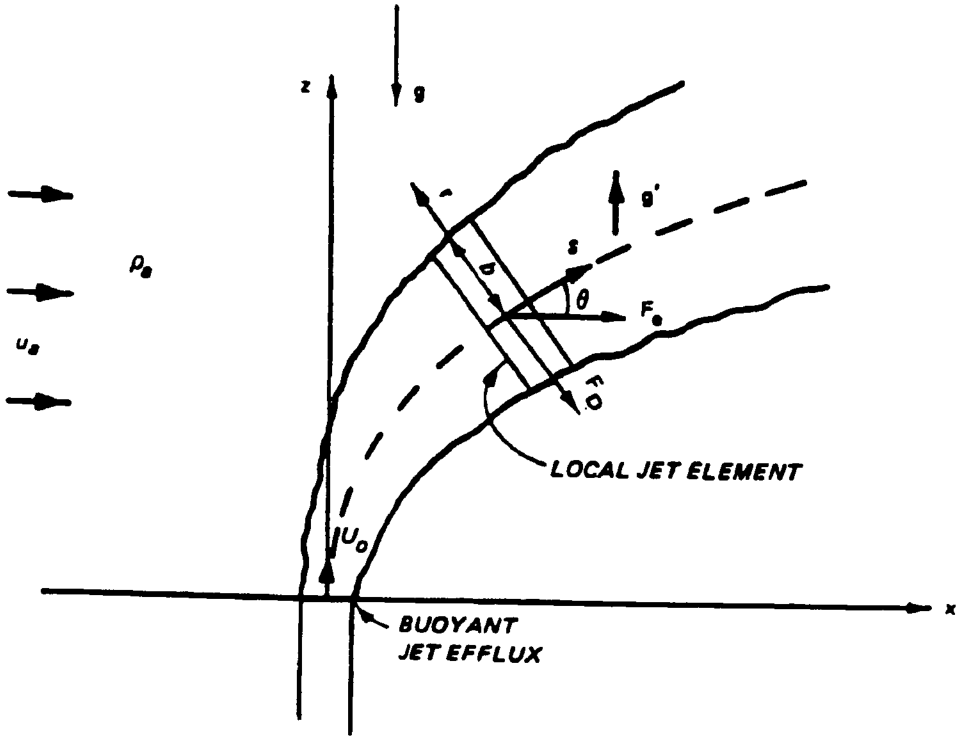


**Figure 2-9. Round Buoyant Jet in Ambient Crossflow with Drag and Entrainment Forces (Example: Vertical Discharge).**

ambient density $\rho_a(z_t)$. The jet will become trapped at this level and spread horizontally in the form of a gravitational current. The jet mechanics prior to the terminal level are readily described with the integral technique if two extensions are made. First, the buoyancy profiles are now defined with respect to the local reference buoyancy

$$g' = \frac{\rho_a(z) - \rho}{\rho_a(z)} g \qquad (13)$$

instead of Equation 2, leading to modification of Equations 3 and 7, respectively. Second, from mass balance requirements, the buoyancy flux is decreasing at the same rate at which it is diluted with ambient water of lesser density. This leads to

$$\frac{dJ}{ds} = Q \frac{g}{\rho_a} \frac{d\rho_a}{ds} \qquad (14)$$

for the round jet, instead of Equation 10. Inherent in these expressions is the assumption that the average density of the entrained water is equal to the density at the level of trajectory (centerline). This excludes cases of very rapid local changes, such as steep pycnoclines in estuaries.

When a round buoyant jet is discharged into an ambient crossflow of velocity $u_a$, then it will be deflected in the direction of the crossflow. This deflection is brought about by two force mechanisms, a pressure drag force $F_D$ and a force $F_e$ due to the entrainment of crossflow momentum. Referring to Figure 2-9, this situation is readily described in the integral analysis framework provided that several adjustments are made. First, neglecting the horseshoe or "kidney" shape (Fischer et al. 1979) which actually exists and assuming that the jet may be approximated by a circular cross-section, the velocity profile in the jet cross-section is given by the sum of the ambient velocity component in the direction of the trajectory, $u_a \cos\theta$, and the bell-shaped jet profile. This, then, affects the definition of all jet bulk flux variables, M, J, Q and $Q_c$. The definition of the drag force normal to the jet axis, and per unit length of the jet axis, is (in kinematic units)

$$F_D = \frac{1}{2} C_D u_a^2 \sin^2\theta \,(2b) \qquad (15)$$

in which $C_D$ is a drag coefficient (of order of unity), and the width of the "jet body" is simply taken as 2b. The entrainment force (entrainment of ambient momentum) is

$$F_e = u_a \frac{dQ}{ds} \qquad (16)$$

The governing momentum equations, Equations 7 and 8 are amplified to

$$\frac{dM}{ds} = 2\pi I_4 g_c' b^2 \sin\theta + F_e \cos\theta \quad (17)$$

$$\frac{d}{ds}(M\cos\theta) = F_e + F_D \sin\theta \quad (18)$$

Also, it is observed in bent-over jets that the entrainment mechanism is considerably more vigorous and the entrainment velocity not simply proportional to $u_c$ as in the previous case. Several analyses have suggested that jet entrainment in crossflows has a second contribution once the jet is strongly bent-over but still slowly rising. This second contribution is similar to that of a horizontal line element of fluid that is rising due to an initial vertical impulse of momentum or due to initial buoyancy in a stagnant ambient fluid. The rising line element experiences turbulent growth and entrainment that is proportional to the velocity of rise. Since the strongly bent-over jet is similar to this line element, this second entrainment mechanism can be added to the original entrainment mechanism associated with the excess of forward jet velocity relative to the surrounding fluid. The result is

$$\frac{dQ}{ds} = 2\pi\alpha u_c b + 2\pi\alpha_2 u_a b \sin\theta \cos\theta \quad (19)$$

where $\alpha$ is of the same form as for a buoyant jet in stagnant ambient (Equation 6) and $\alpha_2$ is the crossflow induced entrainment coefficient.

### 2.4.3 *Overview of Jet Integral Models Available for Mixing Zone Analysis*

A large number of jet integral models for submerged single port or multiport discharges are reported in the literature. However, only a few of these are available for practical mixing zone analysis in the form of computer programs accessible to the analyst. Several of these are discussed below.

The validity and reliability of a jet integral model should be promulgated on at least two considerations: First, is its theoretical formulation sound and does it perform accurately under limiting conditions (e.g. the pure jet or pure plume)? Second, how do the model predictions compare with available data, preferably field data? No complete evaluation on these grounds of integral jet models is attempted here, but some important model features will be addressed in Section 3. It is stressed again that none of the following integral jet models include any form of boundary interaction processes; in a sense they all assume an unlimited receiving water body.

The U.S. EPA has published a set of five buoyant jet integral models (Muellenhoff et al., 1985), all with different capabilities. These models include computer programs written in FORTRAN for micro or minicomputers.

(1) The computer model UPLUME describes a buoyant jet issuing from a single port into a stagnant environment with arbitrary stratification. UPLUME is based on Abraham's (1963) original development using a jet spreading equation for closure. Empirical adjustment expressions are included for the zone of flow establishment.

(2) The model UOUTPLM (based on Winiarski and Frick, 1976) uses a somewhat different Lagrangian description of buoyant jet mechanics instead of the Eulerian system of equations given in Section 2.4.1. Thus, a plume element is tracked in its time-dependent evolution. However, the mechanisms actually included are similar to the ones discussed above with the exception of the omission of the ambient drag force. The model is applicable to a uniform crossflow with co-flowing or cross-flowing single port orientation (excluding counterflows) and with arbitrary density stratification. The model is not applicable for stagnant conditions.

(3) The model UMERGE is an extension of UOUTPLM applicable to multiport diffusers with perpendicular alignment. Merging is assumed to occur when geometric overlap of the individual equally spaced round jets occurs. After merging, the flow is described by the time-dependent motion of two-dimensional plume elements.

(4) UDKHDEN is a model that computes three-dimensional trajectories from either single port or multiport discharges in crossflows with arbitrary velocity (shear flow) and density distributions. The model is based on the development by Hirst (1971) and later generalizations by Kannberg and Davis (1976). The initial zone of flow establishment is computed in detail with Hirst's model. The three-dimensional equation system is a generalization of the type discussed in the preceding section. An entrainment function with dependence on a local densimetric Froude number is used for closure. A special geometric merging routine describes the gradual transition from individual round plumes to the two-dimensional plume. However, the same entrainment coefficient is used for round and for plane buoyant jets, making it impossible to verify the model for well-known asymptotic conditions. The diffuser alignment relative to the crossflow must be predominantly perpendicular.

(5) The model ULINE is strictly speaking not a jet integral model but uses an analytical solution for the two-dimensional slot plume dilution as a function of elevation. This solution is modified on the basis of Roberts' (1977) experimental results for the effect of

alignment on a diffuser line plume in crossflow. Also a stepwise algorithm is included to compute local mixing in an arbitrary crossflow and stratification. The model omits the merging process, thus assuming an initially merged (e.g. closely spaced) diffuser discharge.

Another buoyant jet model is that of Jirka and Fong (1981) to predict general three-dimensional trajectories for a single port discharge in a crossflow with arbitrary stratification. The model uses empirical descriptions for the zone of flow establishment as proposed by Schatzmann (1978). The model includes an entrainment closure that meets several limiting conditions and that has been extensively verified by Wong (1984) in application to ambient stratification. An additional element of the Jirka-Fong model is the description of the internal vortex mechanism in crossflow that can lead to plume bifurcation when a flow boundary or terminal level is encountered.

## 2.5 CORMIX: Expert System Methodology for Mixing Zone Analysis

### *2.5.1 Introduction*

The Cornell Mixing Zone Expert System (CORMIX) is a series of software elements for the analysis and design of submerged buoyant or nonbuoyant discharges containing conventional or toxic pollutants into stratified or unstratified watercourses, with emphasis on the geometry and dilution characteristics of the initial mixing zone. Subsystem CORMIX1 (Doneker and Jirka, 1990) deals with single port discharges and subsystem CORMIX2 (Akar and Jirka, 1991) addresses multiport diffusers. The system is implemented on microcomputers with the MS-DOS operating system.

The user supplies CORMIX with information about the discharge and ambient environment. CORMIX returns information detailing the hydrodynamic mechanisms controlling the flow, dilution, geometric information concerning the shape of the pollutant plume or flow in the ambient water body, and design recommendations allowing the user to improve the dilution characteristics of the flow. If specified by the user, CORMIX also presents information about legal mixing zone dimensions and dilution and about toxic mixing zone requirements.

CORMIX contains two key elements. The first is a rigorous flow classification scheme that classifies any given discharge/environment situation into one of several flow classes with distinct hydrodynamic features. The classification scheme places major emphasis on the near-field behavior of the discharge and uses the length scale concept as a measure of the influence of each potential mixing process. Flow behavior in the far-field, mostly in the form of boundary interactions, is also considered.

The second key element is a collection of predictive elements (modules) that are executed according to a protocol that pertains to each distinct flow class as determined by the classification scheme. These predictive elements are all based on simple analytical perturbation solutions for each flow process. Furthermore, transition rules are used to describe the spatial extent of each flow process.

The final result is a robust composite flow and mixing zone prediction that is applicable to a diverse variety of discharge/ambient conditions. CORMIX1 and 2 have been extensively validated with both laboratory and field data.

The geometric schematizations assumed in CORMIX have been summarized in Figures 2-6 to 2-8, respectively. In addition, CORMIX assumes a uniform unsheared ambient velocity profile represented by the mean velocity $u_a$. Furthermore, CORMIX requires that the ambient density profile be approximated by one of four representative stable profiles as shown in Figure 2-10. A dynamically correct approximation of the actual distribution should keep a balance between over- and under-estimation of the actual density data. The simplest case is a linear density profile shown in Figure 2-10a (Stratification Type A). Figure 2-10b describes two uniform density layers with a density jump (pycnocline) between layers (Stratification Type B). Figure 2-10c illustrates a two layer profile in which the upper layer is uniform, the lower layer has a linear stratification, and a density jump occurs between layers (Stratification Type C). Finally, Figure 2-10d presents a two layer system with a uniform upper layer and a linearly stratified bottom layer with no density jump between layers (Stratification Type D). The uniform upper layers in Stratification Types B, C, or D are representative for the well mixed upper layer that is found in many types of ambient water bodies and occurs due to wind induced turbulent mixing.

### *2.5.2 Length Scales*

Length scales, obtained from dimensional analysis, describe the relative importance of discharge volume flux, momentum flux, buoyancy flux, ambient crossflow, and density stratification in controlling flow behavior. The length scales will describe the distance over which these dynamic quantities control the flow, in particular within the subsurface buoyant jet regions of the mixing process.

#### 2.5.2.1 Single Port Discharges

Given the important flux parameters, $Q_o$, $M_o$ and $J_o$ (see Figure 2-5), the ambient velocity $u_a$, and the

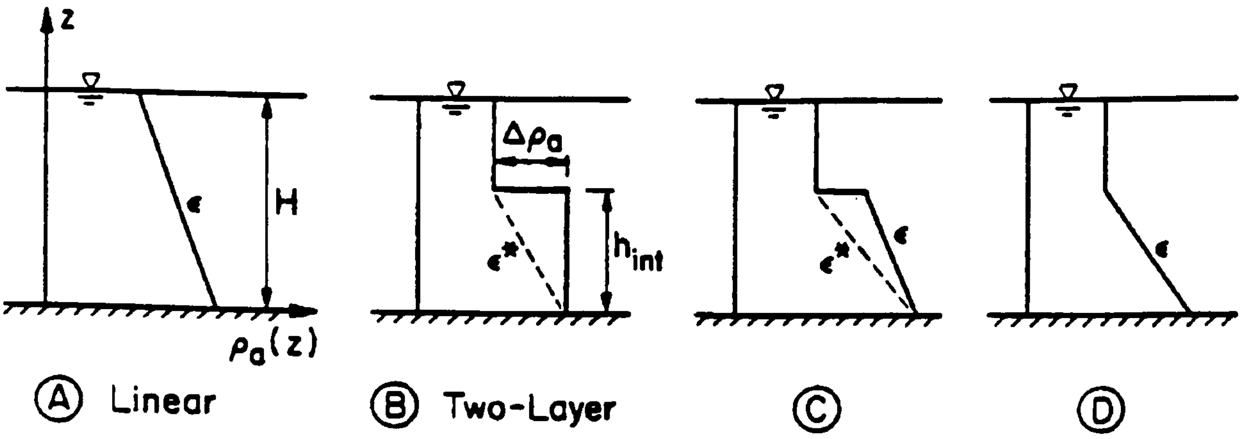


**Figure 2-10. Schematic Ambient Density Profiles for Use in Expert System CORMIX.**

buoyancy gradient $\varepsilon = -(g/\rho_a)(d\rho_a/dz)$ of a linearly stratified ambient, the following dynamic length scales can be derived for a single port discharge:

$L_Q = Q_o/M_o^{1/2}$ = discharge (geometric) scale

$L_m = M_o^{3/4}/J_o^{1/2}$ = jet/plume transition scale

$L_m = M_o^{1/2}/u_a$ = jet/crossflow scale

$L_b = J_o/u_a^3$ = plume/crossflow scale

$L_m' = (M_o/\varepsilon)^{1/4}$ = jet/stratification scale

$L_b' = J_o^{1/4}/\varepsilon^{3/8}$ = plume/stratification scale

The meaning of these scales is further illustrated in Figure 2-11. For example, the jet/crossflow length scale is a measure for the distance over which a pure jet will intrude into a crossflow before it gets strongly deflected (or affected). It should be noted that the length measures are only "order of magnitude"; precise coefficients have to be determined from experiments or from more detailed flow analysis.

### 2.5.2.2 Multiport Diffusers

The general diffuser flow field is, of course, three-dimensional. However, for near-field mixing analyses the two-dimensional flow parameters are dynamically relevant. For this purpose, the details of individual discharge jets with port diameter D and spacing l are neglected and replaced by an equivalent slot width B $= (\pi D^2)/(4\,l)$ on the basis of equivalency of momentum flux per unit diffuser length. This concept has been discussed by Jirka (1982b) among others, and has been shown to be a dynamically accurate representation. The main parameters for the two-dimensional slot discharge are the diffuser total flowrate $Q_0$ and the discharge buoyancy $g_o'$. This leads to the following flux parameters (per unit diffuser length), all expressed in kinematic units: $q_o = Q_o/L_D$ = volume flux (flowrate), $m_o = q_o U_o = U_o^2 B$ = momentum flux, and $j_o = q g_o' = U_o g_o' B$ = buoyancy flux, in which $U_o$ = discharge velocity, and $L_D$ = diffuser length.

Through interaction with the ambient parameters, the following length scales describe a multiport diffuser discharge:

$l_q = q_o^2/m_o$ = discharge geometric scale

$l_m = m_o/u_a^2$ = plane jet/crossflow scale

$l_M = m_o/j_o^{2/3}$ = plane jet/plane plume scale

$l_m' = (m_o/\varepsilon)^{1/3}$ = plane jet/stratification scale

$l_b' = j_o^{1/3}/\varepsilon^{1/2}$ = plane plume/stratification scale

$l_a = u_a/\varepsilon^{1/2}$ = crossflow/stratification scale

It is interesting to note that no plume/crossflow length scale can be defined on dimensional grounds for the two-dimensional plume. This is in contrast to the three-dimensional round plume and arises from the fact that the vertical velocity of a two-dimensional plume is constant, $\sim j_o^{1/3}$, leading in the presence of a constant crossflow to a straight-line trajectory. Thus, no distinction can be made of a plane plume in a weakly deflected stage followed by a strongly deflected stage. However, it is possible to define a non-dimensional parameter $j_o/U_a^3$ whose magnitude will be a measure of the slope of the plume trajectory.

### 2.5.3 *Near-Field Flow Classification*

The classification scheme used in CORMIX puts major emphasis on the near-field flow configuration. This is because a large number of flow configurations can occur due to the multiplicity of possible interaction processes; in contrast the far-field flow is generally much simpler with limited shoreline or bottom contact possibilities.

#### 2.5.3.1 Single Port Discharges (CORMIX1)

In the near-field the dynamic length scales $L_M$, $L_m$, $L_b$, $L_m{}'$ and $L_b{}'$ ($L_Q$ has less significance) describe the interaction with the geometric properties of the water body, its depth H or the depth $h_{int}$ to the density jump (in general, both of those are indicated by a layer depth $H_s$). Also the orientation angles $\theta_o$ and $\sigma_o$ of the discharge are important (Figure 2-6).

Given the possible ambient stratification types a classification procedure (in Doneker and Jirka, 1990) is used to classify the near-field behavior of a given discharge into one of 35 generic flow classes that are summarized in Figures 2-12 to 2-15. The four major flow categories indicated by CORMIX1 are: i) flows affected by linear stratification leading to internal trapping (S classes, Figure 2-12), ii) buoyant flows in a uniform ambient layer (V and H classes, Figure 2-13), iii) negatively buoyant flows in a uniform ambient layer (NV and NH classes, Figure 2-14), and iv) bottom attached flows (A classes, Figure 2-15).

Each of the flow classes is indicated on the figures by a sketch that shows its main features in a side view or plan view. All flow criteria shown on the figures are given as "order of magnitude" relations; somewhat different forms and numerical constants may be contained in CORMIX1.

A wide spectrum of near-field flow configurations is possible: these range from flows trapped in linear stratification, buoyant jets that are strongly affected by the crossflow and gradually approach the layer boundary (surface or pycnocline), weakly deflected buoyant jets that impinge on the boundary leading to upstream spreading and/or unstable recirculation, negatively buoyant jets that form density currents along the bottom, and dynamic attachment along the bottom with or without eventual buoyant lift-off. It is stressed also that (i) each of these flow classes can occur in combination with an upper stratified layer (see stratification types B, C, or D on Figure 2-10) and (ii) the designation "uniform ambient layer" in Figures 2-13 and 2-14 can, in fact, also apply to a stratified layer if it has been found that the stratification is too weak to trap the flow. Thus, in essence, the actual number of flow configurations that can be classified by CORMIX1 is much larger than the 35 generic flow classes shown on these figures.

#### 2.5.3.2 Multiport Diffusers (CORMIX2)

The classification scheme used by CORMIX2 relies on the same methodology as for single port discharges. The length scales of the two-dimensional slot jet, $l_M$, $l_m$, $l_b$, $l_m{}'$, and $l_a$, are compared with the layer depth $H_s$ and with the diffuser variables, its length $L_D$ and its orientation angles, $\theta, \gamma, \beta, \sigma$ (see Figure 2-7). The classification procedure (see Akar and Jirka, 1991, for details) yields 31 generic flow classes that fall into three major categories: (i) flows affected by linear stratification leading to internal trapping (MS classes, Figure 2.16), ii) buoyant flows in uniform ambient layers (MU classes, Figure 2.17), and iii) negatively buoyant flows in uniform ambient layers (MNU classes, Figure 2.18).

While there are some obvious analogies in their appearance to the flows produced by single port discharges, the major difference for multiport diffusers lies in the vertically fully mixed (over the layer depth) plumes that can be produced by the large momentum sources of unidirectional or staged diffusers.

### 2.5.4 *Predictive Elements*

The detailed hydrodynamic prediction of the effluent flow and of associated mixing zones in CORMIX is carried out by appropriate flow modules that are executed according to a protocol that pertains to each distinct flow configuration as determined by the classification scheme. These flow protocols have been constructed on the basis of the same length scale arguments that have been used for the flow classification. The spatial extent of each flow module is governed by transition rules. These determine transitions between different near-field and far-field mixing regions, and distances to boundary interaction.

The flow modules for single port discharge predictions (CORMIX1) are listed in Table 2-1. All modules present basic analytical solutions for one particular flow process with the perturbing influence of one or more other variables superimposed. For example, the module for the weakly deflected jet in crossflow (MOD11) is based on a pure jet solution that experiences a gradual advection by the crossflow. The group of near-field modules (MOD01 to MOD22) represents, in total, the same predictive ability as buoyant jet integral models (valid in the subsurface region without boundary interaction).

The flow modules for multiport diffuser prediction (CORMIX2) are given in Table 2-2. Several groups of modules, notably those for the far-field, are similar, or even identical, to those of CORMIX1.

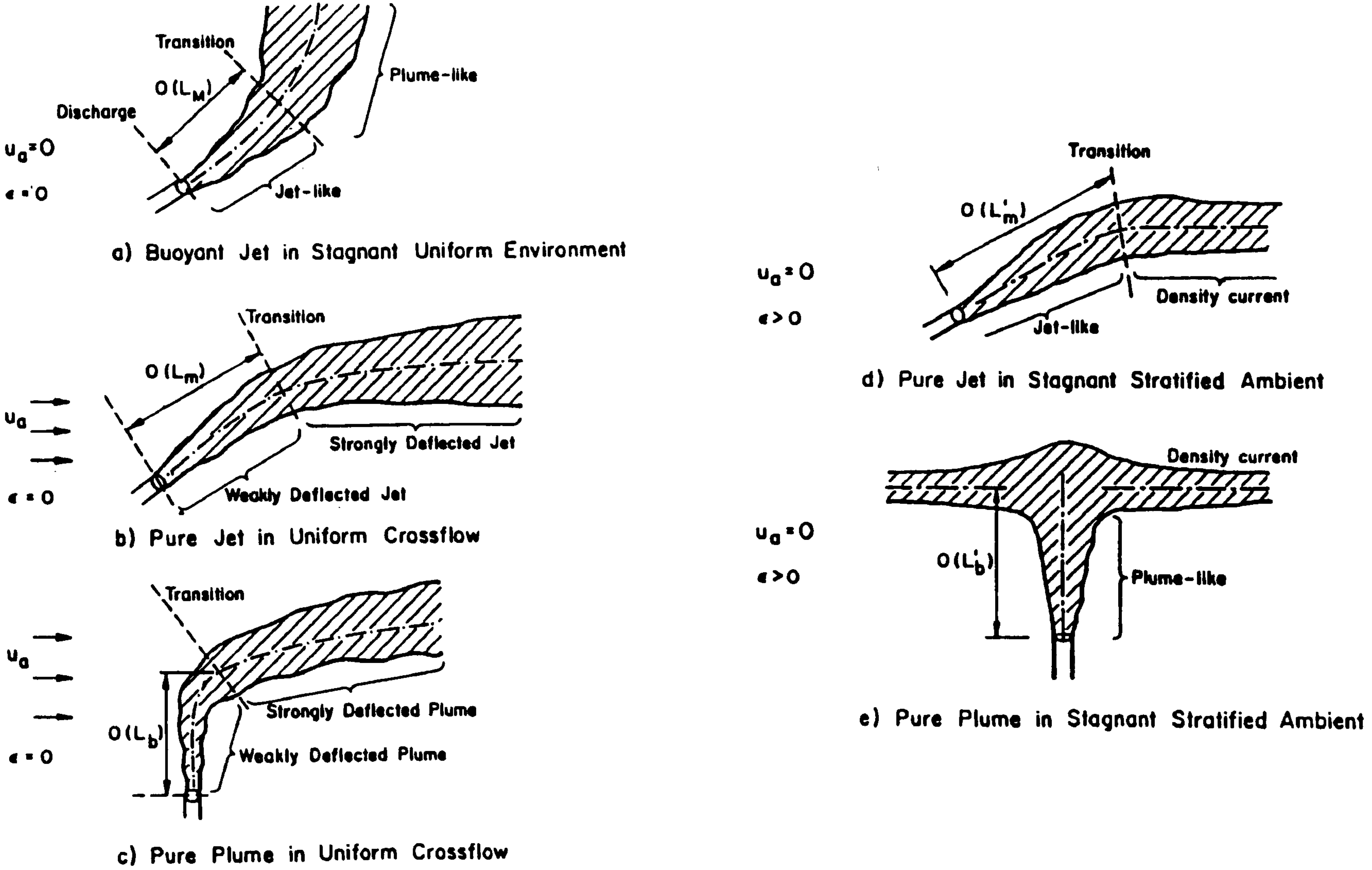


**Figure 2-11. Length Scales Measuring the Effects of Momentum Flux, Buoyancy Flux, Crossflow and Stratification of Submerged Jet Behavior.**

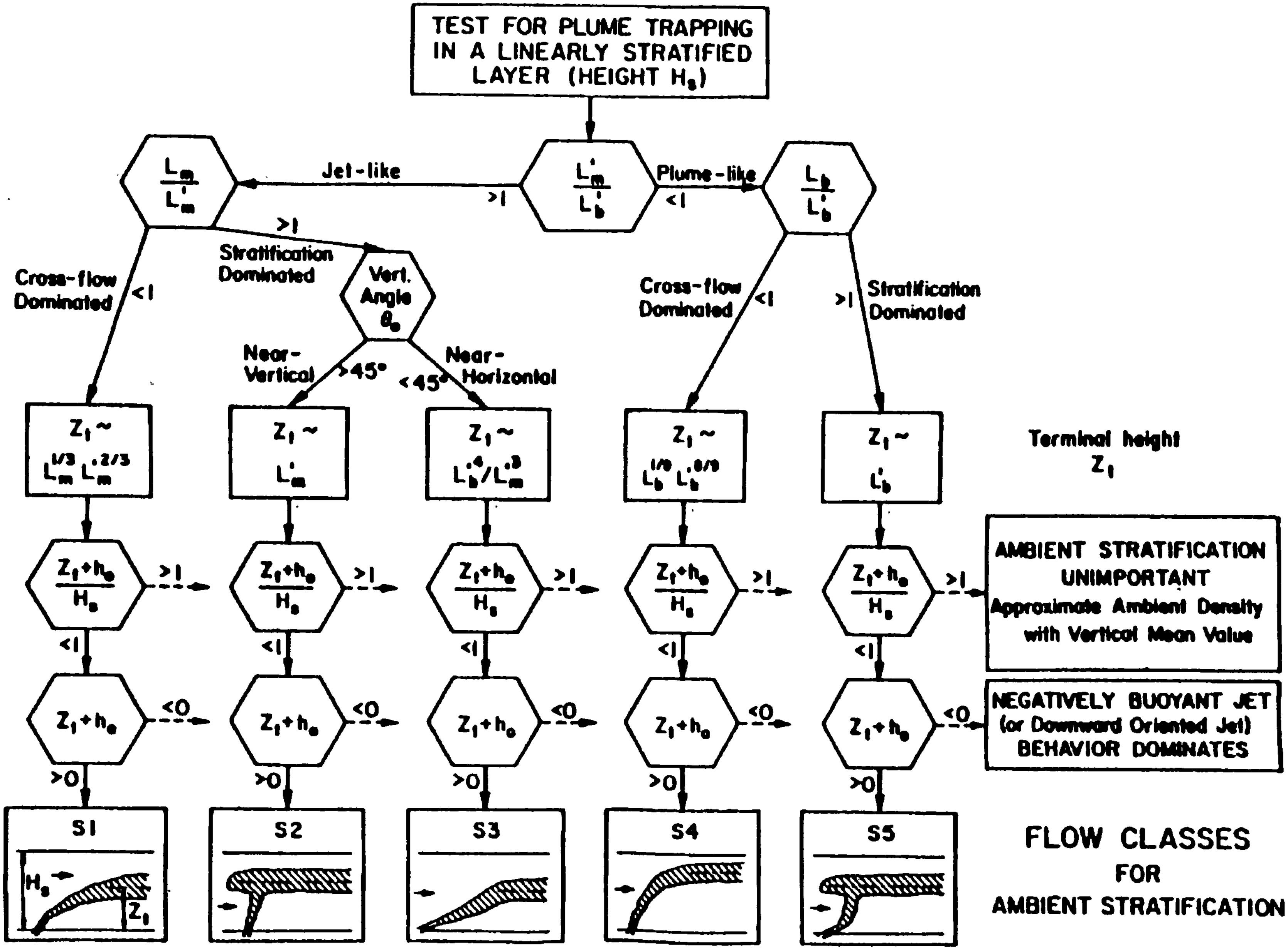


Figure 2-12. CORMIX1 Sub-Classification: Assessment of Density Stratification and Flow Classes for Internally Trapped Single Port Discharges.

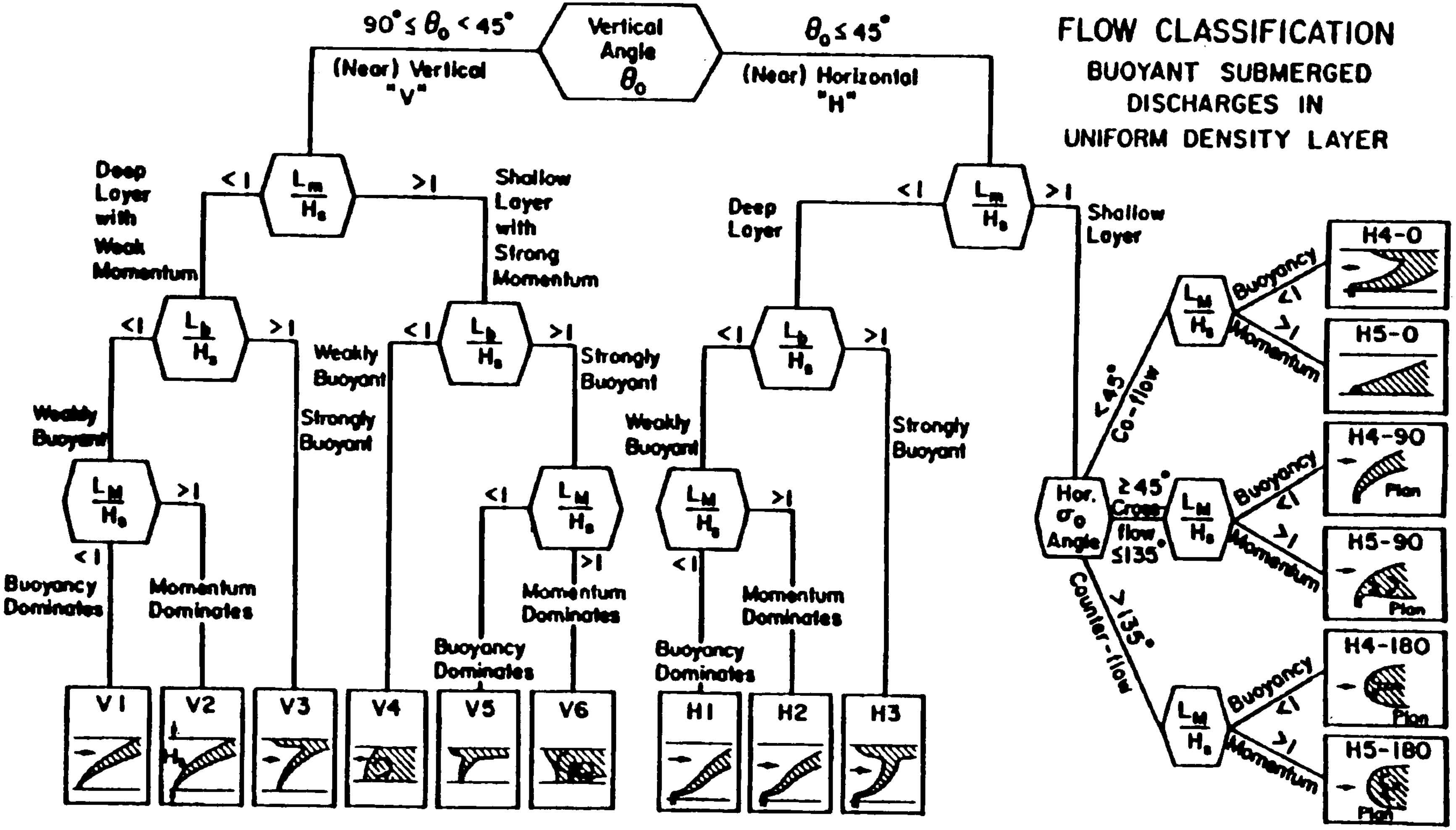


Figure 2-13. CORMIX1 Sub-Classification: Flow Classes for Positively Buoyant Single Port Discharges in Uniform Ambient Layer.

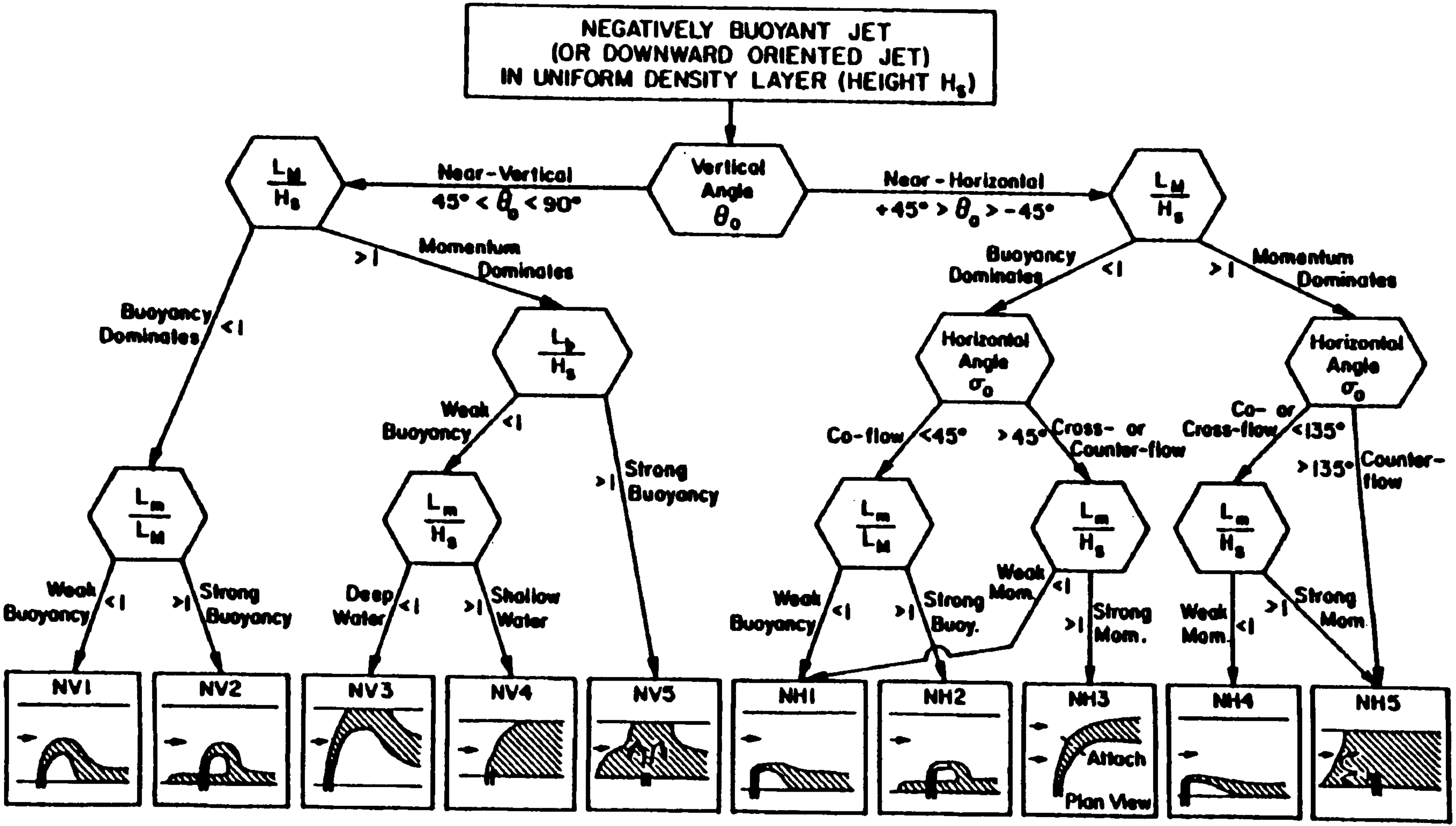


Figure 2-14. CORMIX1 Sub-Classification: Flow Classes for Negatively Buoyant Single Port Discharges in Uniform Ambient Layer.

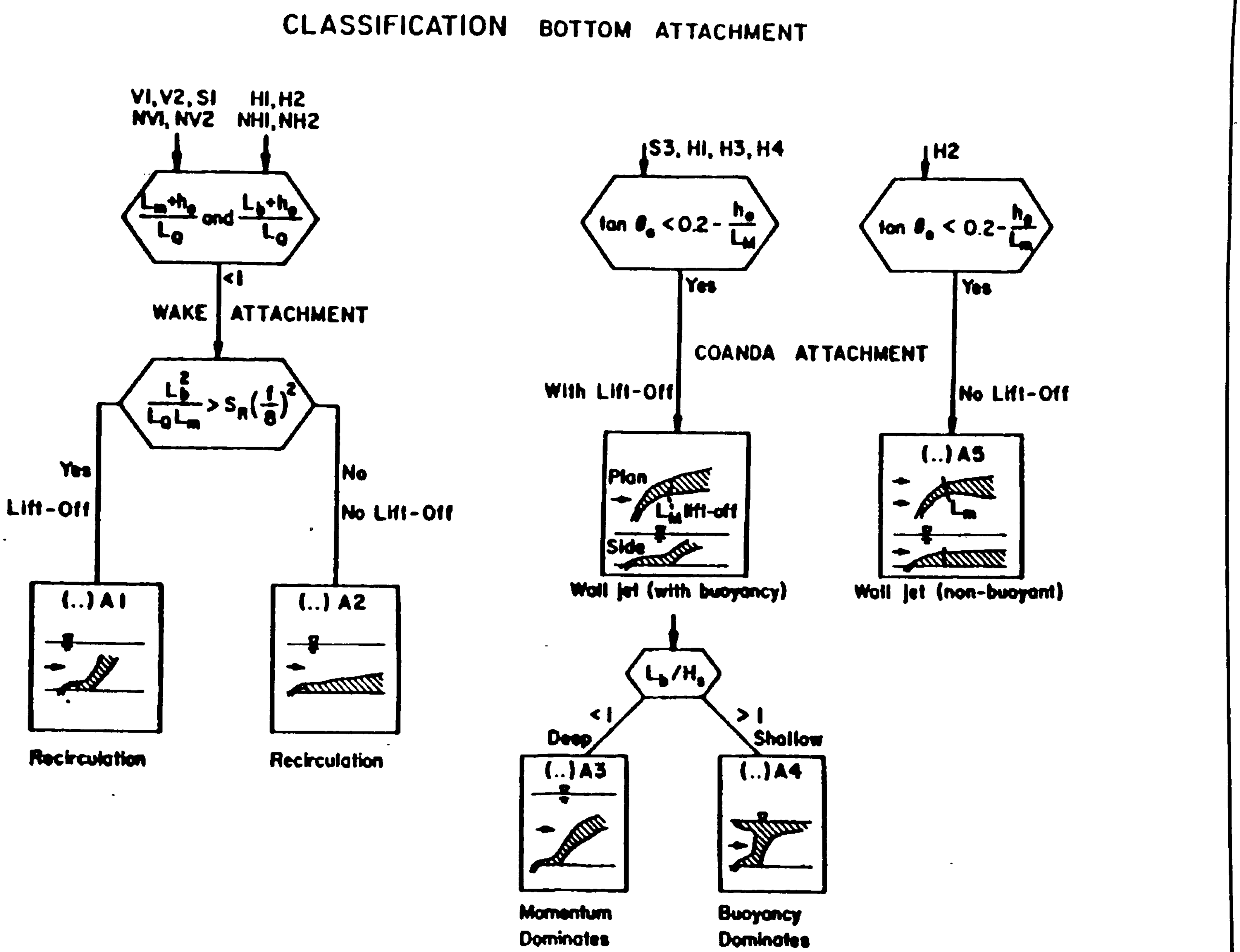


Figure 2-15. CORMIX1 Sub-Classification: Assessment of Dynamic Bottom Attachment Processes and Flow Classes for Bottom-Attached Flows.

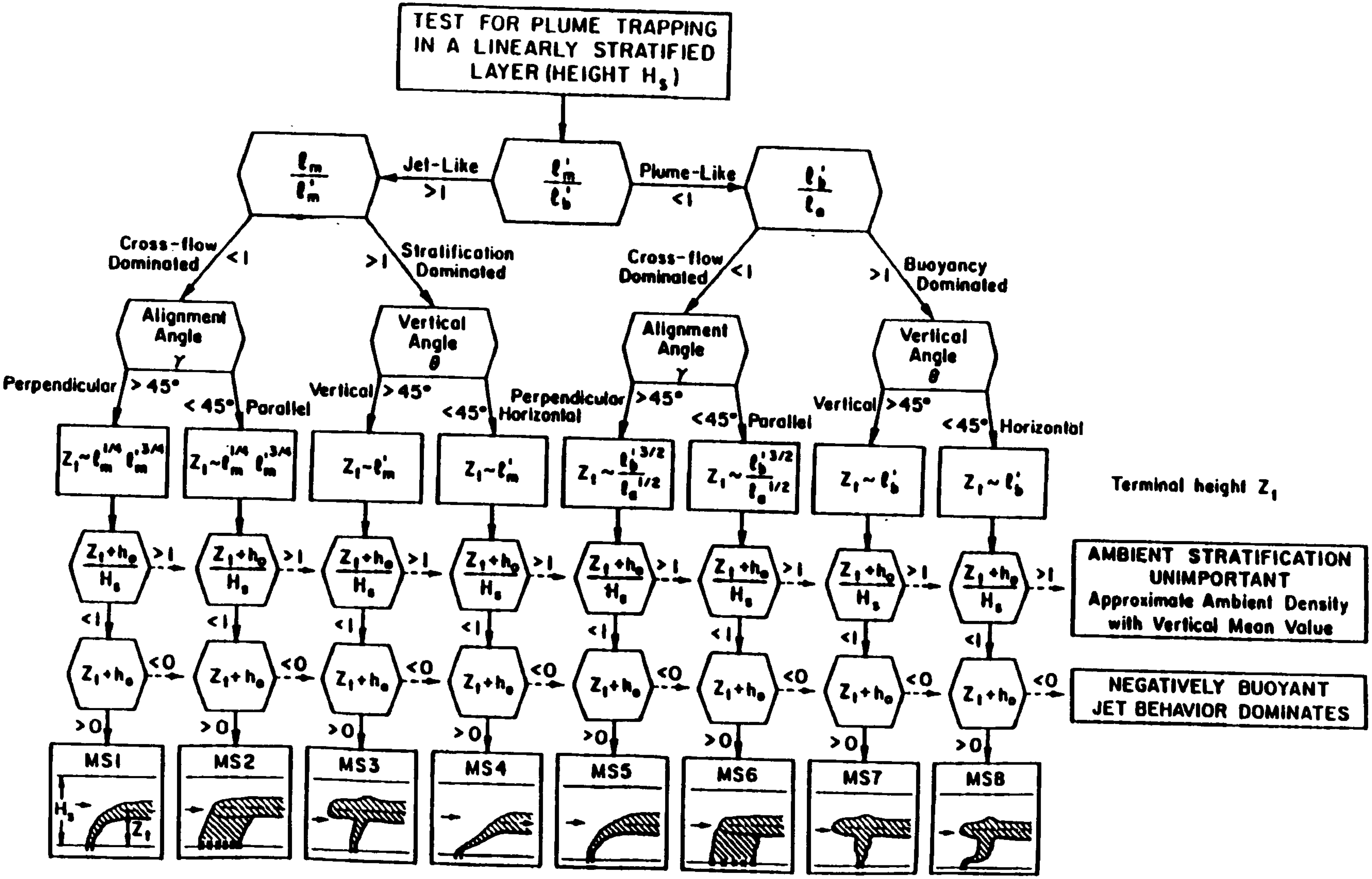


Figure 2-16. CORMIX2 Sub Classification: Assessment of Density Stratification and Flow Classes for Internally Trapped Multiport Discharges.

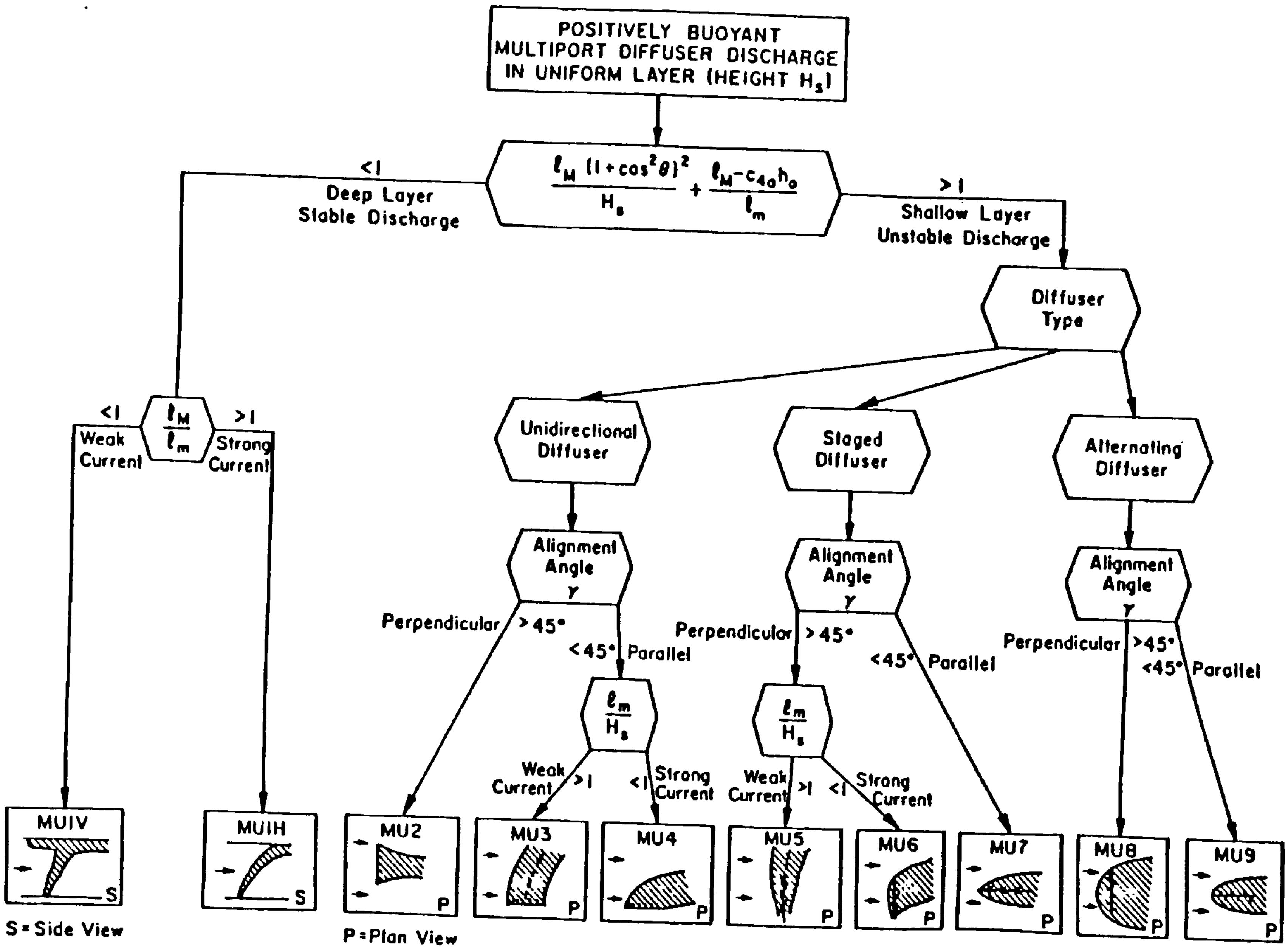


Figure 2-17. CORMIX2 Sub-Classification: Flow Classes for Positively Buoyant Multiport Discharges in Uniform Ambient Layer.

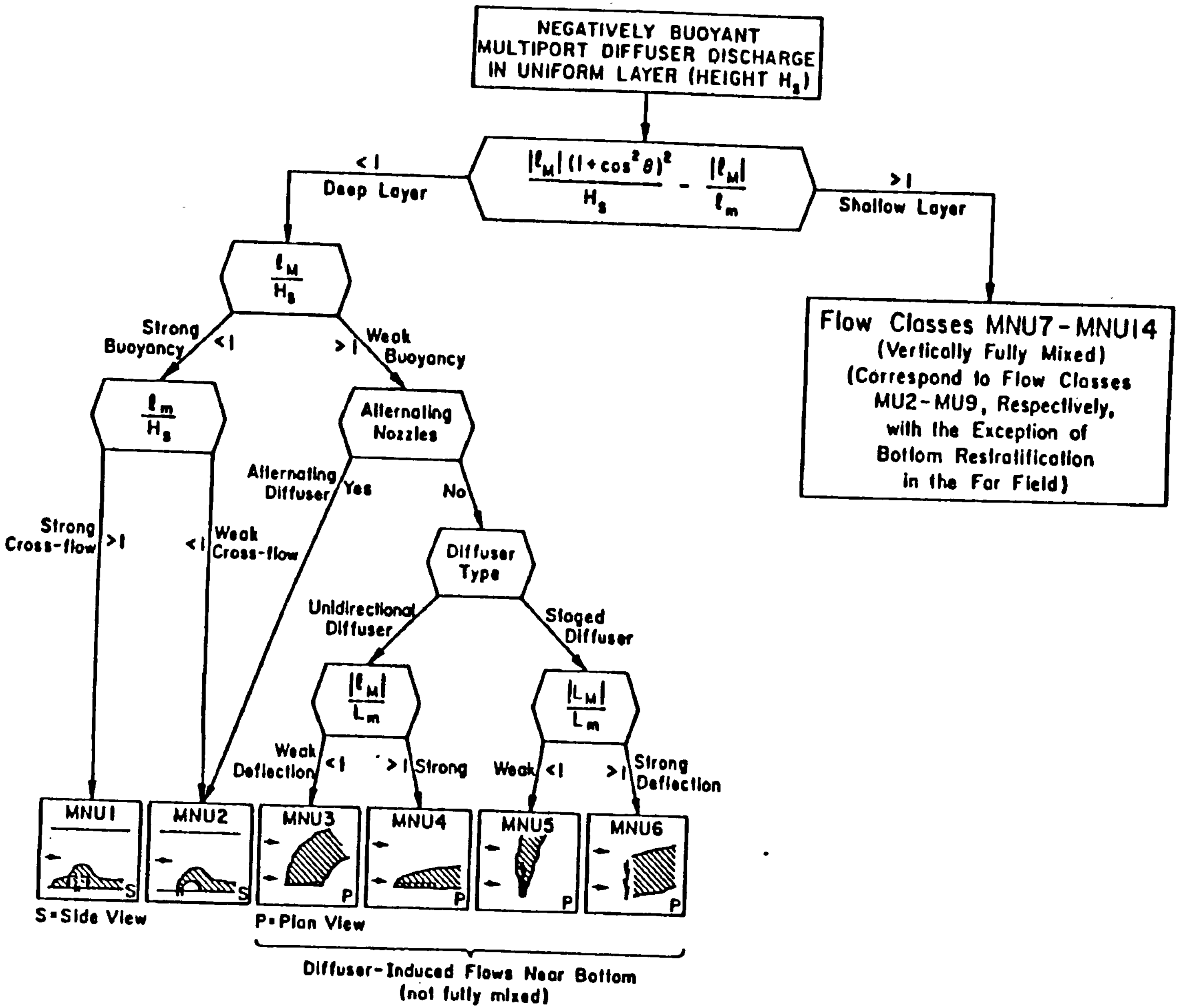


Figure 2-18. CORMIX2 Sub-Classification: Flow Classes for Negatively Buoyant Multiport Discharges in Uniform Ambient Layer.

Table 2-1. **Flow Prediction Modules of CORMIX1 (Single Port Discharges)**

| **Modules for Buoyant Jet Near-Field Flows** |
|---|
| zone of flow establishment |
| weakly deflected jet in crossflow |
| weakly deflected wall jet in crossflow |
| near-vertical jet in linear stratification |
| near-horizontal jet in linear stratification |
| strongly deflected jet in crossflow |
| strongly deflected wall jet in crossflow |
| weakly deflected plume in crossflow |
| strongly deflected plume in crossflow |
| **Modules for Boundary Interaction Processes** |
| near-horizontal surface/bottom/pycnocline approach |
| near-vertical surface/bottom/pycnocline impingement with buoyant upstream spreading |
| near-vertical surface/bottom/pycnocline impingement with vertical mixing |
| near-vertical surface/bottom/pycnocline impingement, upstream spreading, vertical mixing, and buoyant restratification |
| terminal layer stratified impingement/upstream spreading |
| terminal layer injection/upstream spreading |
| **Modules for Buoyant Spreading Processes** |
| buoyant layer spreading in uniform ambient |
| buoyant spreading in linearly stratified ambient |
| **Modules for Attachment/Detachment Processes** |
| wake recirculation |
| lift-off/fall-down |
| **Modules for Ambient Diffusion Processes** |
| passive diffusion in uniform ambient |
| passive diffusion in linearly stratified ambient |

Extensive comparisons have been conducted for CORMIX1 and 2 with available laboratory data and a few limited field data cases, as well as with buoyant jet integral models. These comparisons (Doneker and Jirka, 1990; Akar and Jirka, 1991) demonstrate that for subsurface flow the CORMIX predictions were at least of the same quality as that of jet integral models. The agreement with data (±20%) for trajectories and dilutions) is of the same order as the usual scatter among different data sources.

Moreover, CORMIX has been shown to be a robust and accurate predictive methodology for more complex flows with various degrees of boundary interaction, such as near-field instabilities, buoyant spreading processes, and dynamic bottom interaction. CORMIX appears to correctly diagnose these processes through its classification scheme and then provides quantitatively reliable predictions of the sequence of mixing processes that characterize a given discharge.

## 2.6 Mixing Zone Predictions Under Unsteady Reversing Tidal Currents

As has been remarked earlier in Section 2.1, the time scale for initial mixing processes is usually short enough relative to the tidal period, so that it is accept-

**Table 2-2. Flow Prediction Modules of CORMIX2 (Multiport Diffusers)**

| **Simulation Modules for Buoyant Multiport Diffusers: Subsurface Near-Field Flows** |
|---|
| discharge module |
| discharge (staged diffuser) |
| weakly deflected plane jet in crossflow |
| weakly deflected (3-D) wall jet in crossflow |
| near-vertical plane jet in linear stratification |
| near-horizontal plane jet in linear stratification |
| strongly deflected plane jet in crossflow |
| weakly deflected (2-D) wall jet in crossflow |
| weakly and strongly deflected plane plume in crossflow |
| buoyant plane plume in stratified stagnant ambient |
| negatively buoyant line plume |
| **Simulation Modules for Unstable Multiport Diffusers: Mixed Near-Field Flows** |
| unidirectional acceleration zone |
| tee acceleration zone |
| strongly deflected tee diffuser plume |
| staged acceleration zone |
| strongly deflected staged diffuser plume |
| alternating perpendicular diffuser in unstable near-field zone |
| negatively buoyant staged acceleration zone |
| **Simulation Modules for Boundary InteractionProcesses for Stable Multiport Diffusers** |
| near-vertical surface/bottom impingement with buoyant upstream spreading |
| near-vertical surface/bottom impingement, upstream spreading, vertical mixing, and buoyant restratification |
| near-horizontal surface/bottom/pycnocline approach |
| terminal layer stratified impingement/upstream spreading |
| terminal layer injection/upstream spreading |
| **Simulation Modules for Unstable Multiport Diffusers: Intermediate Field Flows** |
| diffuser plume in co-flow |
| diffuser plume in crossflow |
| **Simulation Modules for Buoyant Spreading Processes** |
| buoyant layer spreading in uniform ambient |
| buoyant spreading in linearly stratified ambient |
| density current developing along diffuser line |
| internal density current developing along diffuser line |
| diffuser induced bottom density current (2-D) |
| diffuser induced bottom density current (3-D) |
| **Simulation Modules for Ambient Diffusion Processes** |
| passive diffusion in uniform ambient |
| passive diffusion in linearly stratified ambient |

able to apply initial mixing models under steady-state conditions, e.g. corresponding to certain stages within the tidal cycle. However, this approach is no longer valid if predictions are desired over a larger area encompassing distances that, in fact, provide a transition to the far-field.

In the present state-of-the-art no complete models for pollutant predictions in the water environment are available (see Section 2.2). This restriction stems from the difficulties of representing the variety of transport processes that govern the distribution in unconfined estuarine or coastal water bodies in a single analytical or numerical technique. Therefore, an integration of near-field mixing models and of predictive techniques for the far-field effects must be employed. Far-field processes, that include the transport by the varying tidal flow, turbulent diffusion, and various biochemical transformation phenomena, have been addressed in Parts I and II of this estuarine waste load allocation manual. The following comments provide some guidance on estimating, the interaction between near-field mixing and far-field accumulation effects. The methodology is adapted from that suggested by Jirka et al. (1976).

### 2.6.1 *Far-Field Accumulation Effects*

The two major methods for estimating the unsteady far-field accumulation of discharged material, at variable distances from the outfall and in an unsteady tidal flow, are either numerical models or field dispersion tests. In the following it is assumed that a dispersion test is being employed, but the comments apply equally well to the results of an unsteady numerical model.

The schematics of a field dispersion test in a reversing tidal current system are shown in Figure 2-19. The tracer release line may represent the location of a submerged multiport diffuser with alternating nozzles. The tidal system is assumed as approximately periodic as indicated by the velocity curve. The figure also shows the hypothetical dye concentration trace C(x,y) measured at some point (x,y) as a function of time. (Note that in practice, fewer discrete measurements over time would be available). If the field dispersion test consists of a tracer release period, n tidal cycles long, then the continuous monitoring would usually indicate a period of concentration build-up, a quasi-steady period and a fall-off period. If an accurate simulation of the pollutant discharge over a large-scale and for a long-term is required, then consideration (and measurement) for at least two of these periods is necessary.

Considering the maximum dye concentration during any tidal cycle at (x,y), the following sequence is generally observable: During the first cycle $C_{max}$ is found, in the second cycle the concentration is $C_{max}$ plus some fraction of dye tracer returning from the previous cycle, thus $C_{max} + r_d C_{max} = C_{max}(1 + r_d)$. If these are continuously repeated, then the quasi-steady maximum concentration $\overline{C}_{max}$ is given by the geometric series

$$\overline{C}_{max} = C_{max}\left(1 + r_d + r_d^{2} + r_d^{3} + \ldots\right) \quad (20)$$

or, in the limit,

$$\overline{C}_{max} = C_{max}\frac{1}{1-r_d} \quad (21)$$

The quantity $r_d$ is labelled the dye return rate of mass discharged in the previous cycle ($r_d$ implicitly includes any dye mass decay during the tidal period). The complement quantity $(1 - r_d)$ is frequently referred to as flushing rate. The return rate will depend on the characteristics of the tidal flow, notably tidal excursion, mean velocity, diffusion, etc. $r_d$ is also dependent on the position (x,y) with respect to the release area. Quasi-steady conditions are typically encountered after about 5 to 10 tidal cycles. Build-up curves, similar to Equation 20 correspond also to other quantities of interest, such as the minimum or average concentrations during a tidal cycle, thus

$$\overline{C}_i(x,y,t) = C_i(x,y,t)\frac{1}{1-r_d} \quad (22)$$

where $C_i(x,y)$ is a single cycle concentration quantity of interest ($C_{max}$, $C_{min}$, $C_{ave}$, etc.).

For the actual pollutant discharge the quasi-steady condition is usually of primary importance. From Equation 22 it is seen that this depends on two factors: the mixing characteristics $C_i$ within a single tidal cycle, and the return rate from previous cycles. To translate the quasi-steady dye concentration conditions into pollutant concentration, therefore, two adjustments are needed:

(a) Within a tidal cycle, the pollutant concentration c is related to the dye concentration C

$$c_i(x,y,t) = C_i(x,y,t)\frac{Q_{co}}{Q_{do}}e^{-(k_c-k_d)t_i(x,y)} \quad (23)$$

where $t_i(x,y)$ = time interval between occurence of event i (maximum, minimum concentration) at (x,y) and time of release of that tracer patch, i.e., travel time. $Q_{co}$ is the pollutant mass release rate and $Q_{do}$ is the dye mass release rate. $k_c$ and $k_d$ represent the decay constants for pollutant and dye, respectively. (for a conservative dye, $k_d = 0$). Determination of $t_i$ depends on the detailed knowledge of the velocity field; for average concentrations the average tidal velocity is representative. It is noted that for points far from the release area - especially more than several tidal excursions away - the exponential correction term in Equation 23 becomes significant. In the discharge vicinity, however, it is frequently negligible, since $t_i$ is less than one tidal period. This is, in fact, the usual assumption in most mixing zone predictions.

(b) The return rate for pollutant $r_c$ is related to the dye return rate $r_d$

$$r_c = r_d e^{-(k_c-k_d)t^*} \quad (24)$$

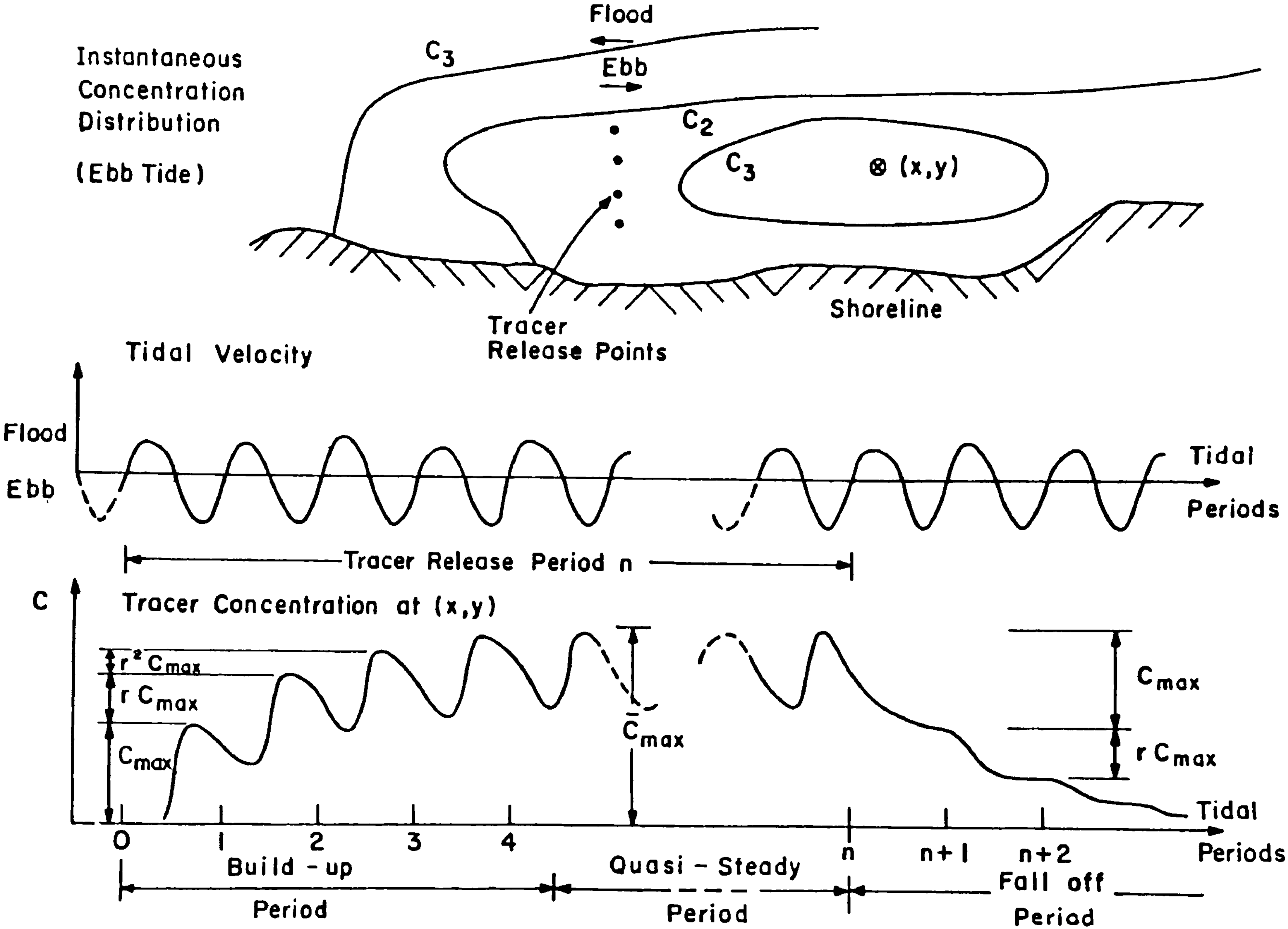


Figure 2-19. Schematics of a Field Tracer Dispersion Test in a Periodically Reversing Tidal System.

where $t^*$ = tidal period (12.4 hours). The quasi-steady pollutant concentration $c_i(x,y)$ is therefore related to the measured single cycle dye concentration $C_i(x,y)$

$$\bar{c}_i(x,y,t) = C_i(x,y,t)\frac{Q_{co}}{Q_{do}}[e^{-(k_c-k_d)t_i}]\frac{1-r_d}{1-r_c}$$

(25)

Hence, for an accurate prediction of far-field effects over a large area (larger than the tidal excursion length) it is necessary to (i) measure the velocity field in some detail so $t_i(x,y)$ can be found for the points under consideration, and (ii) measure not only the quasi-steady period of tracer distribution, but also the build-up or fall-off period so the dye return rate $r_d$ can be evaluated as shown in Figure 2-19. In actual tracer monitoring it is not always possible to have continuous records. Nevertheless, a few measurements during the build-up or fall-off period usually give some indication of $r_d$.

If attention is restricted to a smaller area around the discharge and if the tracer used is relatively conservative (small $k_d$), then both correction factors in Equation 25 are negligible and the measured concentrations can be used directly to evaluate the pollutant accumulation in the far-field.

### 2.6.2 *Linkage to Initial Mixing Predictions*

All initial mixing models discussed in the preceding are steady-state models <u>and</u> do not consider the far-field return (accumulation). The following procedure provides an approximate linkage:

(a) Carry out a series of initial mixing predictions using a steady-state near-field mixing model for different intervals (e.g. 6 or 12, corresponding to 2 or 1-hour intervals, respectively) within the tidal cycle. The predictions at any point of interest (e.g. at the boundary of a Legal Mixing Zone) provide approximate time-dependent predictions for pollutant concentration $c_i(x,y,t)$ within a tidal cycle.

(b) Use the far-field pollutant return rate $r_c$, that applies for the region of interest (e.g. the Legal Mixing Zone), to calculate the quasi-steady (i.e. long-term) pollutant concentration

$$\bar{c}_i(x,y,t) = c_i(x,y,t)\frac{1}{1-r_c} \qquad (26)$$

The return rate $r_c$ that applies to the area of interest can be estimated using the procedures outlined in the preceding paragraph, i.e. relying on a dye dispersion test or numerical model. It should be noted that $r_c$, in turn, is a function of the distance from the outfall: $r_c$ tends to be very small in the immediate near-field, where the pollutant concentrations are high; $r_c$ becomes larger for increasing distances, where the induced concentrations are falling off, however! This dependence suggests - in the absence of detailed measurements or predictions for $r_c$ the following practical guidelines:

- For Toxic Dilution Zone (TDZ) predictions, the effect of far-field return is always negligible ($r_c \approx 0$) due to the strong spatial restriction of the TDZ.
- For most Legal Mixing Zone predictions, the $r_c$ factor can be expected to vary in the range of $\leq 0.1$ to $\approx 0.5$ (highly conservative estimate). It is very small ($\leq 0.1$) for deep water discharges in the open coastal zone that are often associated with internal trapping or buoyant surface layer formation. In those cases, the initial (buoyant jet) mixing is, in fact, quite independent of far-field effects. It may be reasonably high (up to 0.5) for shallow water, vertically mixed, discharges in strongly restricted estuaries with weak flushing. For additional flushing estimates in such tidal channels, see the methods discussed in Fischer et al. (1979).

## 2.7 References

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# 3. Case Studies of Mixing Zone Prediction

## 3.1 Introduction

### 3.1.1 *Objectives*

This case study section has several objectives: (1) To demonstrate the typical procedures and data requirements involved in mixing zone analysis; (2) To demonstrate that legal mixing zone definitions may require the analysis of both near-field and far-field processes; and (3) To show the relative merits and flexibility of different methodologies, including jet integral models and the expert system CORMIX.

All four case studies deal with hypothetical conditions that may, however, exhibit some features of existing discharges. In the first case study major emphasis is put on various regulatory criteria. None of the case studies is intended to document model validation. This cannot be done since no actual field or laboratory data exist for these hypothetical situations. For validation of models reference should be made to the original literature on the various models as listed in Section 2. However, a few comments on model validity are made in the first case study in order to explain some large differences in various model predictions.

### 3.1.2 *Data Needs*

As discussed in Section 2.1, the initial mixing of an effluent depends on the interaction of ambient and discharge conditions. In estuaries or coastal waters these conditions may be highly variable. In evaluating water quality effects and mixing zone compliance, appropriate design conditions must be chosen. Generally, the critical design conditions relate to those environmental and discharge factors that lead to the lowest dilution and at times when the environment is most sensitive. However, it is not always straightforward for the analyst to estimate exactly what combination of factors will lead to this critical condition. For this reason, an evaluation under a variety of conditions always seems necessary to obtain information on mixing zone behavior and its sensitivity to design criteria. Data uncertainty is also a factor of concern. The following considerations, taken from Muellenhoff et al. (1985), apply here:

"Predicting dilution reliably depends on the availability of statistically valid data with which to estimate ambient conditions. The statistical uncertainty in estimates of absolute worst case conditions is generally great. Also there are inherent biases to some oceanographic measurements. For example, current measuring instruments have finite thresholds. It therefore becomes difficult to distinguish low values (which may be as high as 5.0 cm/sec) from zeroes in these data sets. In estimating environmental conditions, a more reliable estimation can be made at the lowest 10 percentile on a cumulative frequency distribution. Data on ambient density structure are not routinely collected. Consequently, there is not usually an existing data set for the site under consideration. To increase the reliability of "worst-case" estimates, data should be evaluated not only for the discharge site but for nearby coastal areas of similar environmental setting."

"Defining 'worst-case' conditions as a combination of those conditions affecting initial dilution, each taken at the worst 10 percentile on cumulative frequency distributions, is recommended by USEPA. This approach allows a reliable estimation of these conditions to be made and prevents the unlikely occurence of more extreme conditions from biasing the predictions. The probability of these conditions occurring simultaneously is much less than 10 percent, ensuring that the predicted dilution will be exceeded most of the time. Application of multiple 'worst case' factors (i.e. flows, stratification and currents) to determine a minimum dilution must be done carefully, however, and in recognition of the criteria for which compliance is being determined. For example, although application of an absolute "worst case" dilution may be appropriate for determining compliance with an acute toxicity limit, it is more appropriate to identify the lowest 6-month median dilution to determine compliance with a 6-month median receiving water limitation."

Since the discharge conditions can also vary (e.g. its flowrate or pollutant concentration) it is necessary to combine the occurences of the varying pollutant loading with the varying ambient parameters in order to find the critical design conditions.

Finally, any set of ambient and discharge conditions will require some degree of schematization in order to meet the predictive model assumptions. This has been discussed in Section 2.3.2 along with Figs. 2-6, 2-7 and 2-8. The literature or user's manuals for the various models usually contain some guidance on how to prepare the data. The expert system CORMIX, in fact, has on-screen advice on data preparation available to the user.

All available mixing zone models assume a conservative pollutant discharge neglecting any physical, chemical or biological decay or transformation processes. For most, substances this is reasonable due to the rapidity of the mixing process, especially in the near-field, relative to the reaction time scale of most

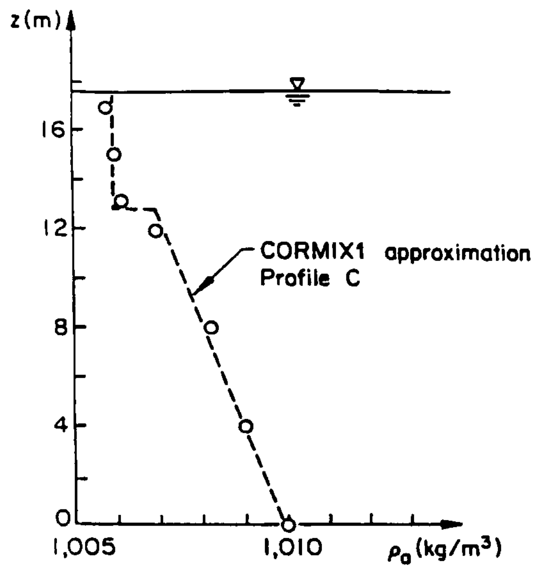



**Figure 3-1. Design Case AA: Vertical Ambient Density Profile in Typical Summer Conditions.**

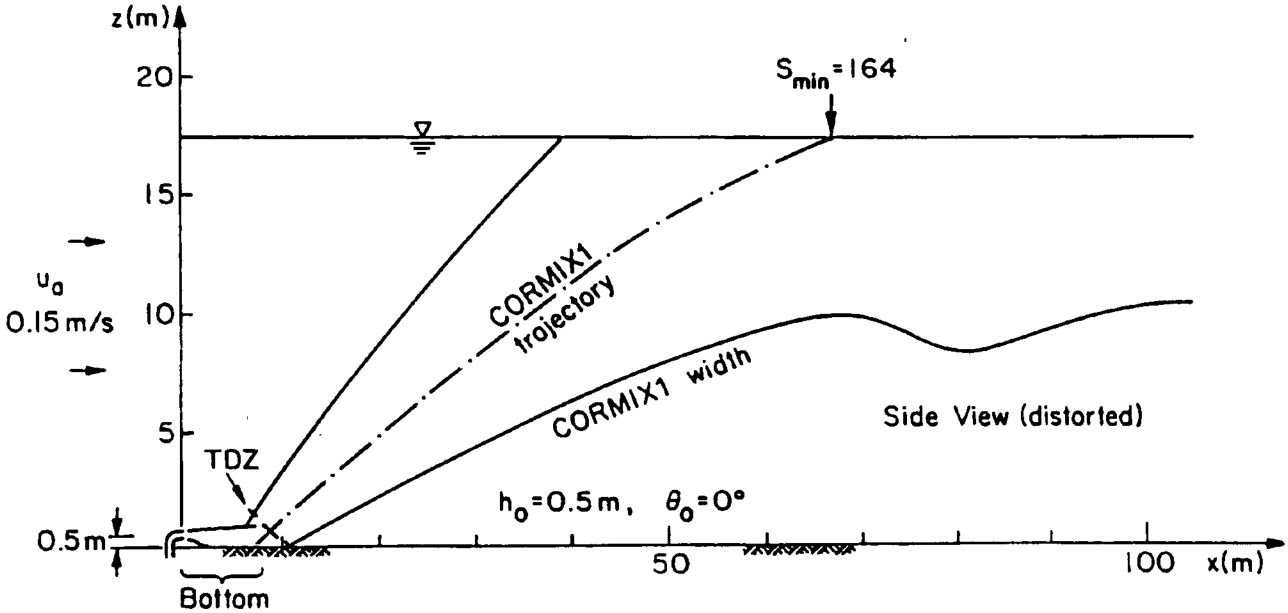
pollutants. If first order reaction processes can be assumed then the model results on concentration can usually be converted with an exponential factor to include the decay process (see Doneker and Jirka, 1990). The consideration of pollutant reactions in the context of far-field accumulation involving a larger time scale has also been addressed in paragraph 2.6.1.

## 3.2 Case AA - Single Port Discharge: Industrial Outfall in Tidal Fjord.

### 3.2.1 *Ambient and Discharge Conditions*

A manufacturing plant is located near the upstream end of a narrow tidal fjord that receives a substantial amount of fresh water inflow. The typical cross-section of the fjord is 600 m wide with an average depth of 16 m. The preferred discharge location is about 90 m from shore where the local water depth is 17.5 m. During typical winter conditions the characteristic ambient (average tidal) velocity is 0.15 m/s and the vertical ambient density distribution is quite uniform with a value of 1,005.5 kg/m$^3$. During summer design conditions, however, the ambient velocity is lower at 0.10 m/s and a significant vertical stratification exists as shown in Figure 3.1. The density varies from a bottom value of 1,010.0 kg/m$^3$ down to a surface value of 1,005.8 kg/m$^3$. The plant operation is also variable. In winter the discharge flow rate is 0.15 m$^3$/s and has a discharge temperature of 10°C. In summer the flow rate is lower at 0.10m$^3$/s with a temperature of 15°C. The discharge flow is essentially freshwater but contains 1000 ppb of some organic toxic material.

Applicable state regulations limit the mixing zone to 25% of the width of the estuary. Furthermore, the special mixing zone requirements for toxic substances (see Section 1.2.2) apply with a CMC value of 100 ppb for the discharged toxicant.




Case AA1: Initial Design, Unstratified Winter Conditions

**Figure 3-2. Case AA1: Single Port Discharge (initial design) Exhibiting Bottom Attachment as Predicted by CORMIX1.**

### 3.2.2 *Case AA1: Initial Design, Winter Conditions*

An inital design proposal calls for a single port discharge with 0.2m port diameter and 0.5 m port height above the bottom. The discharge velocity is 4.8 m/s. The port is oriented in a co-flowing arrangement pointing horizontally along the direction of the ambient current.

Figure 3-2 shows a side view of the near-field of the discharge plume predicted by CORMIX1 (flow class A5). The model shows strong dynamic attachment of the plume to the bottom. After this a gradual buoyant rise to the surface takes place with a minimum surface dilution $S_{min}$ = 164. The extent of the toxic dilution zone (TDZ) is about 10 m, essentially comprising the entire bottom attached zone. Thus, benthic organisms will be exposed to toxicant concentrations above CMC values. This initial design is considered undesirable and rejected from further consideration.

In view of this bottom attachment, none of the jet integral models, included in Section 2.4, i.e. the USEPA models, UOUTPLM and UDKHDEN or the Jirka-Fong model, would be applicable. Therefore, their predictions are not shown on Figure 3-2.

### 3.2.3 *Case AA2: Modified Design, Winter Conditions*

In order to eliminate plume bottom interference, a modified design is proposed with an increased port height of 1.0 m and a vertical discharge angle of 10°. This modified design, indeed, does not exhibit any bottom attachment as shown in Figure 3-3.

The trajectory predictions of three buoyant jet integral models (UOUTPLM, UDKHDEN and JF [Jirka-Fong]) and of CORMIX1 (flow class H2) are given in Figure 3-3. Also shown is the width prediction for CORMIX1. All four submerged plume trajectories are qualitatively similar; the deviations among trajectories is contained within the plume outline (as indicated by CORMIX1) and well within the usual scatter of experimental data. The TDZ is again limited (order of 10m) as predicted by any of the four models. The jet integral models are, of course, limited in their applicability to the submerged jet region before surface interaction. Only CORMIX1 is applicable to the actual interaction process and the subsequent buoyant spreading along the water surface. This process is indicated by the width boundary in Figure 3-3.

Considerable differences exist in the predicted surface dilution at the point of surface interaction. UOUTPLM and UDKHDEN predict a flux-averaged dilution of 212 and 495, respectively. On the other hand, JF and CORMIX1 predict minimum (centerline) dilutions of 220 and 146, respectively. Even if the UDKHDEN model predictions are divided by a factor of 1.7, in order to account for the typical ratio of flux-averaged and minimum dilutions a considerable difference remains relative to the lower dilution value of CORMIX1.

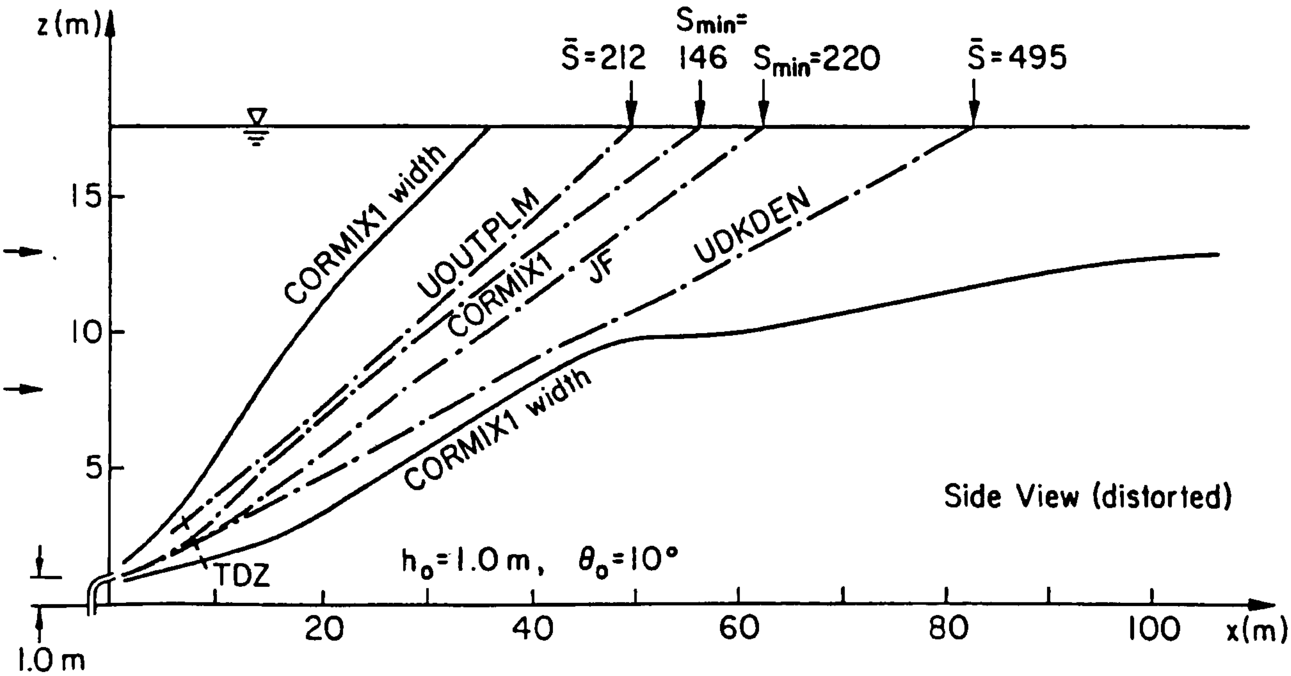



**Figure 3-3. Case AA2: Single Port Discharge (modified design) in Unstratified Winter Conditions; Comparison of Jet Integral Models and CORMIX1.**

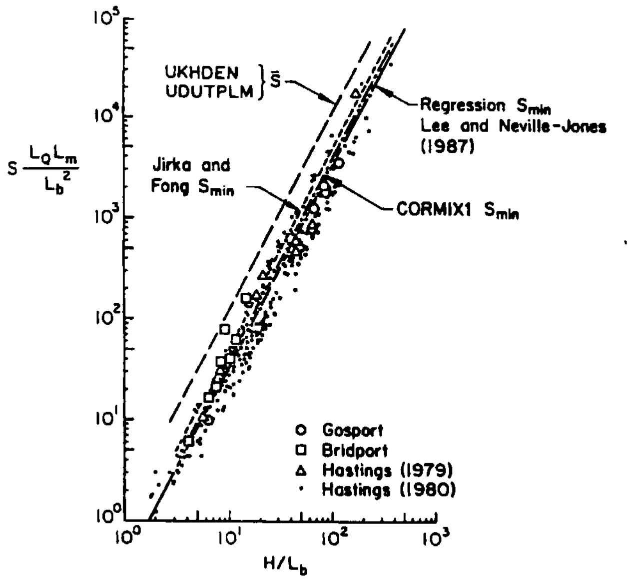



**Figure. 3.4. Comparison of Observed Minimum Surface Dilution for Three Submerged Single Port Outfalls (Lee and Neville-Jones, 1987) with Predictions of Jet Integral Models and CORMIX1.**

To shed further light on this disagreement the predictions of the four models can be compared to what is probably the most reliable and comprehensive available field data set on submerged discharges. Lee and Neville-Jones (1987) report several hundred individual observations of minimum surface dilution for three single port submerged outfalls for municipal discharges in the United Kingdom. All of these outfalls are somewhat more dominated by buoyancy than design case AA2. (This is indicated, for example, by the fact that CORMIX1 predicts a flow class H1 for these outfalls). The predictions of all four models are compared with the normalized field observations for minimum surface dilution (Figure 3-4). The solid line presents the best-fit regression line for all data points. The average dilution given by both USEPA models is a factor of 4 (300%) larger than the observed minimum dilution. When the dilution predictions are converted to minimum dilutions (factor 1.7) the overprediction is still by about 130%. The JF model overprediction is about 50%. CORMIX1, on the other hand, lies within about 15% with the observations. (Note that the model coefficients of CORMIX1 have been chosen through extensive comparison with basic laboratory data, so that this good agreement presents indeed a model validation and not some forced best-fit!). On the basis of this comparison it may be concluded that the jet integral

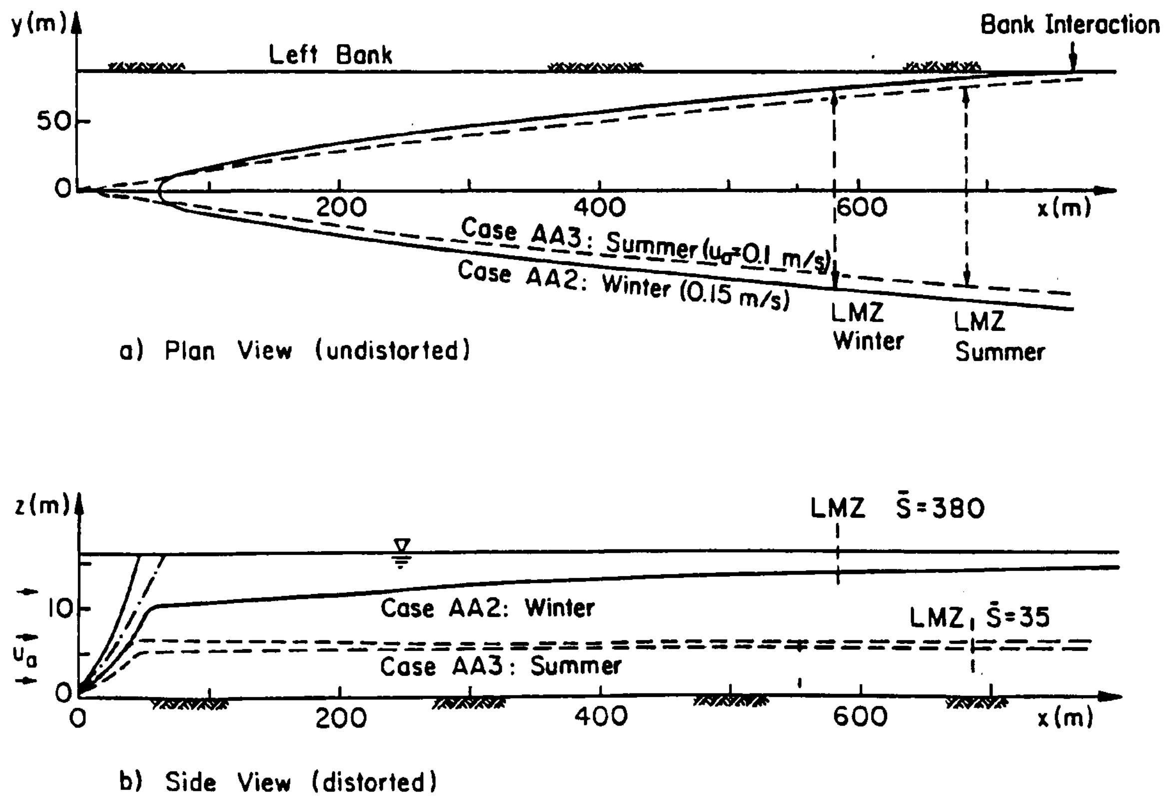



**Figure 3-5. Cases AA2 and AA3: Predicted (CORMI1) Far-Field Behaviour for Single Port Discharge (modified design) in Winter and Summer Conditions.**

models (notably UOUTPLM and UDKHDEN) are quite non-conservative and tend to overestimate actual plume dilutions, at least for unstratified ambients. The prediction disagreement for Case AA2 (Figure 3-3) may be considered in light of this conclusion.

The legal mixing zone LMZ (25% width) is not attained in the hydrodynamic near-field but rather in the far-field as shown by the CORMIX1 predictions of Figure 3-5. In fact, the LMZ is reached at a downstream distance of about 600 m when the surface plume is in the buoyant spreading regime. At this point, the average dilution has increased to about 250 and the plume half-width is about 75 m with a plume thickness of 1.7 m. Actual plume interaction with the bank takes place at a further downstream distance of about 760 m. This result illustrates the practical fact that legal mixing zone definitions can often imply sufficiently large distances which then include far-field mixing processes. Simple jet integral models do not address this aspect, while CORMIX1 has been implemented to deal with such generalities.

### *3.2.4 Case AA3: Modified Design, Summer Conditions*

The drastic effect of ambient stratification on plume near-field behavior is shown in Figure 3-6. With any of the four predictive models the plume is predicted to reach its terminal level of about 3 to 5 m above the bottom at a distance of about 10 m downstream. The differences among the predicted trajectories are small. The TDZ is reached about 8 m downstream as indicated by CORMIX1 (flow class S3). The predicted dilution values at the terminal level show, again, more variability. If minimum terminal dilutions are compared, then UOUTPLM, $S_t$ = 16/1.7 = 9, CORMIX1, $S_t$ = 16, and UDKHDEN, $S_t$ = 26/1.7 = 15, provide lower-end (conservative) predictions, while JF, $S_t$ = 26, is somewhat higher.

The CORMIX1 predictions in Figure 3-6 also show the formation of the internal stratified layer (initial thickness 2.4 m) and its gradual collapse and widening with additional mixing. The full development in the far-field is illustrated again in Figure 3-5. The behavior under stratified summer conditions is in marked contrast with the unstratified winter conditions (Case AA2). The difference in dilution is notable (related to the much shorter buoyant jet trajectory in the near-field) as is the much thinner internal layer. The LMZ is reached at about 680 m where the plume half-width is about 75 m and the plume thickness about 0.3 m.

## 3.3 Case BB - Multiport Diffuser: Municipal Sewage Discharge into Coastal Bay

### *3.3.1 Ambient and Discharge Conditions*

A multiport diffuser is used for the discharge of treated sewage water from a municipality located on a bay. The proposed diffuser location is 10 km offshore with an ambient water depth of 30 m. In a preliminary evaluation two ambient design cases are to be investigated; 1) A weakly stratified ambient with a density variation from 1,023.2 kg/m$^3$ at the surface to 1,026.4 kg/m$^3$ at

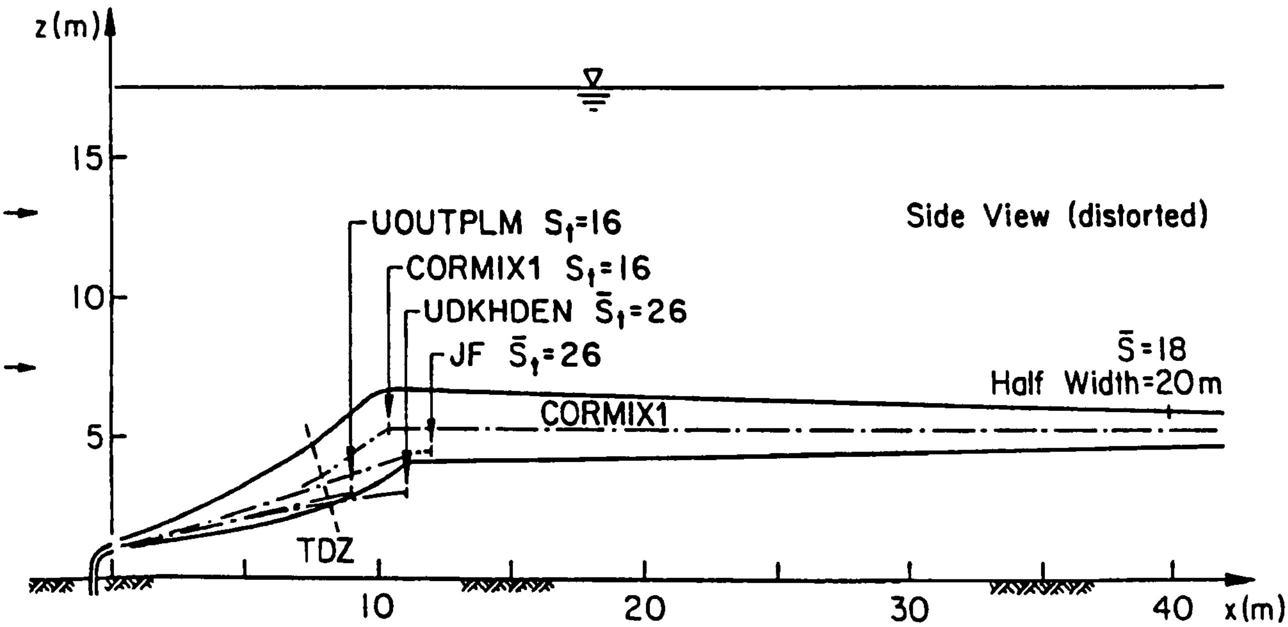



**Figure 3-6. Case AA3 : Single Port Discharge (modified design) in Stratified Summer Conditions; Comparison of Jet Integral Models and CORMIX1.**

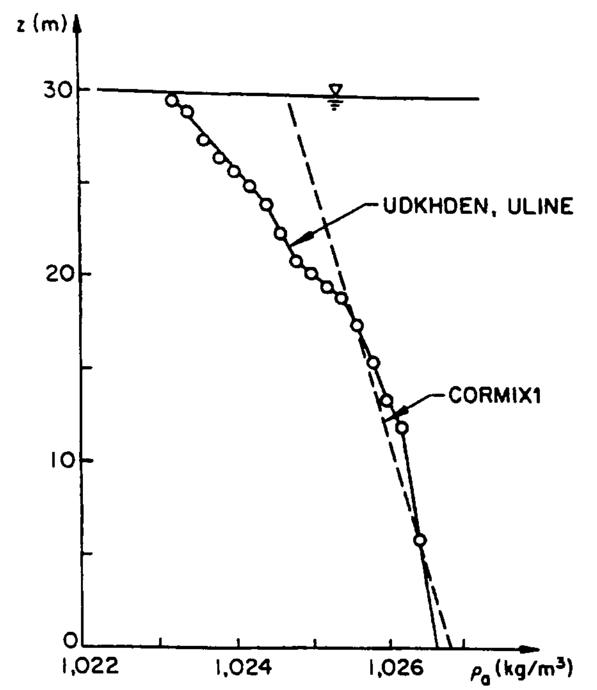



**Figure 3-7. Design Case BB: Vertical Ambient Density Profile for Design Conditions.**

the bottom. Figure 3-7 shows the actual density variation, together with the schematizations adopted for different models. 2) A uniform ambient with a density of 1,026.0 kg/$m^3$. In both cases the ambient design velocity is 0.156 m/s for the prevailing coastal current. The discharge flow rate is 20 $m^3$/s (460 MGD) with a freshwater density of 998.0 kg/$m^3$.

The preliminary design calls for a total diffuser length of 2000 m with a perpendicular alignment relative to the prevailing current direction. The diffuser employs 80 vertical risers with 8 ports attached per riser and discharging in a circular fashion. The port diameter is 0.14 m, the port height is 1.5 m above bottom and the port angle is 0° (i.e. horizontal).

The legal mixing zone (LMZ) is prescribed by a distance of 30 m extending in any direction from the diffuser line. No toxic substances are included in this discharge.

### *3.3.2 Case BB1: Stratified Ambient*

When applying any model to a complex diffuser geometry with riser/port assemblies, some model simplification is needed. In case of the USEPA multiport models (UDKHDEN,UMERGE and ULINE) the user must, in fact, substitute a series of single ports equally spaced along the diffuser line (thus, in this present case 80 x 8 = 640 ports). On the other hand, the input element of CORMIX2 collects all the pertinent information about the riser/port assemblies, the system then concludes that the net horizontal momentum flux for this diffuser is zero and treats the diffuser as an alternating diffuser with a vertical equivalent slot discharge. Thus, in either case, the local details of the eight individual buoyant jets discharging from each assembly are neglected.

Figure 3-8 summarizes the predictions of the jet models UDKHDEN and ULINE and of the expert system CORMIX2 (flow class MS5). All three models indicate a terminal layer $z_t$ at about 10 m above the bottom varying between 8 m and 12 m. Also all three models show limited variability for the predicted average dilution at the terminal level, $\bar{S}_t$, which is 137 for ULINE, 212 for UKHDEN, and 166 x 1.4 = 232 for CORMIX2, using an average/minimum dilution factor of 1.4 for two-dimensional buoyant jets. All these dilution values may

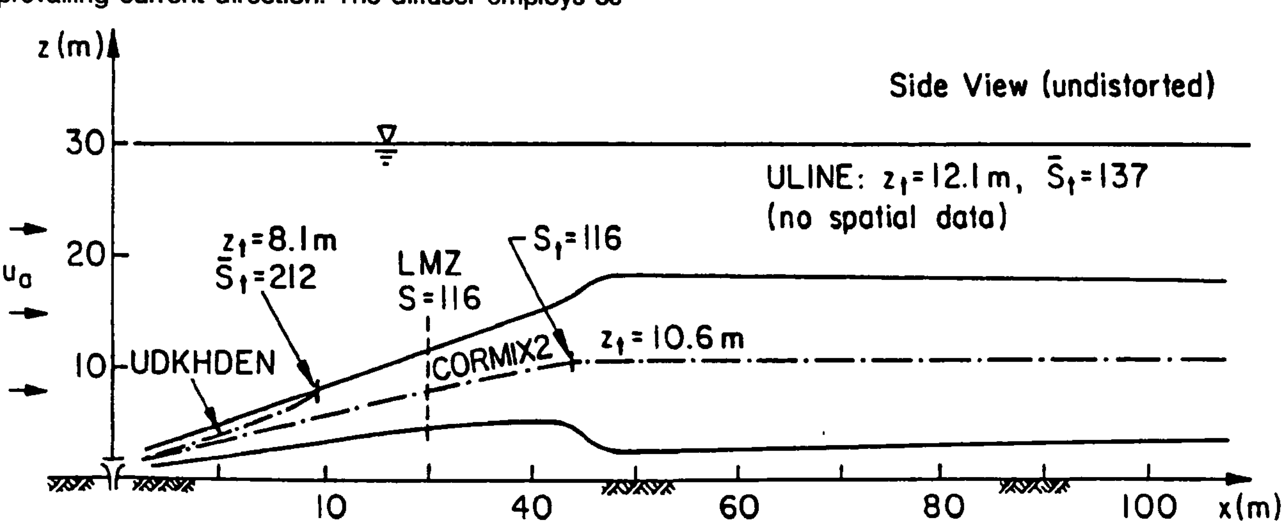



**Figure 3-8. Case BB1: Multiport Diffuser Discharge under Stratified Conditions; Comparison of Jet Integral Models and CORMIX2.**

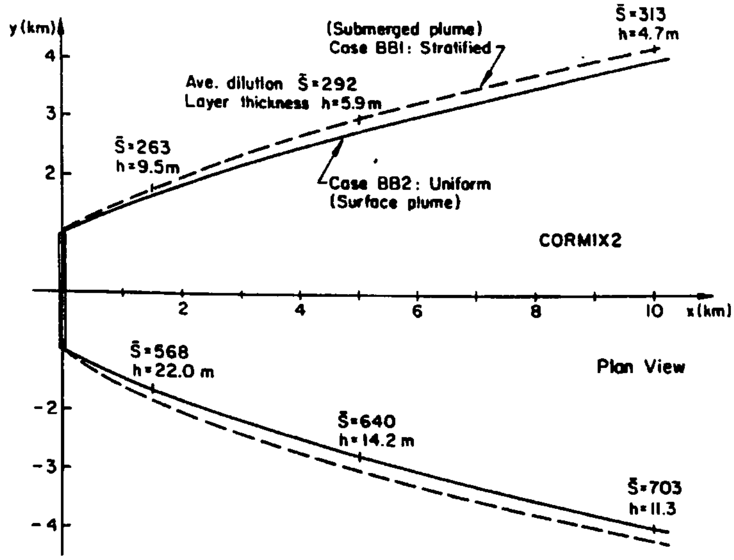



**Figure 3-9. Case BB1 and BB2: Predicted (CORMIX2) Far-Field Behavior for Multiport Diffuser Plume in Stratified and Uniform Conditions.**

be scrutinized as to whether the mixed effluent flow per unit diffuser length, $\bar{S}_t\ Q_o/L_D$, exceeds the available ambient approach flow, $u_a z_t$, for the layer between bottom and terminal level. Denoting the ratio $R = (\bar{S}_t Q_o/L_D)/(u_a z_t)$ one finds $R = 0.7$ for ULINE, $R = 1.7$ for UDKHDEN, and $R = 1.4$ for CORMIX2. In a strictly two-dimensional flow (i.e. if a diffuser section or the entire diffuser length were bounded by lateral walls) any value $R > 1$ is not possible in steady-state. However, for the actual three-dimensional diffuser the diffuser entrainment demand can also be met by lateral flow toward the diffuser line. Futhermore, additional freedom to entrain water exists for the internally trapped plume ($z_t <$ H where H is the water depth). Also, note that for low ambient velocity conditions ($u_a \rightarrow 0$) the above test becomes unreliable for evaluating model performance. Thus, for the present case of an internally trapped plume from a three-dimensional diffuser all three model predictions appear reasonable

Note that trajectory information is provided by UDKHDEN and CORMIX2 while ULINE does not provide any spatial data on plume behavior. The LMZ is predicted by CORMIX2 to have a minimum dilution of 116.

At the transition to the far-field CORMIX2 indicates an initial internal layer thickness of about 16 m. As shown in the far-field plan view of Figure 3-9 this internal layer is gradually spreading, decreasing in thickness, and experiencing a slight additional mixing in the buoyant spreading phase. Thus, at 10 km downstream from the diffuser line the average dilution is 313, with a half-width of the effluent field of 4.2 km and a thickness of 4.7 m.

### *3.3.3 Case BB2: Uniform Ambient*

The corresponding model predictions for the unstratified case are given in Figure 3-10. CORMIX2 indicates a flow class MU8 which includes a vertically fully mixed near-field with an average dilution, $\bar{S}$ = 512. Although its model printout does not specifically state so, ULINE also predicts a vertically mixed flow with a lower dilution $\bar{S}$ = 368. In contrast, UDKHDEN does not recognize the destabilizing effect of the vertically limited environment in crossflow and predicts a plume with a high surface dilution $\bar{S}$ = 835 and with width dimensions that are of the order of the water depth (Figure 3-10)! Defining the ratios $R = (S\ Q_o/L_d)/(u_a H)$ one finds $R = 0.8$ for ULINE, $R = 1.0$ for CORMIX2 and $R = 1.8$ for UDKHDEN. The latter result, together with the fact that the model - while predicting plume dimensions of the order of the water depth - does not address the constraint of the limited ambient depth, indicates that UDKHDEN is not applicable in this case. More generally, it appears that UDKHDEN is an unreliable model for most multiport diffuser applications in unstratified ambients. The same reservation would hold for the model UMERGE (not plotted here). ULINE indicates slightly more conservative dilution values than CORMIX2. It may be overly conservative, however, since the ULINE model coefficients are based on a single set of experiments by Roberts (1977) which did not include the additional mixing effect of the high velocity discharge jets as is common in actual diffuser installations (this has been pointed out in a discussion by Jirka, 1979).

The far-field behavior of the diffuser plume is plotted in Figure 3-9. While the plume is fully mixed in the near-

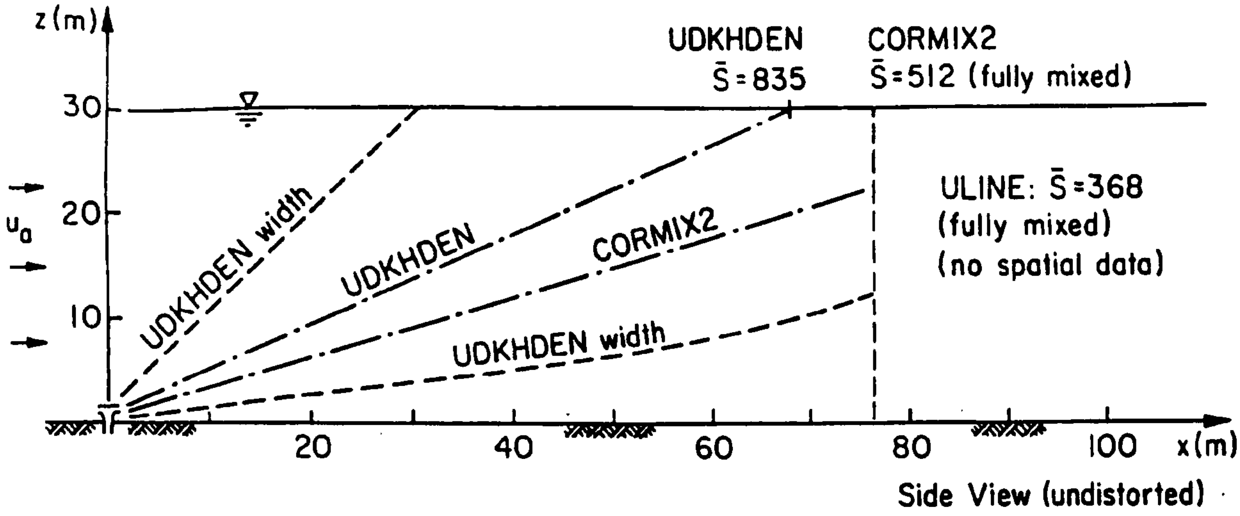



**Figure 3-10. Case BB2: Multiport Diffuser Discharge in Uniform Ambient; Comparison of Jet Integral Models and CORMIX2.**

field (about 100 m downstream; see Figure 3-10) it restratifies and lifts off from the bottom. At a distance of 1.5 km downstream the vertical thickness has reduced to 22.0 m (compared to the initial thickness of 30.0 m equal to the water depth). At 10 km downstream the plume has thinned to about 11.3 m while spreading to a half-width of 4.0 km and attaining an average dilution of 703.

## 3.4 Case CC - Single Port Discharge: Brine Discharge From an Oil Field

### *3.4.1 Ambient and Discharge Conditions*

Brine from drilling operations in a coastal oil field is to be discharged into coastal waters. The proposed discharge site is 250 m offshore at a local water depth of 20 m. The ocean water is weakly stratified with a pycnocline at 15 m above the bottom. However, because of the strongly negatively buoyant brine discharge the density distribution above the pycnocline appears unimportant and the ambient can, in fact, be assumed at a constant density of 1,025.0 kg/m$^3$ corresponding to the lower layer density. Ambient design velocities range from 0.1 m/s to 0.25 m/s. The bottom is sandy with a Darcy-Weisbach friction factor of 0.015.

The brine flow rate is 0.03 m$^3$/s with a density of 1,070.0 kg/m$^3$, thus much heavier than the ocean water. The effluent contains several toxic metals, including copper at a concentration of 380 ppb. The extent of the LMZ corresponds to the water depth of 20 m. The TDZ is governed by a CMC concentration for copper of 40 ppb.

The initial design proposes a low velocity discharge (3.8 m/s) with a port of 0.1 m diameter at a 2.0 m height above the bottom, angled at 60$^o$ above horizontal and pointing laterally across the cross-flow (cross-flowing discharge).

### *3.4.2 Case CC1: Low Discharge Velocity Design, Weak Current*

Even though, in principle, they ought to be applicable for negatively buoyant discharges the USEPA models (UOUTPLM and UDKHDEN) do not provide any predictions for this cross-flowing upwardly angled discharge with a complex three-dimensional trajectory. Predictions are limited to CORMIX1 and the Jirka-Fong (JF) integral model. The near-field plume configuration for the two model predictions is shown in Figure 3-11a with (i) longitudinal and (ii) transverse side views, respectively. CORMIX1 predicts a flow class NV2 with buoyant upstream intrusion along the bottom after impingement of the falling jet. The two buoyant jet trajectories (JF and CORMIX2) are in reasonably good agreement prior to impingement. The predicted minimum dilution is lower for CORMIX1 ($S_{min}$ = 22) than for JF (56). The extent of the upstream intrusion is of the order of 20 m from the impingement point. A thin bottom layer of about 0.5 m thickness is formed and spreads laterally as the bottom plume is advected downstream. The TDZ is very short, of the order of 1 m from the efflux point. The conditions at the LMZ (not shown in Figure 3-11a) indicate a thin layer of 0.35 m thickness, 18.0 m half-width with an average dilution of 40.

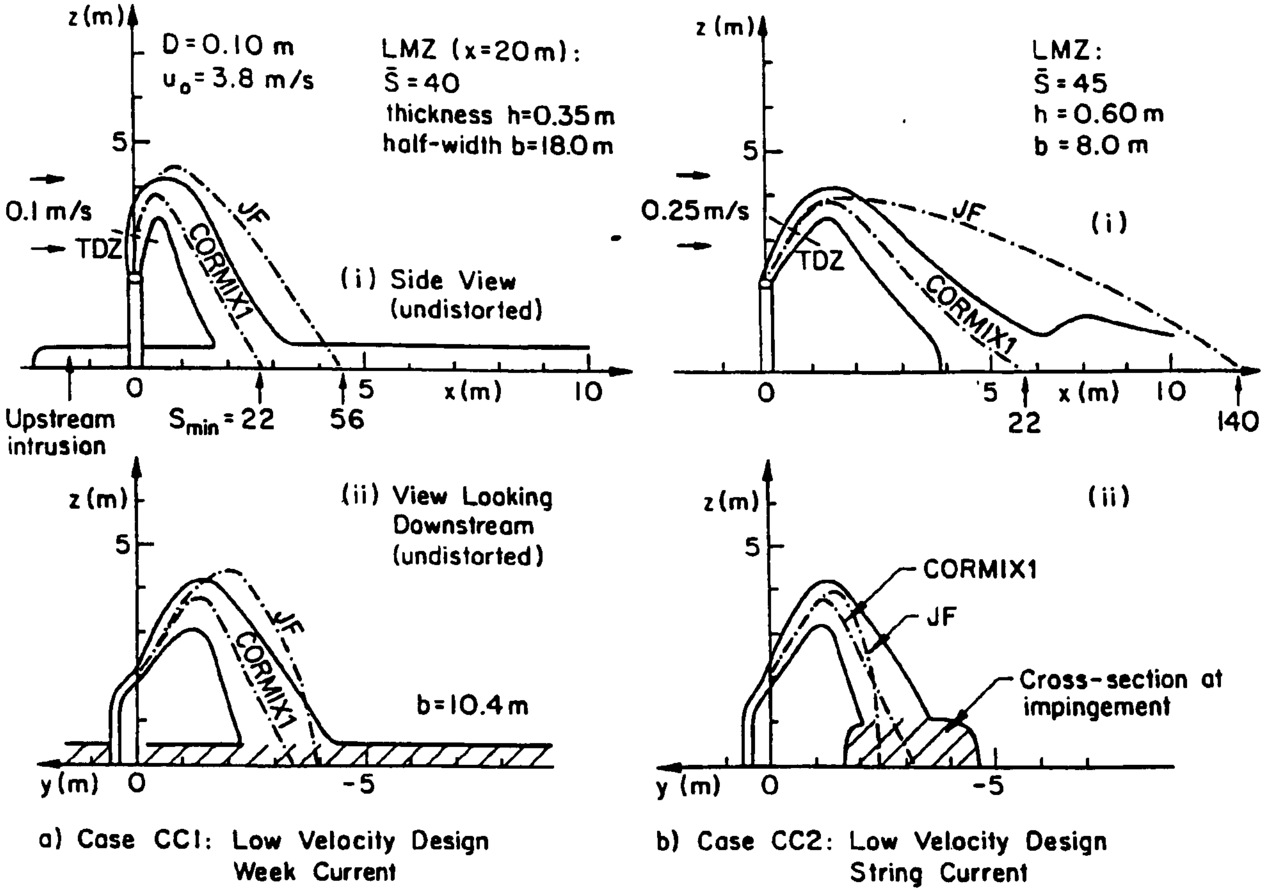



**Figure 3-11. Cases CC1 and CC2: Negatively Buoyant Discharge from Single Port; Low Exit Velocity Design under a) Weak and b) Stronger Ambient Current.**

### *3.4.3 Case CC2: Low Discharge Velocity Design, Strong Current*

When the ambient current increases from 0.1 m/s to 0.25 m/s the downstream buoyant jet deflection is accentuated while the upstream buoyant extension is minimized. Figure 3-11b shows CORMIX1 (flow class NV2) and JF predictions. The discrepancy between predicted minimum dilutions is further increased ($S_{min}$ = 22 versus 140). Such complex three-dimensional trajectories represent some of the most severe tests for model application, and in the absence of detailed experimental data for such phenomena it is difficult to favor one model over another.

The upstream intrusion along the bottom is minimal in the present case (order of 2 m) and the bottom density current is thicker and less wide. At the LMZ distance the plume half-width is only 8.0 m with a thickness of 0.60 m and an average dilution of 45.

### *3.4.4. Case CC3: High Discharge Velocity Design, Strong Current*

In order to maximize near-field dilution a high exit velocity design (15.2 m/s) is evaluated by halving the port diameter to 0.05 m. The results are shown in Figure 3-12. When compared to Figure 3-11b, this shows the significant effect of increased jet diffusion in the near-field. The buoyant jet shows much more rapid mixing, and, consequently, is more liable to advection by the ambient current. CORMIX1 (flow class NV1) no longer predicts an upstream intrusion after the more gradual bottom approach. There are differences in the predicted jet trajectories, as far as maximum height of rise and bottom approach are concerned. At the LMZ these buoyant jets are predicted to be in the water column without any bottom contact yet. The minimum dilution values are $S_{min}$ = 247 for JF and 119 for CORMIX1, respectively. The comparison between Figure 3-11b and 3-12 illustrates how LMZ constraints sometimes are met in the hydrodynamic near-field and at other times in the far-field, depending on the interplay of ambient and discharge conditions.

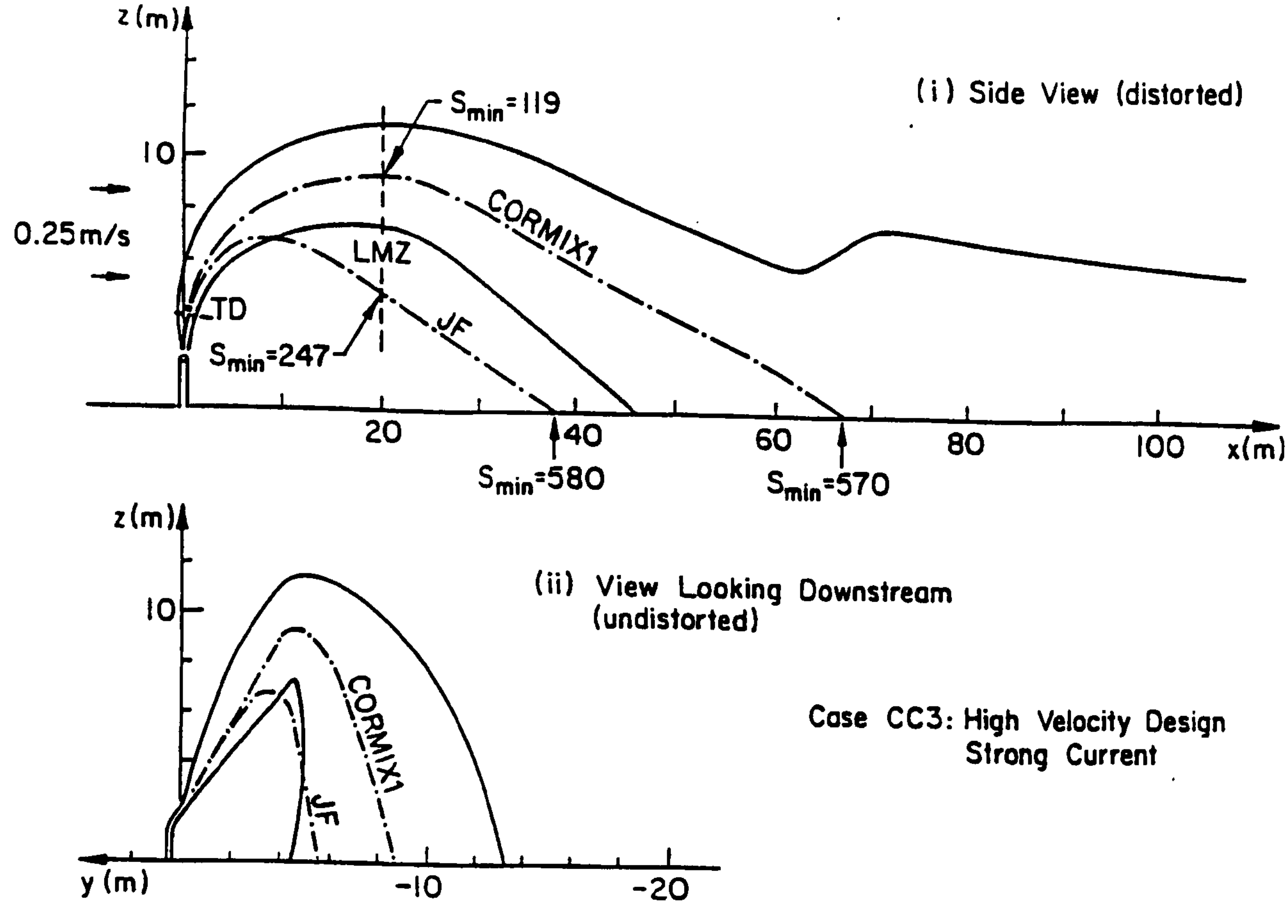



Figure 3-12. Case CC3: Negatively Buoyant Discharges from Single Port; High Exit Velocity Design with Strong Ambient Current.

## 3.5 Case DD Multiport Diffusers: Cooling Water Discharge into Shallow Sound

### *3.5.1 Ambient and Discharge Conditions*

A once-through cooling water system for a thermal-electric power plant discharges the heated cooling water through a submerged multiport diffuser. At a distance of 500 m offshore, a shallow relatively flat area exists with an ambient water depth of 10.3 m.

The water is unstratified with an average temperature of 20$^{o}$C and ocean salinity. The velocity field is tidal ranging from slack tide (0.0 m/s) to weak velocities (about 0.1 m/s) to a maximum velocity (0.5 m/s). The cooling water flow rate is 67 m$^3$/s with a discharge temperature rise of 20.5$^{o}$C above ambient and the same salinity.

A staged diffuser design of 260 m length is proposed with a perpendicular alignment relative to the tidal currents. The diffuser consists of 32 ports with a port height of 0.5 m, port diameter of 0.6 m and a vertical angle of 20$^{o}$ above horizontal.

No LMZ is specified. Rather, the predictive results are to be interpreted so as to make an LMZ proposal to the state regulatory authority.

### *3.5.2 Case DD1: Weak Tidal Current*

None of the USEPA diffuser models are applicable for such shallow water diffusers with strong momentum flux and unstable near-field mixing. If they were used, UOUTPLM and UDKHDEN would predict vertical plume width far in excess of the available water depth. ULINE, on the other hand, is limited to pure plume discharges without any directed discharge momentum flux.

Thus, reliable predictions are limited to CORMIX2 as shown in the plan view of Figure 3-13. For this case of a weak current, CORMIX2 (flow class MU5) indicates an initially, vertically fully mixed diffuser plume. The plume gets gradually deflected by the weak crossflow

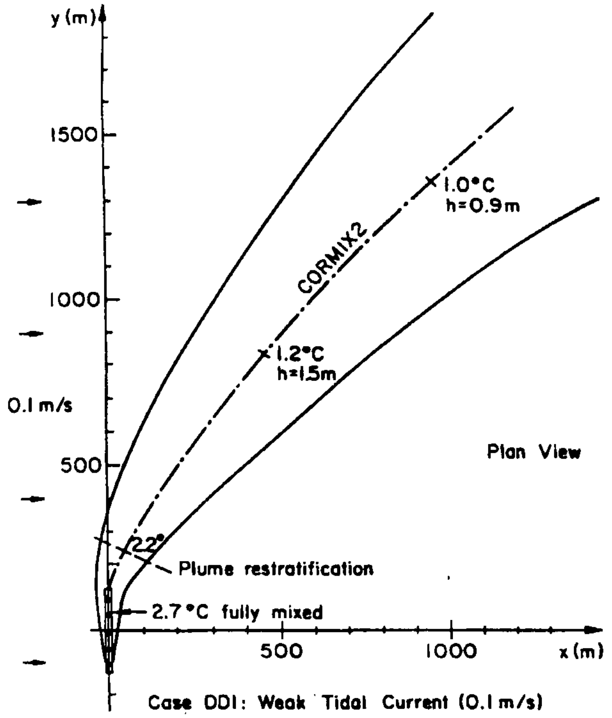



**Figure 3-13. Case DD1: Staged Multiport Diffuser for Cooling Water Discharge; CORMIX2 Predictions for Weak Tidal Current.**

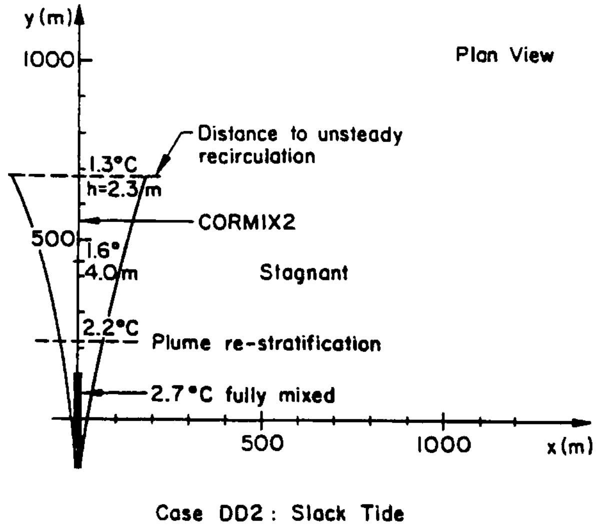



**Figure 3-14. Case DD2: Staged Multiport Diffuser for Cooling Water Discharge; CORMIX2 Predictions for Slack Tidal Conditions.**

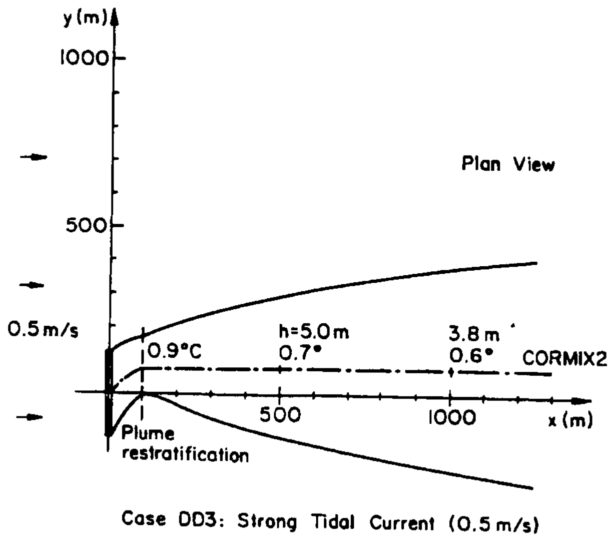



**Figure 3-15. Case DD3: Staged Multiport Diffuser for Cooling Water Discharge; CORMIX2 Predictions for Strong Tidal Current.**

and begins to re-stratify (lift off the bottom) after a distance. Gradual, lateral spreading and vertical thinning of the diffuser plume takes place. The induced temperature rise is 2.7°C in the near-field and drops to 1.0°C at a distance of about 1500 m. (Any potential heat loss to the atmosphere is neglected in these conservative mixing predictions).

Figure 3-13 illustrates vividly the strong effect of the directed momentum flux from shallow multiport diffusers and the ability to induce currents over considerable distances.

### *3.5.3 Case DD2: Slack Tide*

Stagnant ambient conditions always represent a limiting case for any mixing analysis. Since there is no ambient advective mechanism they are always associated with an unsteady flow field and mixing process, including potential large scale recirculation effects.

The CORMIX2 (flow class MU5) predictions are given in Figure 3-14 for unsteady conditions. The plume is now undeflected, but has similar mixing characteristics as the slightly deflected plume of Case DD1. However, at some distance (about 680 m) the predictions are terminated since the induced plume velocities have become negligibly small so that a transient recirculating flow would be set up. Corresponding messages are printed out by the expert system along with the advice to conduct predictions for stagnant ambients only as a special limiting condition.

### *3.5.4 Case DD3: Strong Tidal Current*

The effect of a strong tidal current (0.5 m/s) is to generate a strongly deflected diffuser plume (Figure 3-15) as predicted by CORMIX2 (flow class MU6). A rapid deflection and greatly increased mixing take place within the diffuser vicinity. The re-stratifying plume is then advected by the ambient current and grows in width and diminishes in vertical thickness, in form of a surface buoyant spreading process.

In summary, the great variability among diffuser plume patterns (Figure 3-13, 3-14, and 3-15) suggests that a complete assessment of initial mixing processes should, indeed, include the whole spectrum of ambient conditions. It is often difficult to define a single "typical" design condition for mixing analysis. On the other hand, a rapid evaluation of several ambient conditions and of alternative designs is readily possible within the framework of presently available models.

## 3.6 References

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