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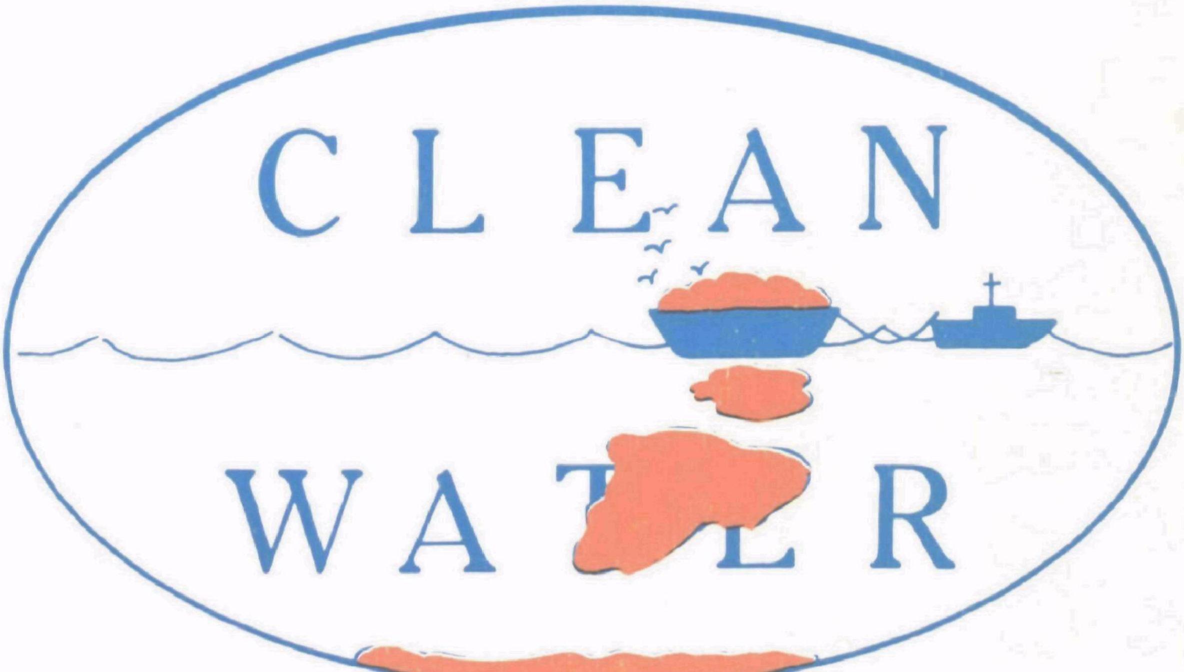
THE BARGED OCEAN DISPOSAL OF WASTES



A Review of Current Practice and Methods of Evaluation

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THE BARGED OCEAN DISPOSAL OF WASTES

A REVIEW OF CURRENT PRACTICE AND METHODS OF EVALUATION

by

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ABSTRACT

This report consists of a broad scope examination of barged ocean disposal of liquid and solid wastes. Basic discussions include: the physical characteristics of various selected wastes, economics as a function of haul distance, reported effects of past discharge operations and the relative importance of environmental factors such as density and current profiles. The major emphasis of the report centers on physical fate prediction methods and describes the physical transport in four separate steps: convective descent, collapse, long term dispersion and bottom transport or resuspension.

An existing mathematical model developed by Koh and Fan is used and demonstrates the complex nature of some of the more obvious parameters, the potential usefulness of the approach to coastline management efforts while serving as a vehicle for the discussion of current state of the art limitations and research needs.

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SECTION I

SUMMARY

The ocean dumping policy recommended by the President's Council on Environmental Quality provides that only under conclusive proof of no damage to the marine environment should dumping be authorized, and even then regulatory control should be exercised based on standards that consider:

1. The present and future impact on the marine environment, human health, and amenities.

2. Irreversibility of the impact from dumping.

3. Volume and concentration of the material involved.

4. Location of the disposal site.

The accomplishment of such a policy clearly shows the need for an areal model with statistical capabilities. Most ocean dumping operations require discharge within specified areas defined by longitude and latitude and consist of a number of dumps rather than a single site. Some important questions regarding the fate of dumped material are:

1. What is the ultimate or equilibrium buildup within the water column or on the bottom?

2. What percent will be retained in the dump area?

3. What is the distribution of the waste within the dump area?

4. Where will the portion not retained go?

5. What is the effect on the marine resource?

It is not only desirable but mandatory that the answers to these similar questions be known within some limit of statistical confidence if such a policy is to be implemented.

This report shows that the barged ocean disposal of wastes is an established practice which has been justified primarily through economic models that exclude consideration of possible damage to the marine resource. The deleterious effects of past operations are outlined in the Introduction, Section III, and serve to reinforce this showing. The objective of this report is not to condemn but to present a discussion of the available methods for determining the physical fate of wastes discharged through barging operations.

The fate models presented here are generally good hydrodynamic models but are quite deficient in allowing for chemical, physical and biological interactions that may occur between the waste, the sea water and its constituents. The use of these models assumes a knowledge of a number of important environmental parameters or characteristics which include:

1. The magnitude of the diffusion coefficients, their variability with scale and depth and density.

2. Ocean shear, drag and added mass effects.

3. Ocean current and density structures.

A computerized analytical technique developed by Koh and Fan (2) was adapted to the barge disposal case and is emphasized as one of the better models available. The program is available for general use and provides the greatest degree of input variability of any model considered.

The physical transport of the waste discharged from a barge was sequentially described by the following four separate transport phases:

1. Convective descent

2. Collapse

3. Long term diffusion

4. Bottom transport and resuspension

The effects of the presence of solids in the wastes was investigated and it was shown that interactions between settling velocity, concentration, and diffusion rates do exist but that the analytical technique is effective only when these effects can be ignored and the solids assumed to act like fluid elements.

The convective descent analysis provides results for the short term distribution of the waste discharge. The results include the effects of shear flows, cloud drag and added mass, entrainment and non-linear density gradients. The results of a series of example cases were presented to identify the effects and trends caused by varying the environmental and discharge parameters. The relationship between penetration and dilution was emphasized and methods of control were discussed.

The collapse phase was the most hypothetical and was recommended only for determining the relative effects on the long term diffusion of the waste. The basic assumption made was that at a position of buoyant equilibrium within the water column, the internal density structure of the cloud seeking a position of hydrostatic equilibrium was characterized by a dynamic horizontal collapse. This collapse was assumed to occur without further dilution and with the effects of particle settling completely ignored.

The example problems presented show that the effects of the collapse mechanism appear to cause variances in the long term diffusion values of several orders of magnitude over those when no collapse is allowed.

These variations are felt to be too large to be ignored and a clear need for research of this phenomenon exists. Future studies should attempt to determine the driving mechanism, the resulting dilution and entrainment while developing criteria for the description of interfacial instability and the effects of particle settling on the internal density structure of the cloud.

In its present form the long term diffusion model is a normalized, dimensionless model that uses the input from the collapse phase to determine the initial conditions. The present uncertainty in collapse phase theory consequently results in low confidence limits for the long term diffusion analysis. However, if the initial conditions are known then this model should give reliable and consistent results. The ouptut tabulates and plots the concentration distribution as a function of both space and time and locates the X, Z positions of the concentration centroid and the cloud center. The X, Z size of the cloud can also be determined. The predictive information is of the form that, within given limits, will be invaluable in establishing effective monitoring and discharge procedures. Its present value is, however, limited and only provides a method whereby the two extremes, either complete collapse or no collapse, can be determined.

A section was included which if complete would require a separate report. This section deals with resuspension and subsequent transport of materials which settle to the bottom. Current mathematical models are not designed to handle this area of concern and circumvent its existence through proper choice of assumptions.

Methods are presented which for a set of assumed or measured conditions will allow settling and shear velocities to be determined and compared to calculated critical shear stresses for particles of prescribed size and density. This section is at most cursory in nature and completely ignores the problems associated with multi-phase wastes which settle at different rates and are distributed in graded form over a varying topography.

Section VII of this report investigates some existing operations, attempting to show the variability in barge size, design and use. The barging costs, excluding loading and shore facilities, were examined through an analysis technique that provides a guide to the decision maker as to the size and number of barges required for a combination of haul distance and annual load.

Practical use methods are discussed in the final section and one example is given which traces the steps required to meet an arbitrarily selected criterion. The data presented were cited as not being general in nature and furthermore not descriptive of any particular operation or geographic area and used only to explore a use method. It was shown that this format could be used to determine the dilution, spread, and drift of the discharged material and was subsequently applied to the determination of the where, when and how of a discharge to preclude violating established water quality standards. The sample problem also evaluated the economics of increasing haul distances to insure such compliance.

SECTION II

RECOMMENDATIONS

This report has established the fact that current ocean dumping operations embody many separate risks to the total integrity of the marine environment. The report attempts to isolate only those problems associated with physical fate prediction from which the following research needs and recommendations are derived.

Techniques must be developed which will allow the material to be discharged to be characterized as a multi-phase rather than a single phase material. The segregation, distribution and deposition of materials must be handled in such a way that physical fate can be predicted for three separate areas (a) the floatable portions that rise to the surface either permanently or for some finite time after which they resettle (b) the portion which remains in suspension due to temperature, density or turbulence levels of the receiving fluid and (c) the portions which settle and are distributed over the bottom.

Phenomena such as the collapse phase have been shown to exist but remain in the realm of the unknown when it comes to the description of the driving mechanism and the resulting dilution and entrainment rates. Therefore, this area is considered one deserving of a great deal of experimental and theoretical research due to its effect on the results of a long term analyses of the physcial distribution of suspended and settleable materials.

The inclusion of particle settling is a necessity and should be coupled with an approach that allows for a variable bottom topography for an adequate description of the subsequent distribution.

One other important area which was not specifically identified in the text exists and this is the description of the initial conditions of the discharge. The question(s) to be answered here is whether the actual barge discharge dimensions are adequate or whether these need to be described in terms of an effective size, flow, etc. to account for possible initial accelerations, decelerations or chemical changes during the free descent of the materials.

The Environmental Protection Agency's National Coastal Pollution Research Program is currently sponsoring research designed to answer several of these needs, however this current effort is in no way sufficient to provide the total information necessary to satisfactorily predict the physical distribution of wastes and only touches on possible chemical and biological effects resulting from discharges to the marine environment.

SECTION III

INTRODUCTION

The by-product of life on this planet is waste; nearly every creature produces a waste product in direct proportion to its population growth rate. Man, the primary exception to this generality, produces a variety of waste by-products at rates that now exceed population growth by several orders of magnitude. Waste disposal has been primarily terrestrial but present population and urbanization trends, fostering competition for available land, have necessitated broad searches for economically feasible, alternative disposal techniques. Seaside communities and industries have found that a system of barged ocean disposal of hard-to treat solids and liquids is an economically feasible solution under existing regulations.

The President's Council on Environmental Quality, in a recent report on ocean dumping (1) shows the current responsiblity for control of disposal to be dispersed among several governmental agencies. The jurisdiction of these agencies, generally confined to areas other than those where the actual disposal occurs, results in what is termed uncontrolled disposal. Conflicts of interest are also pointed out for agencies possessing both regulatory and operational responsibilities in the same area. The Council recommends a national policy that would ban all unregulated disposal and would place sole responsibility and control in the hands of a single agency. This agency, through the establishment of discharge regulations and evaluation procedures, would "regulate" all ocean disposal operations. The processes of establishing regulations, and evaluating permit applications depend on an understanding of limitations in existing methods for analyzing the fate of materials dumped from barges.

Purpose and Scope

The primary purpose of this report is to document currently available methods and approaches for evaluating the physical fate and distribution of wastes discharged to the ocean environment. Emphasis is on the local as opposed to global distributions. This is only one aspect of a waste's total effect on the marine environment but one that must be understood prior to setting standards, as well as evaluating the biological and chemical effects which, of course, may be different for each type of waste and each bio-geographical coastal province. Where general mechanisms are involved or can be approximated, they are included.

This report first classifies the wastes giving typical characteristics and reported effects of current operations. A discussion of the theoretical transport mechanisms is then presented. A Methods of Analysis Section explores solution techniques and presents typical examples, followed by a section discussing barging costs. The report is concluded with recommendations for operation and for research, supplemented with an extensive bibliography.

SECTION IV

WASTES: CHARACTERISTICS AND EFFECTS

Wastes are discharged from barges at over 250 U. S. coastal locations with the majority of sites in nearshore waters less than 100 feet deep. Table 1, taken from a Dillingham Corp. report (3) shows the breakdown for 1968 by area and waste type.

Projections for the year 1980 (1) show expected increases in bulk quantity of most wastes to exceed 100 percent of the 1968 values and, without a major change in policy, most of this is expected to be barged and dumped at sea.

For the purposes of this report wastes will be classified as:

1. Dredge spoils

2. Sewage sludge

3. Industrial wastes

4. Radioactive wastes

5. Fly ash and incinerator residue

6. Garbage and refuse

Dredge Spoils

The major disposal of wastes to the oceans is in the form of dredge spoils, a practice in existence since man first found a need to maintain and improve harbors.

TABLE 1

OCEAN DUMPING: TYPES AND AMOUNTS (in tons), 1968*

	Atlantic	Gulf	Pacific	Total	Percent of total
Dredge spoils	15,808,000	15,300,000	7,320,000	38,428,000	80
Industrial wastes	3,013,200	696,000	981,300	4,690,500	10
Sewage sludge	4,477,000	0	0	4,477,000	9
Construction and demolition debris	574,000	0	0	574,000	<1
Solid waste	0	0	26,000	26,000	<1
Explosives	15,200	0	0	15,200	<1
Total	23,887,400	15,996,000	8,327,300	48,210,700**	100

* Reference (3)

** A recent study by the F.D.A. has shown this total to be closer to 62 million tons. The report will be published in early 1971.

Dredging operations are usually carried out in estuaries where the primary sediment source is the adjacent watershed and its drainage system; however, additional sediments may be deposited due to:

1. Littoral drift

2. Incoming tides

3. Estuary banks

4. Mud flats

5. Man made waste discharges

Estuarine sediments range in size from finely divided colloidal clays, a fraction of a micron in size, to larger particles of a few centimeters. These sediments may include variable amounts of organic and inorganic solids. The sediments are indigenous to the area and reflect the history of sediment sources. Development and utilization of lands in the drainage basin have resulted in additional problems. These problems are in the form of sediment contamination from fertilizers, chemicals and pesticides as well as a variety of industrial wastes which create a polluted sediment that when dredged or otherwise disturbed may adversely affect the marine environment.

To determine the physical fate of the sediment, the following waste characteristics must be specified:

1. The size distribution of the solids

2. The density distribution

3. Chemical flocculation tendencies

Table 2 gives some freshwater dredge spoil characteristics as reported by the University of Wisconsin (4) for the Great Lakes. It should be emphasized that these characteristics may be entirely different for marine sediments. Some characteristics of marine sediment are given in an extensive survey of the literature on ocean sedimentation and deposition near structures conducted by Einstein and Weigel (5).

Reported Effects of Dredging Operations

A report of a cooperative study between the Corp of Engineers and FWPCA (6) described a two-year study of harbor dredging operations as they affect water quality in the Great Lakes. The authors found that the effects of dredge spoil dumping in open lake areas remain open to question, but concluded that in-lake disposal of heavily polluted dredgings must be considered presumptively undesirable pending further study.

The U. S. Fish and Wildlife Service (7) has just published an investigation of the effects of dredging operations in San Francisco Bay on the fish and wildlife resource. The report indicates that spoiling results in a temporary reduction in fish abundance. Hopper dredge spoiling was found to create an oxygen sag of a temporary nature with measured values as low as 0.1 ppm in bay waters. The effects of increased turbidity were investigated in a series of laboratory experiments the results of which indicate that fish exposed to high turbidity levels may exhibit a weight loss and an increase in the level of pesticide concentration.

The effects of dredging on the waters of Chesapeake Bay were studied by Briggs (8) who found that the spoils were spread over an area 5 times that of the defined disposal area and that the total phosphate and nitrogen in the overlying waters was increased 50 to 100 times normal values. Material collected from bottom cores was found to be more than 90 percent silt and clay in the area to be dredged but was reduced to 75 percent in the spoils area.

TABLE 2

GREAT LAKES DREDGING SPOIL CHARACTERISTICS*

Location	Percent Solids	Average Density gm/ml	Settling Velocity ft/hr a/	Average Percentage by Weight Gravel $d>2$ mm	Sand $63\mu<d<2$mm	Silt $4\mu<d<63\mu$	Clay $d<4\mu$
Buffalo	37.0	1.27	0.068	0.1	18.4	70.6	10.7
Calumet	40.7	1.33	0.144	0.2	20.8	48.5	31.1
Cleveland	44.9	1.36	0.201	1.9	9.1	72.3	16.0
Green Bay	43.0	1.37	0.103	10.6	29.2	53.1	13.8
Indiana	35.2	1.23	0.150	1.9	29.2	53.1	13.8
Rouge River	43.7	1.28	0.290	1.9	40.9	35.9	20.7
Sodus Bay	53.1	1.51	0.506	0.0	50.8	41.2	8.1
Toledo	39.0	1.30	0.023	0.8	10.9	47.2	41.1

a/ Based on 30 minute settling

*Reference (4)

Servizi, et al., (9) reported on the effects of a proposed dredging operation in Puget Sound on the salmon fishery. Two types of sediments were involved: a highly organic, putrifying pulp fiber with a high concentration of hydrogen sulfide and a natural silt of low organic concentration. The authors concluded that because of the highly toxic nature of the sediments to the salmon and because various methods of dispersal appeared impractical, land disposal of the pulp fiber sediments would be necessary to protect the fish stock. It was determined that a 1000 to 1 dilution would otherwise be necessary to protect and prevent toxicity problems to the salmon.

Brehmer (10) outlined some of the detrimental effects of suspended and sedimenting solids in estuaries and concluded that turbidity and siltation reduce the quality of estuarine waters and degrade the system as a biological habitat. O'Connor and Craft (11) in a study of the Mersey Estuary in England found fine sediments that settled as flocules. An isolated investigation of individual flocules revealed an inorganic core surrounded by organic material. The Mersey has a strong salinity gradient over a tidal cycle with a net landward movement of water near the bed. This action was found to result in a buildup of organic material in the estuary with the presence of the large amounts of fine suspended material creating a buoyant system for larger solids and thus fostering and encouraging siltation of this material. Brown and Clark (12) found that dredging for navigational purposes in Arthur Kill near Raritan Bay resuspended bottom sediments having a relatively high BOD.

Sewage Sludge

The inherent public health hazard and the potential for buildup of organic solids on the ocean bottom makes the disposal of sewage sludge one of the most significant wastes considered.

The characteristics of the sludge necessary to predict its physical fate are essentially the same as those of dredge spoils. The bulk specific gravity can be controlled to some degree through watering processes or through the use of additives such as incinerator residue or fly ash.

Normally a primary sludge will have a solid content of between 2 and 5 percent with 70 to 80 percent volatile matter. A well-digested sludge will contain 5 percent solids which can be increased upward to 10 percent upon dewatering with a 40-50 percent content of volatile matter. Typical values of sludge characteristics for both aerobic and anaerobic processes are given in Table 3.

The settling velocity distribution of digested sludges in the sea water was investigated by Brooks (13) and Orlob (14) for Santa Monica and San Diego, California, respectively. Their results indicate a high proportion of solids have very low settling velocities, with 90 percent at Santa Monica and 100 percent at San Diego settling at rates less than one centimeter per second.

TABLE 3

TYPICAL DIGESTED SLUDGE CHARACTERISTICS*

Characteristics	Anaerobic		Aerobic	
Total solids	34,000	68,000	-----	-----
Percent volatile	48	48.6	47	48.9
Specific gravity	1.011	-----	-----	-----
pH	7.7	7.2	6.7	5.6
Max. particle in microns	2,000	-----	-----	-----

*References (15), (16), and (17)

Reported Effects of Sludge Disposal Operations

Philadelphia's disposal of digested sludge to the ocean via barges was initiated in 1961 and has been discussed frequently in the literature (18, 19, 20). The dumping is confined to an area of one square mile, ten miles off the coast near Cape May, New Jersey. By 1969 (21) the annual volume had reached 115 million gallons.

The sludge dumping grounds in the New York Bight area, located 11 miles off the coast in waters no less than 72 feet, have been described as a vast desert on the ocean bottom (22). Another study of the area stated that, "the bottom of the area of the mud, rubble-excavation and sewage sludge dump is so badly fouled that changes in the dump location would be of little help to the immediate area." (17).

Beulow (23) reported on a bacterial study made in the New York and Philadephia sludge dumping grounds. While it was noted that the coliform concentration decreased quite rapidly in the waters receiving the sludge, high levels of fecal coliform contamination were found in surf clams, forcing the closure of affected areas to further harvesting. It was also noted that there was considerable sludge covering the bottom.

Beyer (24) reported on an investigation of sludge dumping in the Oslo Fjord with primary emphasis on the spreading of sinking particles. It was reported that heavy sludge particles sank to the bottom rapidly and adhered to meshes of shrimp trawlers in the area, while a cloud of polluted water was visible at the surface for long periods of time.

There have also been numerous studies of ocean outfalls for sewage sludge disposal on the West Coast which are pertinent because of the reported effects. Orlob (14) reported on the effects of digested sludge discharged approximately two miles off the San Diego shore in 200 feet of water. The author's analysis estimates a sludge accumulation rate of one tenth inch per year near the outfall with 40 percent of the solids settling at such slow rates that their accumulation within a five mile area could be considered negligible. Grease and floatables were identified as potential problems but were not defined quantitatively. Apparently, little consideration was given the ultimate fate of the solids which are carried away from the discharge site.

Brooks (13) studying the sedimentation and dilution of digested sludge in Santa Monica Bay for Hyperion engineers, concluded that sludge accumulation rates should average 2-3 inches per year within a 500-foot radius decreasing to 0.25 inches per year at a two-mile radius from the outfall. This analysis assumed a constant current of 0.2 knot with equal frequencies in all directions. These rates of accumulation were considered unobjectionable based on 1956 standards. Other studies of this area (25, 26) have reported that the disposal of approximately 4000 tons of solids per day has had no apparent effect on fish abundance. Another study (27) however, has indicated that California's giant kelp is being adversely affected by increases in sea urchin population apparently fostered by waste disposal operations along the coast.

In the Puget Sound area, the disposal of digested sludge through outfalls has also prompted studies on effects and fates. Brooks, et al, (28) studied the outfall design and gave predictions for sludge accumulation. An earlier study by Sylvester (29) in 1962 also discussed this problem and pointed out the potential problems that could arise from:

1. The increased nutrient content of the water

2. Sludge accumulation

3. Floatable materials

4. Effects on the marine ecology

Industrial Wastes

Industrial wastes vary greatly in both physical characteristics and toxicity. The severe effects that may result from the disposal of these wastes present the greatest potential hazard to the total marine environment of any of the wastes discussed.

For industrial wastes, the solid concentration, bulk specific gravity and solubility in sea water are the minimum characteristics necessary for the evaluation of the local physical fate of the material. Characteristics of some industrial waste components may be determined from standard references.

Reported Effects of Industrial Waste Barging Operations

Hood (3) reporting on the disposal of chlorinated hydrocarbons by the Shell Oil Company, stated that the organisms endemic to the disposal area were either killed or seriously imparied immediately upon contact with the waste. The area was found to return to near normal in three to eight hours. The author concluded that toxic wastes could be disposed of beyond the littoral zone of the sea, resulting in only a slight effect on organism biomass. Dispersal was found to be slow, hence to avoid contamination of fishing grounds and areas of upwelling, disposal within the Gulf of Mexico was recommended only beyond the 2400-foot depth line.

The toxicity of ferrous sulfate and sulfuric acid was investigated by the National Lead Company in relation to dumping operations they carried out in the New York Bight area. Reported conclusions (30) claim no permanent effect on plant, fish, or animal life. The report mentions similar studies and conclusions for both containerized and liquid wastes discharged by U. S. Steel, Champion Paper and Fiber, and National Aniline Division of Allied Chemical and Dye.

Radioactive Wastes

Radioactive wastes are a potential hazard to man because of radiation received from the immediate environment and by substances taken into the body by ingestion, inhalation, or absorption through the skin. It is feared wastes may reduce the life span, impair the functioning of parts of the body, or increase the mutation rate altering the inherited characteristics in future generations (31). The disposal of radioactive wastes is generally accomplished either by containment--allowing for natural radioactive decay, or by dispersal--diluting the radioactivity to permissible levels, or a combination of the two. In the past, ocean disposal has required containment and placement in waters exceeding 6000 feet in depth. The increased use of radioactive materials by universities, hospitals, and research facilities has resulted in a corresponding increase in low-level radioactive wastes. The AEC licenses commercial firms for the disposal of these wastes in coastal waters.

The NAS-NCR conducted study (31) considers the disposal of radioactive wastes into the Atlantic and Gulf coastal waters and reports safe levels for radioactive wastes, containment requirements and recommends specific disposal sites. This study also discusses the hazards associated with disposal in relatively shallow water, e.g., recovery by fishermen, buildup of radioactivity in marine organisms, and washup on beaches of contaminated materials.

Joseph (32) presented a summary of U. S. disposal operations through December 1956 stating that the operations were considered to be under controls adequate to preclude hazards in handling and disposal. He estimated that 8500 drums of 55-gallon capacity had been dumped in the Atlantic and over 13,000 drums in the Pacific, representing a combined total of nearly 16,000 curies.

Waldichuck (33) reported on the containment of radioactive wastes off the Canadian Pacific coast and Collins (34) discussed container construction laws, possible discharge limits, liquid effluents, volatile reduction, and biological concentrations.

Koczy (35) discussed the distribution of radioactive materials in the sea providing the information on the variation in dispersion rates. Isaacs (36) discussed the magnitude of disposal of low level radioactive wastes into Pacific coastal waters as did the Coast and Geodetic Survey (37). The Pneumo Dynamics Corporation conducted a survey of radioactive waste disposal sites (38), and an evaluation of sea disposal containers (39). This problem has been studied in the United Kingdom (40, 41) and, no doubt, elsewhere.

Sabo (42) discussed the river and tidal characteristics of the Savannah Estuary and described the accumulation of nuclides by organisms. Pursuhathaman and Gloyna (43) reported on the effects of sedimentation on the transport of certain radionuclides. Sheh and Gloyna (44) also reported on this subject and presented a mathematical model to predict the influence of sediments on the transport of solubles in open channel flow.

Fly Ash and Incinerator Residue

Fly ash generated by fossil fuel power stations, represents only a minor percent of the total volume of wastes discharged to the ocean but is worthy of discussion for possible desirable properties.

Tenny and Cole (45) reported on the use of fly ash as a sludge conditioner and examined the subsequent effect on vacuum filtration methods of dewatering. They found that the addition of fly ash to a sludge reduced the volume of filtrate due to the absorptive capacity of the fly ash. Table 4 summarizes the typical characteristics of the fly ash generated from pulverized coal fired plants. The particle size distribution of the material appears to be describable as a log normal distribution.

TABLE 4

TYPICAL CHARACTERISTICS OF FLY ASH*

Parameter	Units	Range
Silica (SiO_2)	mg/l	34-48
Alumina, Al_2O_3	mg/l	17-31
Iron Oxide, Fe_2O_3	mg/l	2-26.8
Calcium Oxide, CaO	mg/l	1-10
Sulfur Trioxide, SO_3	mg/l	0.2-4
Percent Vol. Matter		0.37-36.2
Particle Sizes	μ	0.5-100
Bulk Density (computed)	PCF	70-80
s.g.		2.1-2.6

* Reference 45

Fly ash possesses an adsorptive capacity which has also been studied for its potential for removing soluble COD. Deb et al., (46) studied the effects of adding fly ash to the sludge at a treatment facility and found it would adsorb soluble COD. The effectiveness of the fly ash reached an upper limit when the concentrations approached or exceeded 4000 mg/l. The effects of the treated sludge when diluted with sea water are not known, therefore it is safe only to consider the physical consequences resulting from the use of fly ash or incinerator residue as an additive to sludges.

The immediately obvious consequence of such additives is the increase in bulk specific gravity that occurs. This control can be put to good use in barging operations as the penetration depth and the dilution of the discharged waste sludges are both sensitive to changes in specific gravity. These effects may be positive or negative dependent upon the actual environmental and discharge conditions.

Garbage and Refuse

The disposal of processed refuse and garbage to the ocean is receiving considerable attention. This is not a common practice yet, but it is approaching an economically feasible status relative to land disposal. One process now being considered involves sinking of properly compressed bales and depends on the increased pressure with depth to maintain a density sufficient to keep the material on the bottom.

A five-year study conducted jointly by the Harvard University School of Public Health and Rhode Island's Graduate School of Oceanography (47, 48, 49, 22) investigated waste incineration at sea and the subsequent disposal of the non-floating residue. The results of this study indicated little or no toxicity to a series of marine organisms and concluded that a depth of 200 feet was sufficient to keep the material from reaching the beaches in the test area. Kinsman (50) however, reports that waves alone have been responsible for sediment movements in water of this depth. To date, the burning of garbage and refuse at sea has not proven to be economically justifiable and current and future air pollution regulations may prevent it from becoming technically acceptable.

Gunnerson (3) notes that in 1968, 26,000 tons of garbage and refuse were dumped into the Pacific Ocean off San Diego and San Francisco. San Diego, however, discontinued this process in November of that year.

SECTION V

TRANSPORT MECHANISMS

The transport of waste materials dumped into the sea depends, in general, upon:

1. What is introduced - its physical, biological, and chemical properties.

2. Where it is introduced - its position with respect to local ambient-density and velocity distributions.

3. How it is introduced - its residual buoyancy and momentum.

This paper emphasizes both the immediate mixing and dispersion of wastes over periods of time that are relatively short when compared to the circulation times of the oceans as a whole and does not consider the physical oceanographic processes, whereby wastes can be diluted and dispersed from one part of the ocean to another. These are known to continually vary with both time and space as well as with changes in boundary condition. This aspect will be discussed only qualitatively to aid in visualizing the applicability and limitations of the analyses subsequently presented.

It is often assumed or theorized (51) that although the ocean is in continuous motion the rates of motion and exchange cover such wide ranges that they can be separated into nearshore horizontal and vertical exchange, intermediate and deep circulation exchange and the exchange associated with coastal and enclosed basin circulation.

In most coastal and open waters agitation and turbulence generated by wind stresses on the surface result in a surface or mixed layer characterized by a near uniform density gradient. This layer varies between 60 and 1200 feet and is separated from the colder deeper waters by a stable layer exhibiting a sharp density gradient - the thermocline or pycnocline. The magnitude of this gradient can vary in both time and space and characterizes the relative stability or strength of the layer.

Wastes introduced into the mixed layer generally will be rapidly distributed vertically throughout this layer due to convection, wind-stirring or mixing, density differences, and internal currents. If they fail to penetrate the pycnocline they will be transported from the area of introduction primarily by wind-driven surface currents which, in general, extend throughout this layer. The analysis of wastes which do penetrate the pycnocline will be influenced, if not controlled, by large-scale global currents such as the Gulf Stream and the Kuroshio. The average location, magnitude, and direction of these currents has been documented (52, 53, 54, 55) and in lieu of on-site determinations their use would produce approximate but reasonable results. Estuarine and nearshore currents have also been studied, although to a lesser degree, and typical values are given by Ippen (56), Orlob (14), and Brooks (11).

The presence of eddies resulting from turbulence can act to vertically disperse waste materials in addition to mean current dispersion. The rapid increase of density with depth in the thermocline inhibits vertical transfer, and eddy diffusion is small compared to that of the mixed surface layer with its near uniform density gradient.

There are other localized phenomenon that can influence the exchange of material between the surface and sub-surface layers. This occurs in areas where:

1. The pycnocline is shallow and subject to disturbances, usually wind generated.

2. Offshore transport of surface waters results in an upwelling of colder sub-surface waters.

3. Downwelling exists caused by an increase in the density of surface waters due to evaporation or cooling.

The first step in a complete analysis of the effects of a waste discharged to the ocean is to predict its physical fate. The objective of the analysis usually dictates a time scale that varies as a function of the waste material itself. For example, the time required to reduce a toxic waste through dilution to a non-toxic concentration may be on the order of hours, if it is susceptible to chemical and biological destruction but on the orders of weeks if it is refractory. The subsequent analyses utilize a variety of simplifying assumptions and are limited to environmental conditions variable only with depth and totally exclude biological and chemical effects.

The total transport of waste materials can be divided into four basic transport phases. Using the terminology of Koh (2), these are:

1. Convective descent

2. Collapse

3. Long-term dispersion

4. Bottom transport and resuspension

These phases are graphically presented in Figure 1. It can be noted that the first two phases, convective transport and collapse are of short duration, when compared to long-term diffusion and, as will be shown later, are important in determining the initial conditions for the long term diffusion stage.

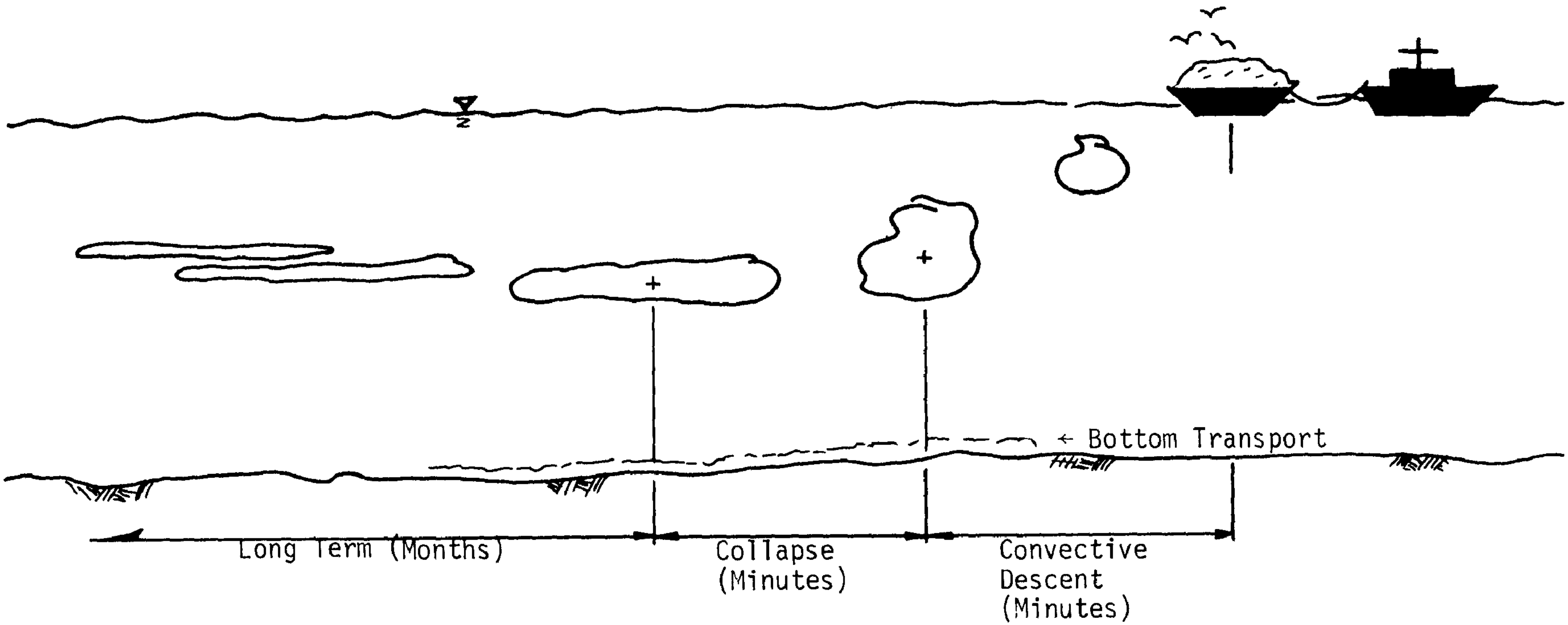


FIG. 1. Basic Transport Phases

Convective Descent

A waste material dishcarged to the ocean from the surface generally possesses an initial downward momentum and a density greater than that of the receiving fluid. These result in forces that cause the waste to settle in the form of a "cloud." As the cloud settles shear stresses are developed at the interface between the moving cloud and the receiving fluid. These stresses result in a dispersion of momentum and in the creation of turbulent eddies that entrain ambient fluid.

Entrainment of the less dense ambient fluid reduces the density differential and tends to slow the descent of the cloud. The descent speed is, at the same time, being reduced as solids with settling velocities greater than the descent speed of the cloud settle out, further reducing the cloud's density. The waste cloud may, in a stably stratified fluid, eventually reach an equilibirium level where the descent velocity is zero and the density of the cloud is in approximate equilibrium with the ambient fluid. This zero velocity state is considered the end of the convective descent stage.

To solve this problem accurately the size and density distribution of the constituent waste elements would have to be known. If solids are considered to settle continuously, the end of the convective descent stage would theoretically never be reached for more than an instant because, due to continual particle settling, the cloud would become positively buoyant and begin to rise. Many studies of this phenomenon have shown that when both the concentration and size of the solids are small the waste slurry will tend to act as a pure liquid. For the wastes commonly dumped into the ocean this assumption is currently made for most classes excepting dredge spoils and industrial wastes having high solid concentrations.

Morton, Taylor and Turner (57) solved the problem for a point source or slug release in a uniformly stratified fluid assuming:

1. Wastes to act as pure liquids.

2. Velocity and buoyancy in the cloud to be of the same form.

3. The mean velocity throughout the cloud to be described by $K(U_t)$

4. Entrainment proportional to the mean velocity and given by $\alpha K(U_t)$

By writing equations for conservation of volume, momentum and buoyancy the authors developed the following equations to predict the final depth of penetration, the final cloud radius and the time of maximum descent.

Final depth $Y_f = b_o \; 1.682 \; (\alpha K)^{-3/4} E^{-1/4}$ ....[1]

Final radius $b_f = b_o \; 1.632 \; (\alpha K)^{-1/4} \; E^{-1/4}$ ....[2]

Max. time $t_f = 3.14 \; K^{1/2} \; E^{-1/2}$ ....[3]

The solution of these equations requires the constants of proportionality α, and K to be determined experimentally while relying on a linear density gradient to determine E defined as follows:

$E = \varepsilon_0 b_0 / \rho_S - \rho_0$ ....[4]

Where,

ε_o = Density gradient $(\partial\rho/\partial Y)$
b_o = Initial cloud radius
ρ_s = Density of waste
ρ_o = Ambient fluid density
g = Acceleration of gravity

Morton's experimental value for the product (αK) is 0.285 and upon substitution allows equations 1 and 2 to be solved. The author gives only a best fit value for α equal to 0.093 which by using the (αK) relationship above, allows equation 3 to be solved.

Baumgartner, et al., (58) used Morton's work to determine the ultimate trap level for a diluted bolus of slurry discharged from a barge as,

$$Y_{(ult)} = 3.8\ b_0 E^{-1/4} \qquad [5]$$

Koh and Fan (2) have developed a model designed to predict the distribution subsequent to a deep underwater nuclear explosion. This model, however, can be used for analyzing the convective descent stage of a surface discharged waste and, under the previous assumptions, will produce results identical to those attributed to Morton, et al. This model is general in nature and was derived under somewhat different governing assumptions. The entrainment coefficient α was assumed to be proportional to the vector difference of the mean cloud and ambient velocities. The momentum equation was expanded to account for entrained momentum and the effects of drag and added mass with the resulting set of equations programmed for numerical computer solution. The program allows for arbitrary, horizontal velocity distributions and can accommodate any depth-dependent density structure desired. Koh and Fan (2), when analyzing the deep radioactive debris cloud, concluded that the inherent errors in the entrainment coefficient (α) more than overshadowed any effects resulting from the inclusion or drag or added mass effects. They also concluded that ambient ocean currents were negligible; however, this was in comparison to relatively high cloud velocities, initially 600 ft/sec. When applying this deep water model to surface disposals one must assume that a cloud of finite dimensions has been formed and can be described in terms of known surface dimensions and velocities. It should also be noted that effects of solid constituents were not present in the radioactive cloud which requires the further assumption of wastes that act as liquids.

The effects of drag and added mass can be removed by choosing $C_D = 0$ and $C_m = 1$, then the maximum depth of penetration can be described for a quiescent receiving body as:

$$Y_t = b_0 \frac{1}{\alpha} \{1 + \frac{4\alpha}{E} (1 + \sqrt{1 + EF'^2})\}^{\frac{1}{4}} - \frac{1}{\alpha} \quad \text{[6]}$$

where, F' the densimetric Froude number is given by:

$$F' = V_0/(g'b_0)^{\frac{1}{2}} \quad \text{[7]}$$

with g', the reduced gravitational potential defined as:

$$g' = g\frac{\rho_o - \rho_s}{\rho_{o(o)}} \quad \text{[8]}$$

Koh and Fan (2) chose (α) equal to 1/6 assuming a range of 1/3 to 1/8 and ran solutions for various values of ε. These solutions were normalized and plotted as functions of the densimetric Froude number and are presented here as Figures 2 and 3. Slight differences will result when comparing these solutions to those using equations 1, 2, and 5 for two basic reasons: (1) the difference in the defined level of descent and (2) the variance in methods and coefficients used to account for entrainment.

Collapse

The second phase of transport, the collapse phase, is the transition between convective descent and long term dispersion. The analysis of this phenomenon assumes that the cloud has come to rest at some equilibrium position and that a dynamic vertical collapse characterized by horizontal spreading occurs. This collapse is driven primarily by a pressure force and resisted by inertial and frictional forces. Many complex actions may be occurring simultaneously here and an analogy to a density underflow is useful in attempting to describe them in qualitative terms. A three-dimensional form of surge head accompanied by the corresponding reverse

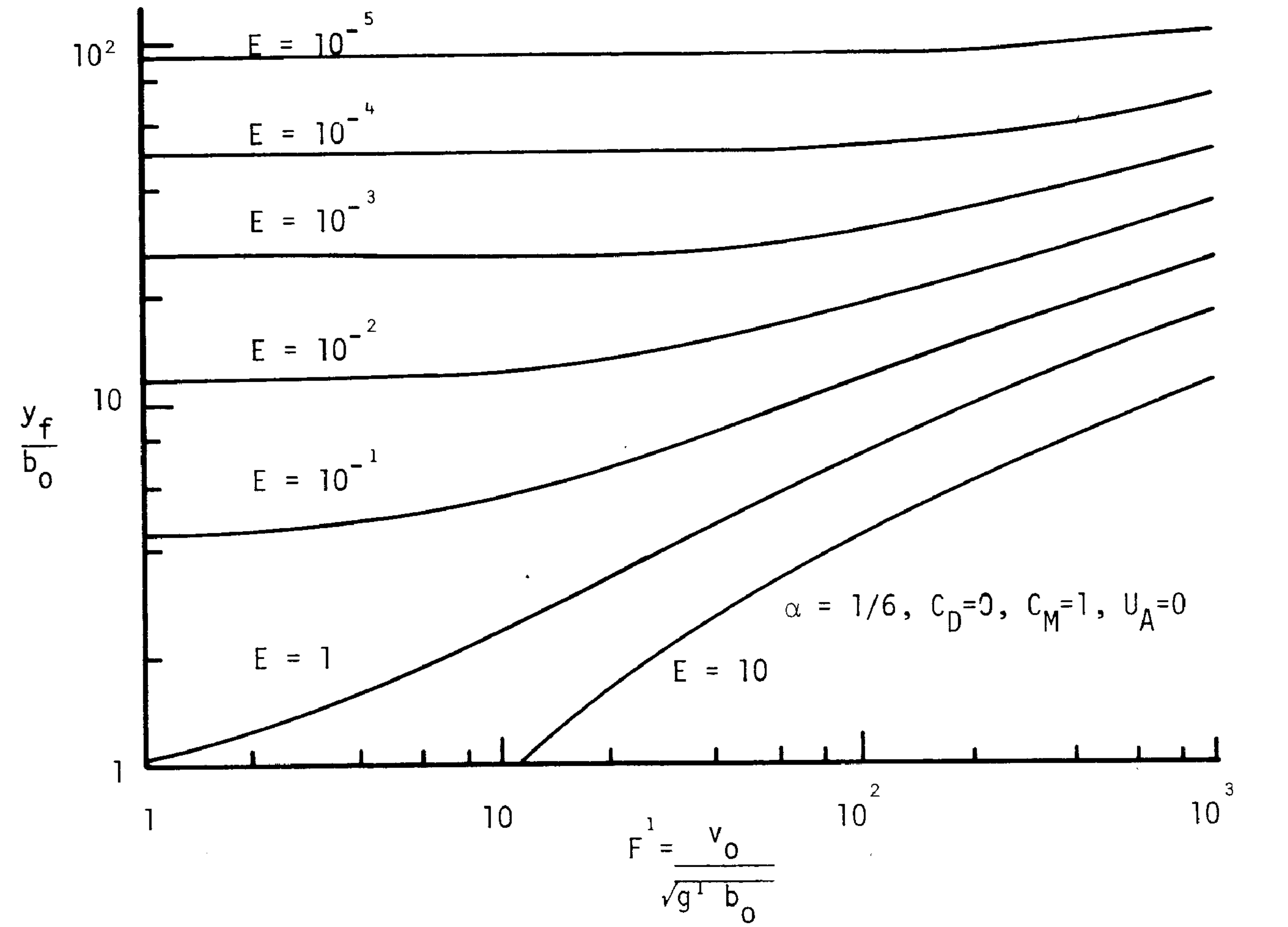


FIG. 2 - Convective Descent Terminal Depth [after Koh & Fan (2)]

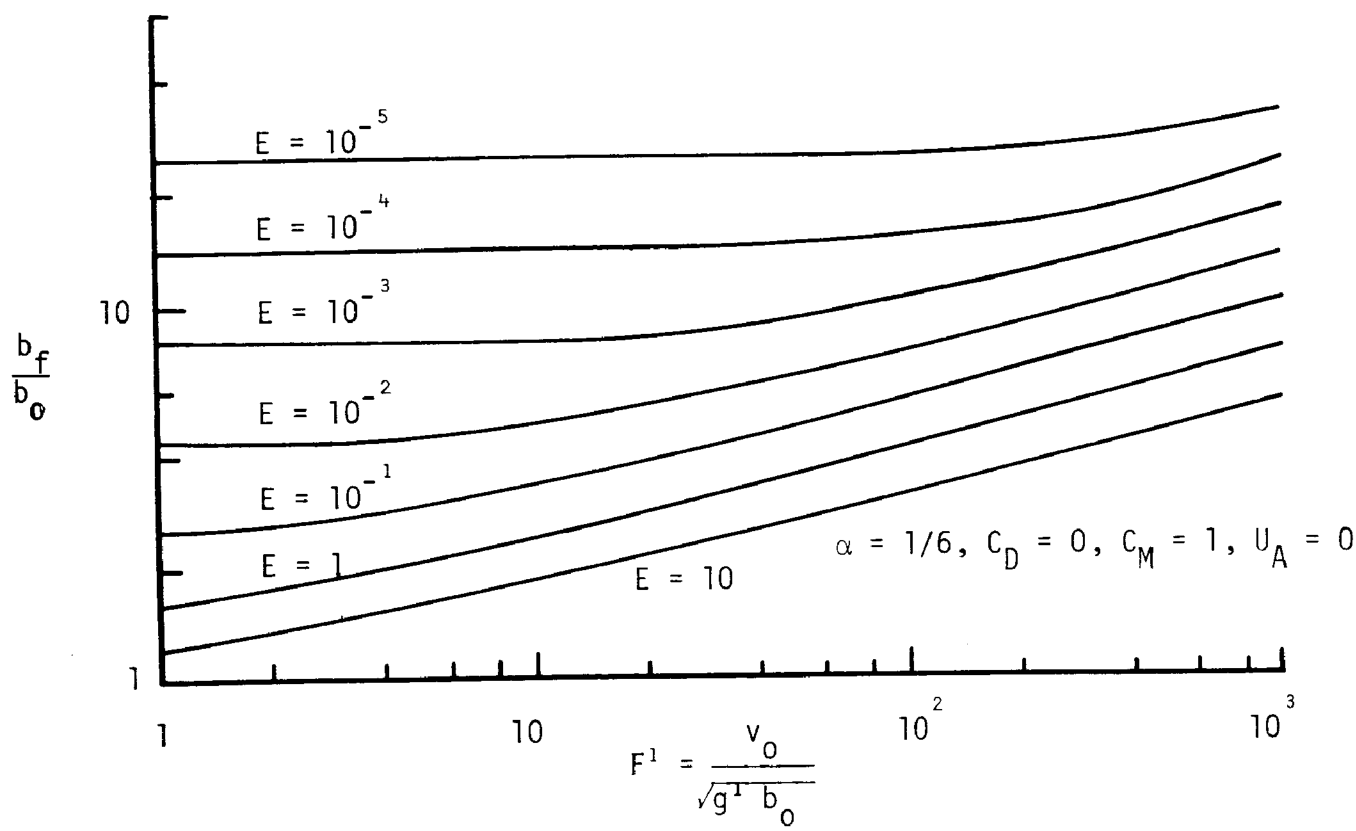


FIG. 3 - Convective Descent Terminal Size [after Koh & Fan (2)]

flows should exist, with the circulation increasing the diffusion in the area of the spread. The internal density structure of the cloud relative to the ambient density structure will exercise control over the magnitude of this spreading rate and instability criteria should exist, similar to that of the two-dimensional case, that will predict breaking interfacial waves for some velocity level. If this occurs, mixing and entrainment will further increase. The near zero vertical velocity of the cloud should allow for an increase in the number of solid elements that can settle out interjecting another action that may foster not only a decrease in the driving force but also an upward motion in the cloud itself.

To date, there is no analysis specifically designed to analyze this problem, however, if one realizes the shortcomings, the analysis presented by Koh and Fan (2) can be applied--providing a feel, at least, for the limiting values. It should be pointed out here that the method described was not intended to describe the collapse phase of a waste slurry and the shortcomings are to some extent a function of its extrapolation.

To apply this analysis one must assume the following:

1. The cloud has an axisymmetric shape at the end of the convective descent stage.

2. The ambient density structure is linear.

3. The internal density structure of the cloud is described by an equation that differs from that for the ambient density through the inclusion of an internal density distribution term (γ). This equation can be written as:

$$\rho_{(y,r)} = \rho_0(1-\gamma\varepsilon y)$$

4. No entrainment occurs during the collapse.

From the equation for the cloud density structure it can be seen that when $\gamma = 0$ the driving force would be the greatest and when $\gamma = 1$ no spreading would occur because the cloud and the receiving fluid would exhibit equal densities at all depths. The validity of this approach, as pointed out by the authors, has not been verified and the results presented here are for theoretical examples designed to explore the interrelationships between the defined terms.

A balance of forces in the horizontal directions resulted in the following equation using the coordinate system shown in Fig. 4.

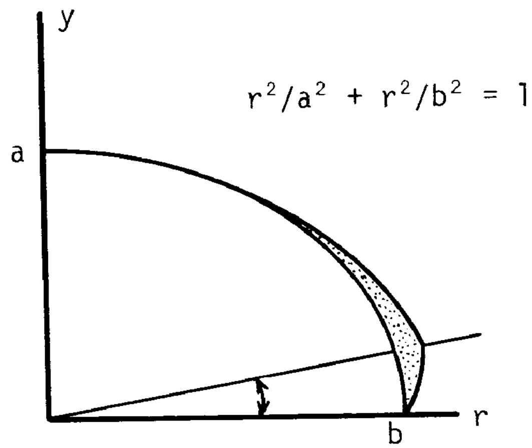


FIG. 4. Coordinate System for Collapse Phase

$$\frac{\rho\pi \frac{(1-\gamma a_o)}{a} g a^3 b d\theta}{16} = \frac{\rho_o \pi a b^2}{16} \frac{d^2 b}{dt^2} d\theta +$$

$$\frac{C_1 \rho_o a b}{4} \left(\frac{db}{dt}\right)^2 d\theta + \frac{C_2 \rho_o \nu b^2}{2a} \left(\frac{db}{dt}\right) d\theta \quad \text{.........................[9]}$$

The term on the left is the pressure force term equated to respectively, a local inertial force, a convective inertial force, and a friction force. The equation is simplified by defining two new terms K_1 and K_2 as:

$$K_1 = 4\, C_1/\pi \quad \text{...[10]}$$

$$K_2 = 8\nu C_2 b_o/\pi\alpha_o^{\,3}\,\sqrt{\varepsilon g} \quad \text{.................................[11]}$$

In lieu of measured values for C_1 and C_2 the authors reasoned that they should be near unity and, therefore, attention was focused on the interrelationship of K_1 and K_2. Figure 5 is typical of the results of this analysis and shows a series of S-shaped curves for a constant value of K_1. This indicates a pool acceleration at small values of time which are independent of K_2 and are interpreted by the authors to indicate the domination of the inertial and pressure forces which gradually and continually decrease until the viscous forces described by K_2 become dominant and collapse ceases. Figure 5 can be used to predict maximum time and cloud dimensions for the case where γ is equal to zero and K_1 is taken equal to 0.1. Examples will be presented in a subsequent section.

It should be pointed out that no ambient horizontal currents are assumed to be acting during this phase, a condition not likely to be found in the shallow waters where barge dumping is common.

Long Term Dispersion

Standardized differential equations are available that describe dispersion and convection in turbulent flows. To date, only simplified solutions have been used. These are usually applicable for open ocean conditions only and presuppose a waste that acts solely as a liquid.

To apply these solutions to a waste cloud it is again necessary to assume a neutrally buoyant cloud acted upon by molecular diffusion, eddy dispersion and mean convective processes. These simplifying assumptions result in a series of differential equations for each phase.

The basic diffusion equation may be written as:

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} = \frac{\partial}{\partial x_j} [D + K_{x_j}] \frac{\partial c}{\partial x_j} + m \quad \text{[12]}$$

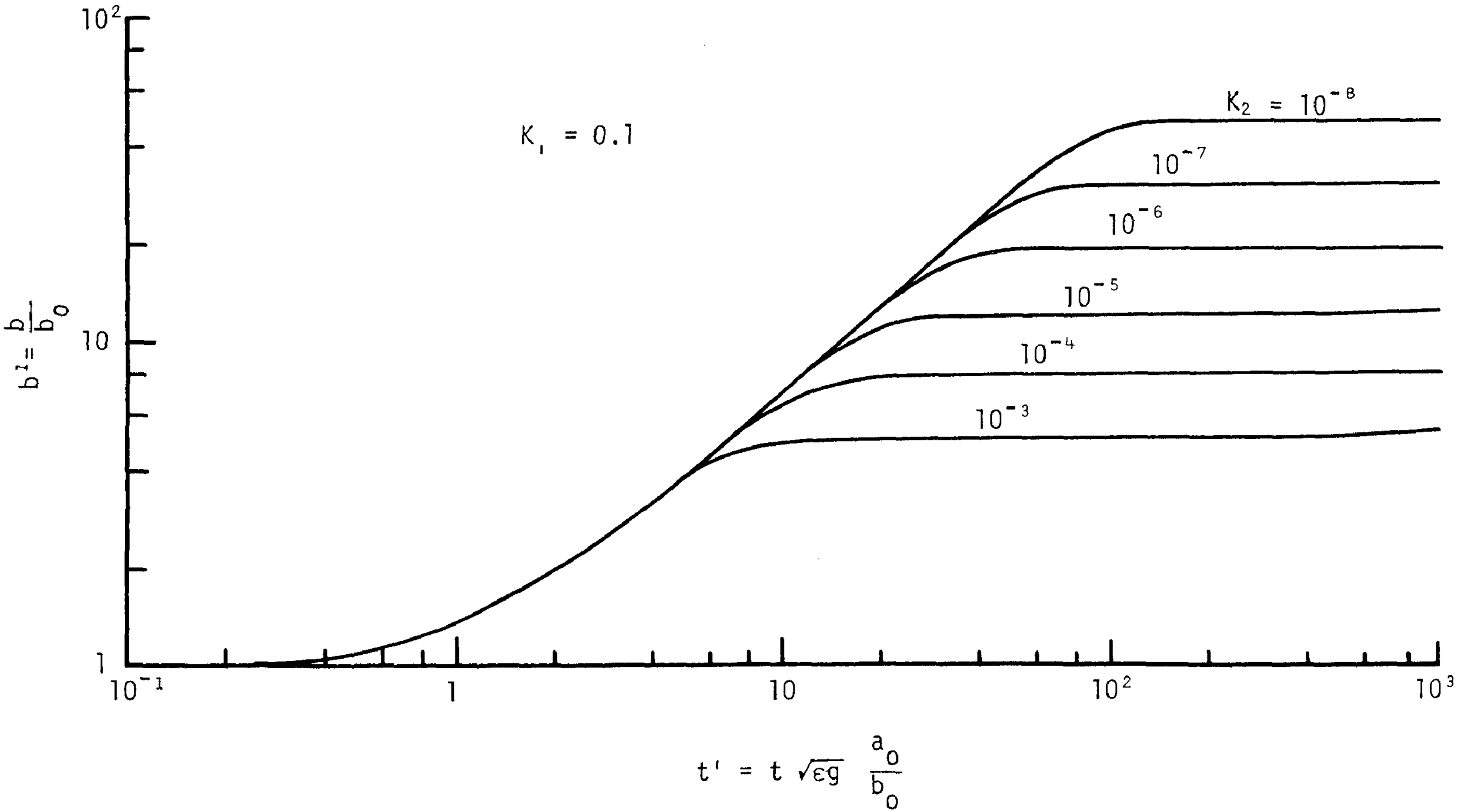


FIG. 5. Collapse Size and Time for $\gamma = 0$ [After Koh & Fan (2)]

where C denotes the concentration of the waste, D the molecular and K_{xj} the eddy diffusion coefficients. The last term (m) represents either a source or a sink. If the waste is subject to decay, flocculation or chemical and biological reactions, these processes might be appropriately estimated by incorporation into a first order reaction function, viz., dc/dt = -cK. The last term of equation 12 would then include (.......-cK) for each process included. If there is only one source or sink term, it need not be included in the differential equation, however, the resulting values of c(t) the so-called conservative values must be multiplied by e^{-kt} to obtain the correct liquid concentrations.

For ocean diffusion problems the molecular diffusion can be shown to be insignificant when compared to eddy diffusion; therefore, the term of interest is K_{xj} which is a function of the flow field rather than of the fluid itself.

The general solution, for instantaneous releases of conservative wastes, can be described by the following equations:

$$c(x,y,z,t) = \frac{M}{(4\pi)^{3/2}(K_x K_y K_z)^{1/2} t^{3/2}} \exp-\left[\frac{(x-ut)^2}{4K_x t} + \frac{(y-vt)^2}{4K_y t} + \frac{(z-wt)^2}{4K_z t}\right] \ldots [13]$$

where M is the mass of waste released.

If the source is fixed and continuous and is being discharged into a uniform flow field the concentration for any time at a point can be described as follows:

$$c(x,y,z) = \frac{c_o\ q}{4\pi(K_y K_z)^{1/2} x} \exp-\left[\frac{y^2 u}{4K_y x} - \frac{z^2 u}{4K_z x}\right] \ldots\ldots\ldots\ldots [14]$$

where q is a measure of the volumetric discharge and has units of $[L^3/T]$, and c_o is the initial waste concentration. For the case given here the current is assumed to be in the X direction with the eddy diffusion in that direction assumed negligible.

Orlob (11) used the two-dimensional form of equation 13 to predict sludge accumulation rates adjacent to an ocean outfall. He redefined the eddy diffusion terms K_{xj} to represent the greater effects of current velocity. Glover (59, 60) also used this relationship to analyze the dispersion of solid and suspended materials in open channel situations.

Simplified versions of these equations have been used by the Atomic Energy Commission to analyze the diffusion of radioactivity subsequent to the sudden rupturing of cubical cannisters residing on the ocean bottom. The assumed conditions reported (61) provided for an instantaneous rupture in the absence of currents. Equation 13 under these assumptions reduces to:

$$c = M/4(\pi K_x t)^{3/2} \quad \text{Where } M \equiv c_0 V \quad \ldots\ldots [15]$$

The assumptions made should be reviewed to reinforce the limitations of these solutions. A constant flow was assumed removing shear effects thus limiting the use of these equations near boundaries. The turbulent diffusion coefficients were assumed constant, an assumption that will subsequently be shown not to be valid for many ocean situations. These solutions cannot be expected to predict the transport of any wastes with high solid concentrations due to the assumed zero settling velocities. It should also be pointed out that in the case of surface dumping of waste materials the initial conditions at the beginning of this phase are described by the waste cloud at the end of the collapse phase. These conditions, at present, cannot accurately be predicted which further effect the reliability of derived results.

Solutions recently presented by Carter and Okubo (62), Okubo (63, 64) and Okubo and Carweit (65) have included shear effects for both continuous and slug releases. These solutions are applicable only when the settling velocity can be assumed zero. The eddy diffusivities have also been considered constant with respect to both time and space based on a division of the turbulence into large and small scale eddies. The small scale eddies were felt to exhibit small time and length scales relative to those of observations, thus allowing the use of mixing length theory to describe this diffusion process. The large scale eddies were assumed to create an inhomogeneity in the flow that could be described by defining the mean velocities as:

$$\bar{V}_x = V_o\ (t) - \Omega_y\ Y - \Omega_z\ Z \quad \text{[16]}$$

$$\bar{V}y = Vz = 0 \quad \text{[17]}$$

where, Ω_x, Ω_z denote constant horizontal and vertical shears. This assumes a mean velocity along the x axis with the z axis vertical and leads to a diffusion equation for their model of:

$$\frac{\partial c}{\partial t} + (V_o - \Omega_y\ Y - \Omega_z\ Z)\ \frac{\partial c}{\partial x} = K_x\ \frac{\partial^2 c}{\partial x^2} + K_y\ \frac{\partial^2 c}{\partial y^2} + K_z\ \frac{\partial^2 c}{\partial z^2} \quad \text{[18]}$$

Computer programmed solutions to these equations have been reported (63) which provide as functions of time:

1. Families of isoconcentration surfaces

2. Dimensions of the contaminated region

3. Volume and quantity of material

Koh and Fan (2) have presented an even more general solution allowing:

1. Turbulent eddy diffusion coefficients variant with both scale and or depth.

2. Current generated shear in both vertical planes.

3. Non-linear density gradients, when applicable.

The environmental conditions are somewhat limited as they are independent of the horizontal coordinates. This limitation is minor in light of the uncertainty that exists around the proper choices for coefficients to describe entrainment, diffusion, drag, and added mass. The analysis does however provide the gross characteristics of the "cloud" which include:

1. The total material distributed over each horizontal plane.

2. The location of the centroids.

3. The standard deviations of the centroids.

4. Estimated characteristic concentrations.

5. Horizontal cloud dimensions.

Bottom Transport and Resuspension

This final transport phase, contrary to the basic assumption made earlier, assumes that the solid constituents of the waste slurry do indeed settle and reach the bottom. This could be accomplished entirely during the convective descent stage if the water depth were less than the predicted or theoretical total penetration depth. The resulting distribution of the solid constituents for this case would become a function of the residual momentum of the cloud as well as the existing density disparity. When the residual momentum is high, a dynamic turbulent rebound effect might be expected, but for near zero momentum the density disparity would cause a spread similar in nature to that of the collapse phase. Two questions are raised regarding the solids once they reach the bottom: [1] will movement occur? and [2] if movement occurs, what form will occur - bed load or resuspension?

In general, it is accepted that motion will be initiated in a flow field when the shear stress on the particle creates a lift force in excess of the submerged weight of the particle. The direction of the initial particle movement will be nearly perpendicular to the plane of the applied shear stress and for a horizontal bed will be near vertical. This force will lift the particle off the boundary and it will resettle, subject to currents and eddies, either to a position in the flow where the resultant lift on the particle just equals its settling velocity (suspended transport), or when the settling velocity exceeds the lift force, to another position on the boundary (bed load transport). Suspended transport is most common when the current shear is nearly constant with bed load motion resulting when an additional shear resulting from turbulent eddies is superimposed.

A method is available whereby one can predict what form of transport will occur. This method assumes steady uniform flow, a logarithmic velocity profile and a linear shear stress distribution with depth. An equation which relates the settling velocity of the particle, the diffusivity of the system and the sediment concentration c is given by:

$$\frac{\partial c}{\partial z} = \frac{-\omega_s c}{K} \quad \ldots\ldots\ldots\ldots [19]$$

where $K = \rho U_* kz$ under the above assumption.

This equation can be rearranged and integrated over a region of interest with the following results:

$$\frac{c}{ca} = \left(\frac{a}{z}\right)^{\frac{-\omega_s}{U_* k}} \quad \ldots\ldots\ldots\ldots [20]$$

Defining $\frac{\omega_s}{U_* k}$ as (q) we can relate the type transport to the magnitude of this parameter. By plotting the ln $(c/_{ca})$ against the ln $(z/_{a})$ it can be seen that 1/q is the slope of the line and is descriptive of the concentration gradient.

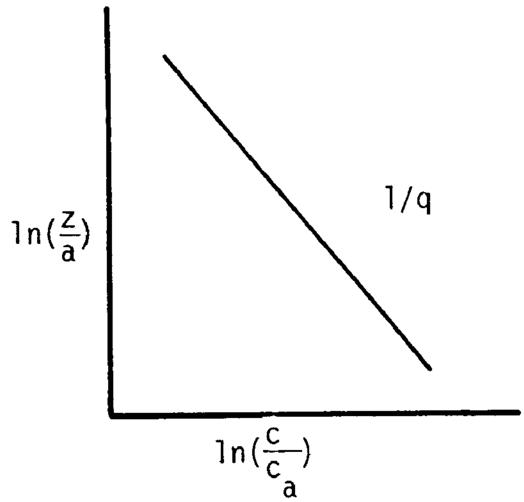


FIG. 6. Sediment Concentration Gradient Definition Sketch

When the magnitude of q is less than unity the effects of the shear stresses are always greater than the gravity effects keeping the material in suspension with what is termed wash load transport resulting. Studies have shown that when q is greater than unity but less than three suspended load transport should be expected with bed load transport predominant when q exceeds three.

To use this relationship the settling velocity of the particle must be determined and related to the existing shear velocity U_*. The shear velocity is governed by the following relationship:

$$U = \frac{U_*}{k} \ln \frac{Z}{Z_o} \qquad [21]$$

where Z equals the point of interest in the flow--measured from the bottom--, Z_0 is the depth where the assumed logarithmic profile goes to zero and k is Von Karman's constant equal to 0.4. Solving for U_* would require an iteration process if the profile is unknown. If shear stress measurements are available U_* can be determined from the following relationship:

$$T_b = \rho U_*^2 \qquad [22]$$

The settling velocity of a particle can also be determined by an iteration process using the following equations and Figure 7 which relates the coefficient of drag to Reynolds number defined using the settling velocity of the particle:

$$\omega_s = \frac{4}{3}\left[\frac{\rho_s - \rho}{\rho}\frac{gd}{C_D}\right]^{\frac{1}{2}} \qquad [23]$$

After determining both U_* and $(\omega)_s$ a direct substitution into the relationship for (q) will give a prediction of the type transport that should be expected.

Another approach can be used which compares the critical shear stress to the calculated or measured stress on the boundary. The critical shear stress is that stress that will just initiate motion for a particle of given diameter (d). This stress can be determined using Fig. 8 and the following equations where the critical shear stress T_c is given by:

$$T_c = f(R_*, \eta) = T_*(\rho_s - 1)gd \qquad [24]$$

with η given by:

$$\eta = \frac{d}{\nu}\left[(0.1)\left(\frac{\rho_s - 1}{\rho}\right)gd\right]^{\frac{1}{2}}$$

For a given U_*, η can be determined and T_* can be read directly from the graph and a simple calculation using Eq. 24 will give the critical shear stress for that combination of shear velocity and particle diameter. Comparing T_c to T_b given by Eq. 22 will reveal if motion should be expected.

These equations are admittedly simplified, and do not represent a complete literature review but within the accuracy of any of the other

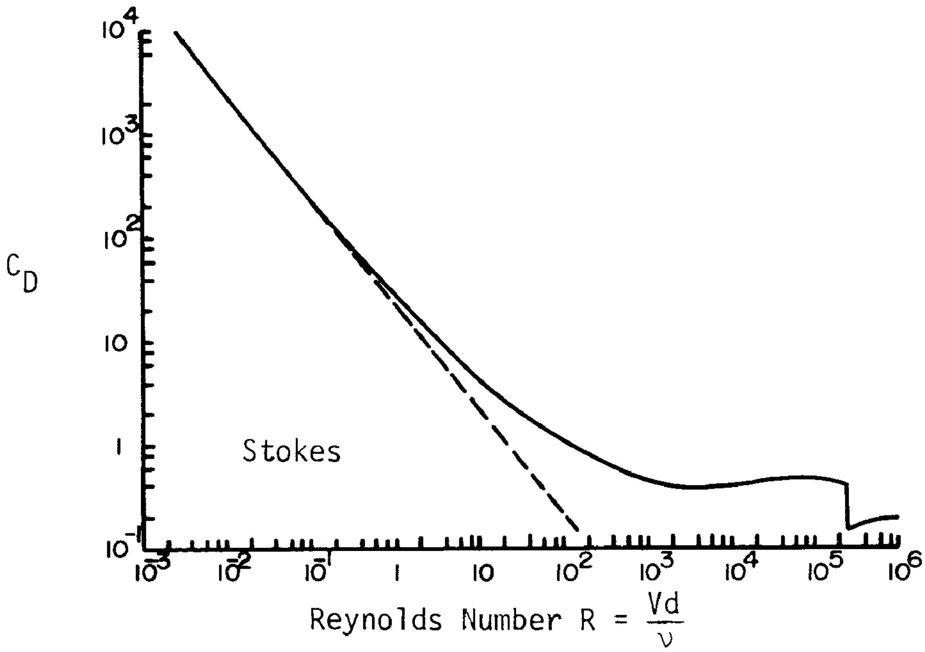


FIG. 7. Drag Coefficient for Spheres as Function of the Reynolds Number

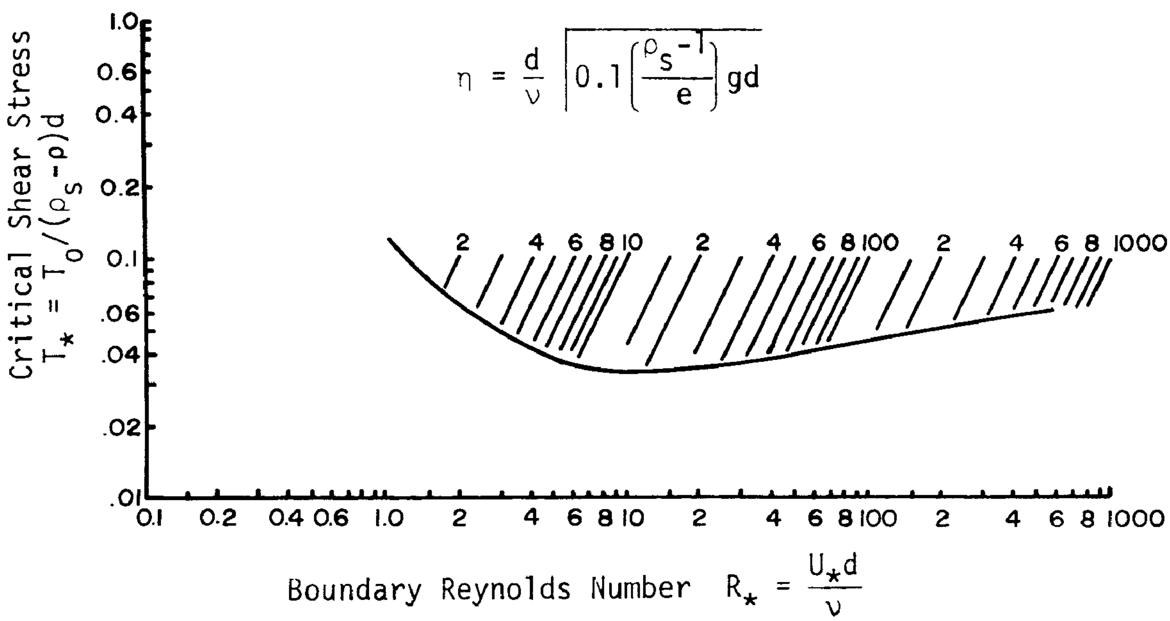


FIG. 8. Shields Diagram, as Modified by Vanoné (1964)

transport phases allows the prediction of motion as well as type transport. These predictions are subject to the several assumptions made, namely:

1. A steady uniform flow

2. A logarithmic velocity profile in lieu of actual bottom shear stress measurements.

3. A horizontal bed of uniform roughness (i.e., no dunes, growth, outcroppings, etc.)

Partheniades (66) presents a State-of-the-Art summary of the behavior of fine sediments in estuaries and documents a number of research needs in this field. The A.S.C.E. Task Force on Sedimentation (67) also presents a summary of applicable approaches and presents relationships which account for non-uniform turbulence.

Other approaches can be found in the work of Schmidt and O'Brien (68, 69), Southerlin (70), Brooks (13), Shields (71), While (72), Vanoni (73), and Anderson (74).

SECTION VI

SOLUTION TECHNIQUES

There is no single analytical method currently available that will completely and accurately predict the dispersion and dilution of a waste material discharged into the marine environment. The general nature of the approach used by Koh and Fan (2) does, however, offer a good means of analyzing these effects for surface discharges under a variety of environmental conditions. This solution technique has been programed for general use and the following section will explore hypothetical case solutions for each of the three separately defined transport phases.

Convective Descent

The convective descent phase allows the initial short term distribution of the waste to be explored for any combination of density and velocity profiles. Two separate cases will be investigated; one with a linear density gradient and the other representative of a strong pycnocline. For these conditions the penetration depth (Y_f) and the dilution (DILN) will be investigated under the existence of a two-dimensional shear flow. Discussions will be two-fold in nature; describing the procedure to be followed to use the program, while pointing out critical parameters and some of the errors inherent in simplifying assumptions commonly made.

The input requirements are listed and discussed in Appendix I complete with a sample problem. The convective descent solution gives incremental penetration depths, dilutions, X Y Z positions of the cloud center all as functions of descent time. The analysis is terminated either when the cloud has reached the bottom or where the cloud becomes neutrally buoyant and its descent is stopped. This latter case is characterized by a reversal in the direction of the cloud velocity with the analysis terminated after one complete cycle.

Discussion of Example Problem Results

A classic example is revealed in Fig. 9 where the dilution is high for high values of the initial densimetric Froude number with a characteristic curvilinear decrease with increases in the penetration depth. For example, an initial densimetric Froude number of 0.09 would tend to concentrate the material at a depth of 185 feet with a dilution of 425. Increasing the Froude number one order of magnitude would decrease the descent to 95 feet but would increase the dilution approximately eight times for a total dilution of 3400. The presence of the strong pycnocline, Fig. 10, at Froude numbers between 0.4 and 2.0 appears to significantly reduce the penetration and dilution with the waste material retained in the pycnocline. This figure also indicates two methods by which the dilution can be increased. An increase in the Froude number between 0 and 0.2 results in higher dilution and it appears that a decrease in large Froude numbers to 0.2 will allow the waste cloud to break through the pycnocline, after which the penetration and dilution rapidly increase.

These results are not descriptive of the general case, but were designed to represent a typical operational evaluation. A series of computer runs were made where the discharge radius was varied while maintaining a flow of 100 cubic feet per second (cfs). This limiting criterion in effect establishes a unique relationship between the radius of the discharge and the initial densimetric Froude number. Two sets of environmental parameters were employed; the first descriptive of the linear density profile, and second, a strong pycnocline. The penetration depth and the resulting dilution were then compared against the initial densimetric Froude number.

Figure 9 for the linear gradient exhibits low penetration and high dilution for Froude numbers of order 10, which, for this example, correspond to a small diameter discharge. This result is predictable if one considers that the entrainment is high and, when applied to a small waste volume, dilution proceeds rapidly and buoyant equilibrium is attained at a shallow depth. The same argument applied at the other end of the scale where the discharge velocity is low, and the radius is large, would predict a slower rate of dilution and a greater penetration, again as shown by Figure 9.

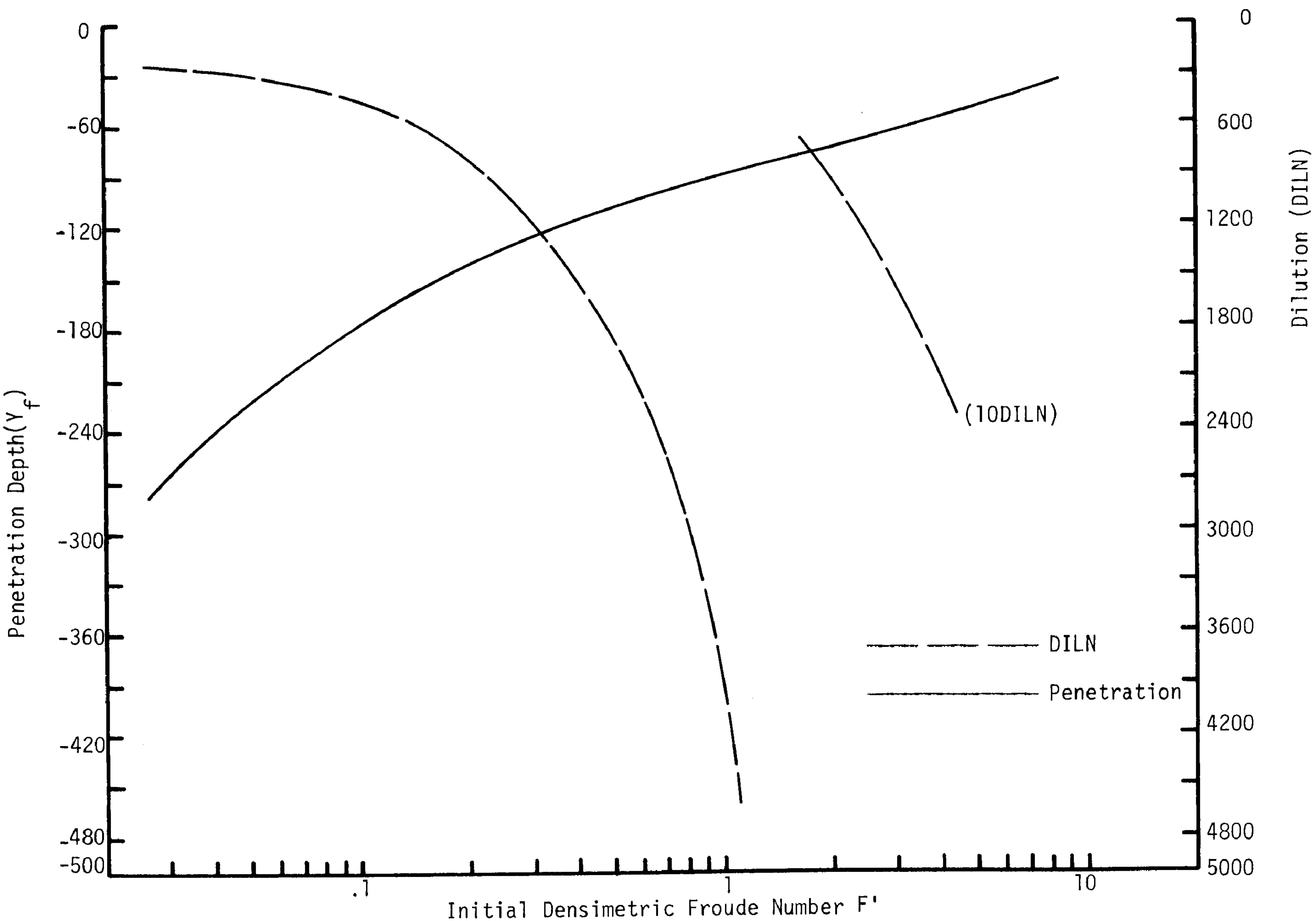


FIG. 9. Penetration Depth and Dilution as Functions of the Initial Densimetric Froude Number under Linear Density Gradient ($E = 1.17 \times 10^{-5}$/ft)

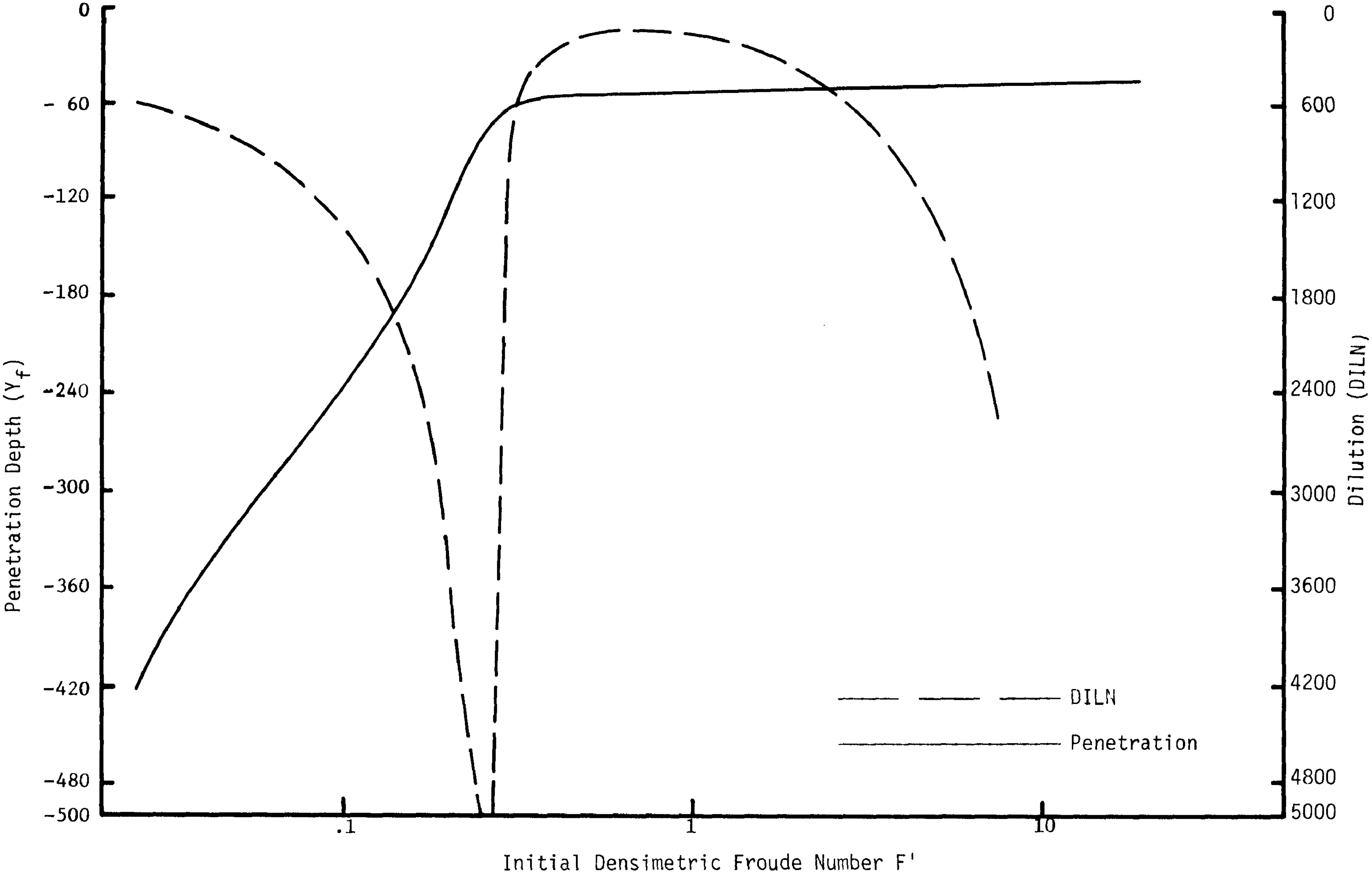


FIG. 10. **Penetration Depth and Dilution as** Functions of the Initial Densimetric Froude Number under a Strong Pycnocline

When the density profile is complicated through the inclusion of a pycnocline, the results take on a different form. For Froude numbers of order 10, the same trend seen for the linear case exists (Fig. 10) with the cloud's descent terminated above the level of the pycnocline and its existence is really of no importance. At the low end of the Froude number scale (F 0.1) entrainment is also reduced and in essence the descent is governed by the linear gradient that exists below the pycnocline. The major difference occurs in the intermediate Froude number range, where entrainment and waste volume are sufficiently interrelated for the cloud to obtain buoyant equilibrium in the pycnocline, but, driven by a high momentum, is carried beyond this position, with both the velocity and the buoyancy becoming positive. The subsequent dilution and ascent are relatively rapid, with the oscillations damped almost immediately.

The sudden shift or increase in dilution that occurs in Figure 10 for Froude numbers of approximately 0.2 results when a cloud has insufficient positive buoyancy to reenter the pycnocline and remains subject to the nearly uniform gradient below. A long period oscillation is developed which results in the rapid increase of the time required for this cloud to reach a stable position (from five minutes to twenty minutes) with an obvious increase in the dilution.

Comparing the results of the two examples reveals that using a linear assumption where, in fact, a pycnocline exists would result in a general overestimage in both the depth of penetration and the dilution. This conclusion is valid only under the previously described conditions; however, generalized plots can be made and presented in a manner similar to that shown in Figures 2 and 3.

The penetration depths as predicted by the various methods discussed in the previous chapters are compared in Fig. 11. Curves 1 and 2

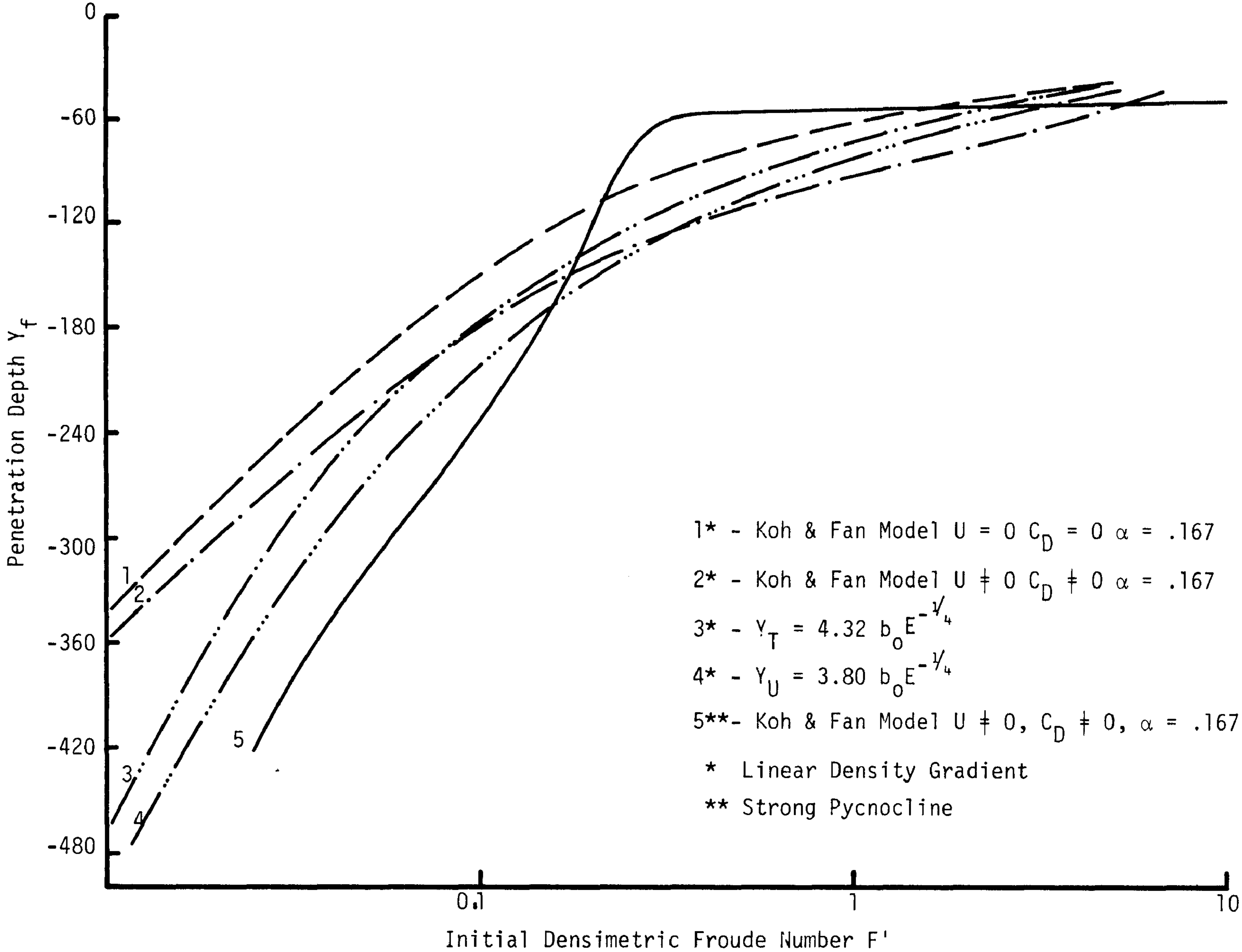


FIG. 11. Comparison of Reported Methods of Predicting Penetration Depths

utilize the same basic equation, however in case 2 the relative effects of introducing cloud drag and current generated shear are responsible for the net differences. The penetration depths for all methods, over the full range of Froude numbers tested, varied a maximum of only fifty percent compared to a variance in dilution which at times exceeded 800 percent. For this reason alone it would seem that dilution, as well as penetration should be given consideration in all predictive convective descent models. The predictive nature of Morton's approach is such that, on the basis of penetration alone, it could be erroneously interpreted as a conservative model over the full range of environmental conditions that might exist.

The penetration depth (Y_f) and the dilution (DILN) have been shown to be conditionally related to the initial densimetric Froude number. Changes in the magnitude of the Froude number can be effected by altering the magnitude of the velocity, the diameter, or the method of the discharge or by modifying physical waste and discharge characteristics. With the exception of the waste specific gravity, physical modification will directly affect only the initial dispersion that occurs during the convective descent stage. Once a cloud attains buoyant equilibrium within the water column or reaches bottom, the subsequent dispersion is entirely dependent on its relationship to the natural environment conditions that exist. This in essence means that any control over the long term dispersion must be exercised during the discharge process in such a way as to alter its convective descent.

Waste Characteristics:

The waste characteristics are infinitely variable; however, in analyzing the initial distribution, only the physical characteristics need be considered. The bulk specific gravity of a waste slurry is one characteristic that, within physical limitations, can be controlled. Changes in the specific gravity of a waste slurry or sludge, whether through the use of a thickening process or through the use of additives, can affect both the resulting dilution and penetration. Such changes may result in changes in either the concentration, density or size of the solid constituents or any combination of the three. The effects of solids on diffusion in fully developed turbulent liquid flows has been investigated by Katta and Hanratti (75), Rouse (76), Vanoni (77), Householder and Goldschmidt (78-79), Singamsetti (80), McNown and Lin (81), and by Ahmadi and Goldschmidt (82). From these studies it is generally concluded that suspensions with grain sizes less than 60 microns can be assumed to act as pure liquids. Inter-relating effects are shown between such parameters as settling velocity and particle concentration with an increase in particle concentration increasing the diffusion while causing a decrease in the settling velocities of the particles.

From data presented by Ahmadi and Goldschmidt (82) the turbulent Schmidt number can be calculated independently of concentration. Such calculations for typical values for dredge spoils and sewage sludges reveal ratios of mass to momentum transport that vary between 1.0 and 1.1, indicating that the motion of the solids is not significantly different from that of the liquid phase. Such analyses provide the justification needed for a pure liquid assumption in waste dispersion studies, and, when made, reduce to one the number of physical characteristics of the waste that must be known; namely the specific gravity.

The approximate specific gravity of waste sludges or slurries can be determined from a knowledge of the percentage of solids and volatile matter or the percent moisture alone when the solid concentration is high. Equations 25 and 26 after Fair and Geyer (83) are commonly used for this purpose.

$$S = \frac{100 S_S\ S_W}{P\ S_S + (100-P)\ S_W} \qquad [25]$$

$$S_S = 100\ S_f\ S_v / 100\ S_v + P_v (S_f - S_v) \qquad [26]$$

where:

S = Specific gravity of waste

S_S= Specific gravity of waste solids

S_W= Specific gravity of water in waste mixture

S_f= Specific gravity of fixed solids (2.5)

S_v= Specific gravity of volatile solids (1.0)

P = Percent moisture by wt.

P_v= Percent volatile matter in sludge

Physical modifications:

Several other controls are available and are of a physical nature. Included among these are the depth, size, and orientation of the discharge outlet, as well as the barge speed and direction, which can be used to influence and control the final distribution to some degree. However, the optimum discharge method must be separately determined for each waste and should include consideration of possible biological and chemical effects. The general influence of changes in density, discharge radius and velocity on penetration and dilution can be evaluated in terms of the changes in the densimetric Froude number. The Froude number can be shown to vary as b_0, the initial cloud radius, to the minus two-thirds power, and directly with the discharge velocity. These relationships are not generally independent and a change in one of the parameters without a compensating change in the discharge rate will necessitate the use of a continuity relationship.

Pump discharges into the wakes of propeller streams of barges cannot be analyzed by the Koh technique and must be handled separately, and in such a manner that the increased turbulence created by the passage of the barge is accounted for. These discharges are usually employed when the waste is toxic, taking advantage of the increased turbulence to maximize the rate of dilution.

If this method of discharge is considered for cases where stable density stratification occurs, the liquid slurry may not settle directly to the bottom upon discharge. This action can then be described in terms of three separate flow regimes as shown in Figure 12.

The longitudinal dimensions of Zone 1 can be assumed to coincide with that distance behind a barge (X') where a fully turbulent wake is established. Schlichting (85) states that this is reached, for a cylindrical object, when the following relationship is realized:

$$X' = 50\ C_D W \qquad [27]$$

where W = barge width and

C_D = drag coefficient

Redfield (86), Ketchum and Ford (87) and Hood (30) have analyzed the discharge of wastes into the wakes of moving barges where mixing was observed to be instantaneous in the vertical direction. Thus, by neglecting vertical dispersion, and transverse dispersion when the barge travel and the ambient currents are along the same axis, the problem becomes one dimensional. With such a simplification the solution in the established flow zone becomes one of two variables--the turbulent diffusivity and the discharge rate.

Equation 12, the basic diffusion equation, applied to the dispersion of a waste in a barge wake has been solved by Ketchum and Ford (87) and Pearson, Storrs and Selleck (88) with the respective solutions describing the median and average concentrations per unit cross section along the centerline of the wake. Both solution equations are identical:

$$c_i = \frac{c_o A_i q}{h U_b (K_x t)^{\frac{1}{2}}} \qquad [28]$$

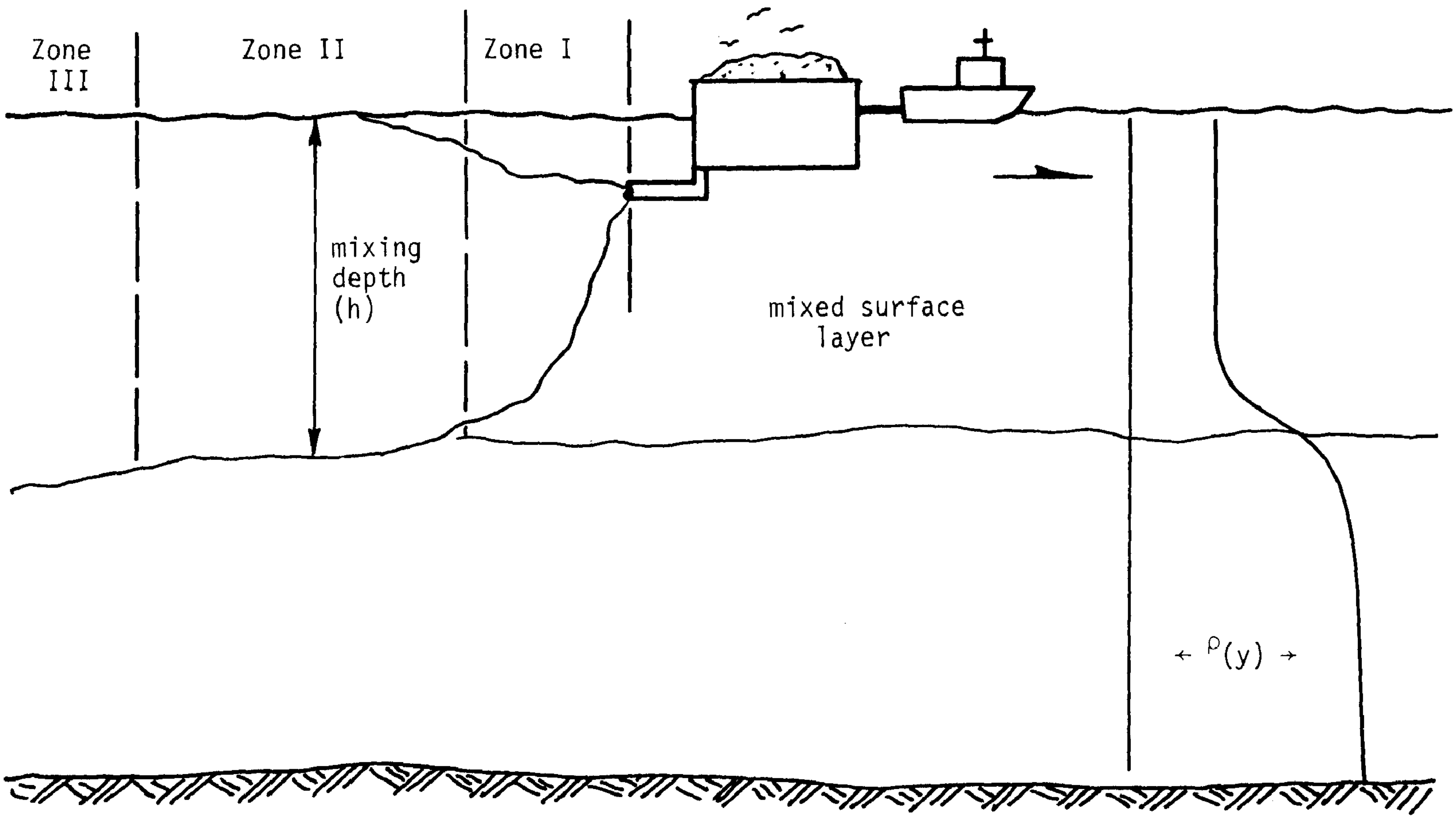


FIG. 12. Schematic Presentation of Fate of Material when Discharged in Barge Wake

where A_i = 0.493 describes the median concentration and A_i = 0.282 the average concentration. The other terms in the equation are:

q = volumetric discharge per unit time $[L^3/T]$

h = mixing depth [L]

U_b = barge speed [L/T]

K_x = turbulent diffusion coefficient for combined system $[L^2/T]$

T = the length of time since the barge has passed the point of interest [T]

c_o = initial concentration of the discharge

Turbulent eddy diffusion coefficients in wakes have been shown, through field determinations (87, 86), to vary between 1.0 ft^2/sec and 30.0 ft^2/sec and should be expected to fluctuate.

Schlichting (85) equates the wake diffusion coefficient to the wake centerline velocity and the defined half width of the barge as follows:

$$K_x = 0.0235\ U_{C_L}\ (X'C_DW)^{\frac{1}{2}} \qquad [29]$$

The turbulence is known to decrease over the length of the wake. This relationship is contained in the above equation since the velocity decreases as the length of the wake to the minus two-thirds power. The wake turbulence in a practical sense, has a lower limit equal to the natural turbulence of the ambient environment. Pearson et al., (88) used the water depth as the length scale (L) and determined a constant average diffusion coefficient as defined by the following relationship:

$$K_x = A_{(\ell)}{}^{L^{4/3}} \qquad [30]$$

The mixing depth (h), the last unknown, is a difficult parameter to determine. Omission of this term from Eq. 28 would result in a description of the concentration per unit cross section of a water column of unknown depth. This form of the equation was the one used by Ketchum and Ford (87) in analyzing the concentration of an iron waste discharged to the wake of a barge.

Results of full scale experiments where a waste was discharged into the propeller stream of a ship are given in a recent report by Abraham and Eysink (84) which discusses the applicability of jet theory to this method of discharge and concludes that the minimum dilution can be determined using jet theory calculations.

When the results of the convective descent stage analysis indicate a situation where the cloud comes to rest at some equilibrium position in the water column, both collapse and long term dispersion must be considered. These are sequential analyses with the output of the collapse phase serving as the initial conditions for long term dispersion. The only method for the analysis of the collapse phase appears to be the one presented by Koh and Fan (2) which is at present hypothetical.

The collapsed dimensions of the cloud can be determined for the case where the constants C_1 and C_2 are assumed near unity and K_1 is assigned a value of 0.10. The initial shape of the waste cloud must be assumed an axisymmetrical ellipsoid with the major horizontal radius (b_0) equal to the predicted cloud radius at the end of the convective descent stage and the minor radius (a_0) defined as (bo/2). The approach is limited by a requirement that the density gradient be linear over the depth of the cloud which precludes its use in cases where the cloud collapse transcends a pycnocline. Conceding this deficiency and choosing a proper set of initial conditions, the cloud dimensions can be determined for the case of a complete collapse.

For the purpose of isolating the effects of a collapse phase on the long term dispersion of a waste, fixed value results for a convective descent stage definitive of a set of intial discharge conditions were chosen where:

B_f = radius at end of convective descent state = 66 feet

Y_f = 159 feet

$E = 1.17$ ft x 10^{-5}/ft.

For these values the initial collapse phase dimensions are b_o = 66 ft, and a minor radius a_o = 33 feet. The collapsed dimensions can be determined directly from Fig. 5 and for this example were taken as:

$$b_f = 264 \text{ feet} \quad a_f = a_o \left(\frac{b_o}{b_f}\right)^2 = 2.06 \text{ feet}$$

The time for this collapse to reach completion was determined as 568 sec.

The question, now, is: What is the effect of such a collapse on the long term dispersion solutions as predicted by this analytical technique?

It was decided to explore these effects for two sets of environmental conditions: Case I investigates the effects of cloud collapse under environmental conditions consistent with a linear density profile and Case II investigates the same cloud effects for parameters descriptive of a strong pycnocline in which vertical transport is suppressed.

The use of this analytical technique requires that the initial distribution of the waste be assumed axisymmetric about the Y axis and confined in an ellipsoidal region with a horizontal distribution of material defined by:

$$C(y_i,0) = (1 - \delta^2 y^2)^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [32]$$

where δ is a dimensionless ratio of the depth of the cloud to its half thickness. The horizontal diffusion coefficients are assumed to follow a 4/3 law relationship and have been defined in terms of the geometric mean of the standard deviations along the principal axes as:

$$K_x = K_z = A(\sigma_x{}^2\sigma_z{}^2 - \sigma_{xz}{}^4)^{1/3} \quad \text{[33]}$$

The standard deviations of the distributions σ_x and σ_z in the above equation are taken as equal to 1/4 the size of the cloud as shown in Appendix II. The coefficient A will be taken to be constant over the depth of the cloud but the solution does permit this to be varied if desired. This coefficient can be determined by considering the 4/3 law governing horizontal diffusion where:

$$K_x;K_z = A_\ell L^{4/3} \quad \text{[34]}$$

$A_{(\ell)}$ is a constant dissipation parameter and (L) is a length scale. For the problem at hand (L) is taken equal to the length of the cloud which is related to the standard deviation of the distribution by:

$$L_c = 4\sigma_x \quad \text{[35]}$$

Substituting we have

$$K_x = A_\ell\ (4\sigma_x)^{4/3} = A\sigma_x{}^{4/3}$$

Where $A = 6.34\ A_{(\ell)}$

The choice of a value for $A_{(\ell)}$ was taken for this example as $1.5\text{x}10^{-4}$ $ft^{2/3}$/sec which makes A equal to 0.001 $ft^{2/3}$/sec the quantity which will be used for this example. The vertical diffusion coefficient K_y, as used in this analysis, must be determined and related to the existing density structure. These coefficients are, in general, smaller than those for horizontal diffusion with the magnitude decreasing with depth to near molecular values in pycnoclines.

There is no apparent universal law or value for K_y but a functional relationship can be shown between vertical transport and the Richardson number (89) which implies a dependence on one or all of the following parameters: density gradient, current generated shear and the type of flow. Reported values for K_y range from 1.075×10^{-5} to 3.215×10^{-3} ft^2/sec with expected variances from flow or density changes. Koh and Fan (2) have presented estimated coefficient ranges for several areas of interest:

K_y.................Mixed layer 2.2×10^{-2} to 2.2×10^{-1} ....ft^2/sec

K_y.................Pycnocline 1.1×10^{-3} to 1.1×10^{-5} ....ft^2/sec

K_y.................Deep layer 1.1×10^{-2} to 1.1×10^{-4} ....ft^2/sec

These are suggested values based on limited past information. For the example problem being considered here a vertical diffusion coefficient equal to 0.1 ft^2/sec will be used for the mixed layer, 1.0×10^{-5} for a strong pycnocline and 1.0×10^{-4} for deep layers.

The output from this analysis describes the concentration distribution in terms of the initial concentration at the beginning of the phase and a normalized elapsed time. The X, Y size of the contaminated area, the X, Y, Z position of the concentration centroids and the distribution of concentration with depth can also be determined. These allow predictions for both the concentration and the environmental exposure time to be made thus aiding in the development of field sampling and monitoring procedures and techniques. The results subsequently presented assume an initial concentration at time zero equal to unity and the cloud at a real depth of

159 feet assigned an X, Y, Z position of (0,0,0). The analyses is terminated when a diffusion time equal to that required for the material to diffuse to surface under a constant vertical diffusion coefficient is reached.

The basic problem being considered here is limited to only the collapse and long-term dispersion phases. For an arbitrarily selected set of initial conditions four individual sets of solutions are being sought. These solutions compare the results for a cloud that exhibits no collapse to one that completely collapses under two sets of environmental conditions. These effects can best be compared through an examination of the magnitude of various parameters such as the maximum surface concentration, the maximum concentration or the location of the cloud or concentration centroid. These same parameters can also be compared on a time base. Such comparisons have been made for the example considered with the real value results given in Table 5 and Figures 13 through 16. By using both the figures and the table trends should be identifiable and observed deviations relatable to either a cloud collapse or a change in environmental conditions. The effects of a cloud collapse does represent the two extremes possible and can be considered a measure of the confidence one can afford any individual prediction.

Discussion of Example Problem Results

Figure 14 relates the maximum concentration to exposure time. Inclusion of either a collapse mechanism or a pycnocline or both acts to decrease the rate at which this dilution occurs thus increasing the exposure time for any given concentration. For example, if the time required for the maximum concentration to reach 1/1000th of the concentration at t=0 the graph can be used to predict 30 hours for the uncollapsed linear case and 100 hours for the collapsed cloud in the pycnocline.

The surface concentration-exposure time relation is given in Figure 13 and reveals that a linear uncollapsed cloud reaches its maximum value in 8.5 hours. If this cloud is collapsed and subjected to the same analysis

TABLE 5

Example Problem Results

Parameter	Linear Gradient No Collapse	Linear Gradient Complete Collapse	Pycnocline No Collapse	Pycnocline Complete Collapse
C_s (Max)	6.2×10^{-4}	3×10^{-6}	1.5×10^{-7}	0
T @ C_s max	7	70	25	70
L_x @ C_s max	940	27,400	3200	-
C_{Ex} @ C_s max	3420	21,600	1900	-
C_{max} at T=70 hrs	1.0×10^{-4}	6.5×10^{-4}	3.7×10^{-4}	4.42×10^{-3}
L_x @ $C_{max\ 70}$	31,400	20,600	15,400	12,500
C_{Cx} @ $C_{max\ 70}$	5,300	440	6,400	386
C_s @ T=70	2.5×10^{-5}	3.0×10^{-6}	7.8×10^{-8}	0
$L_{x(s)}$ @ T=70	22,200	27,400	12,700	0
$C_{Ex(s)}$ @ T=70	32,500	21,500	34,000	-

C_s = Maximum Surface Concentration

L_x = X Dimension of Cloud (ft)

C_{Ex} = X Centroid Location of Concentration Distribution (ft)

T = Time in hours

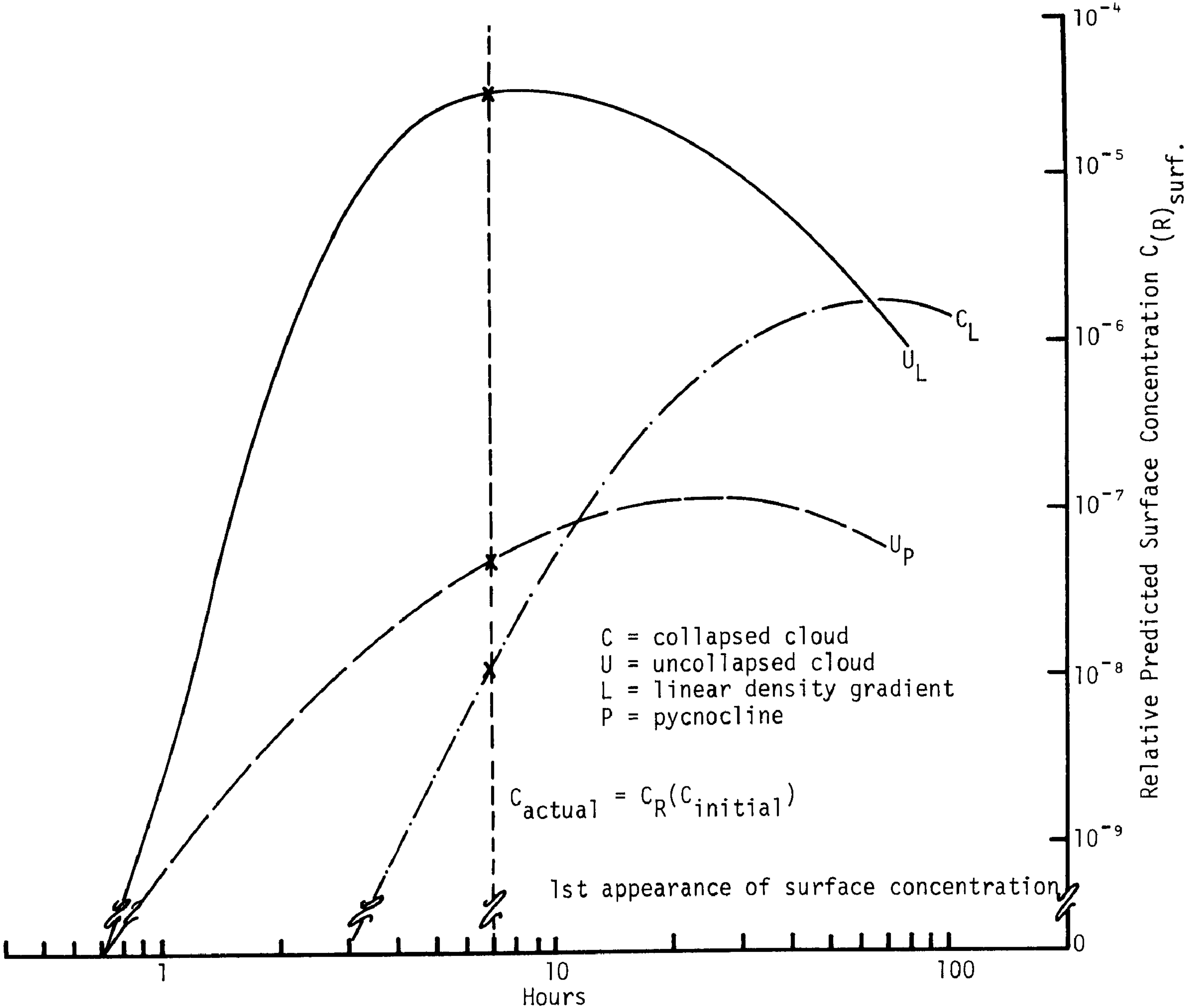


FIG. 13. Predicted Relative Surface Concentrations for Long-term Dispersion Phase

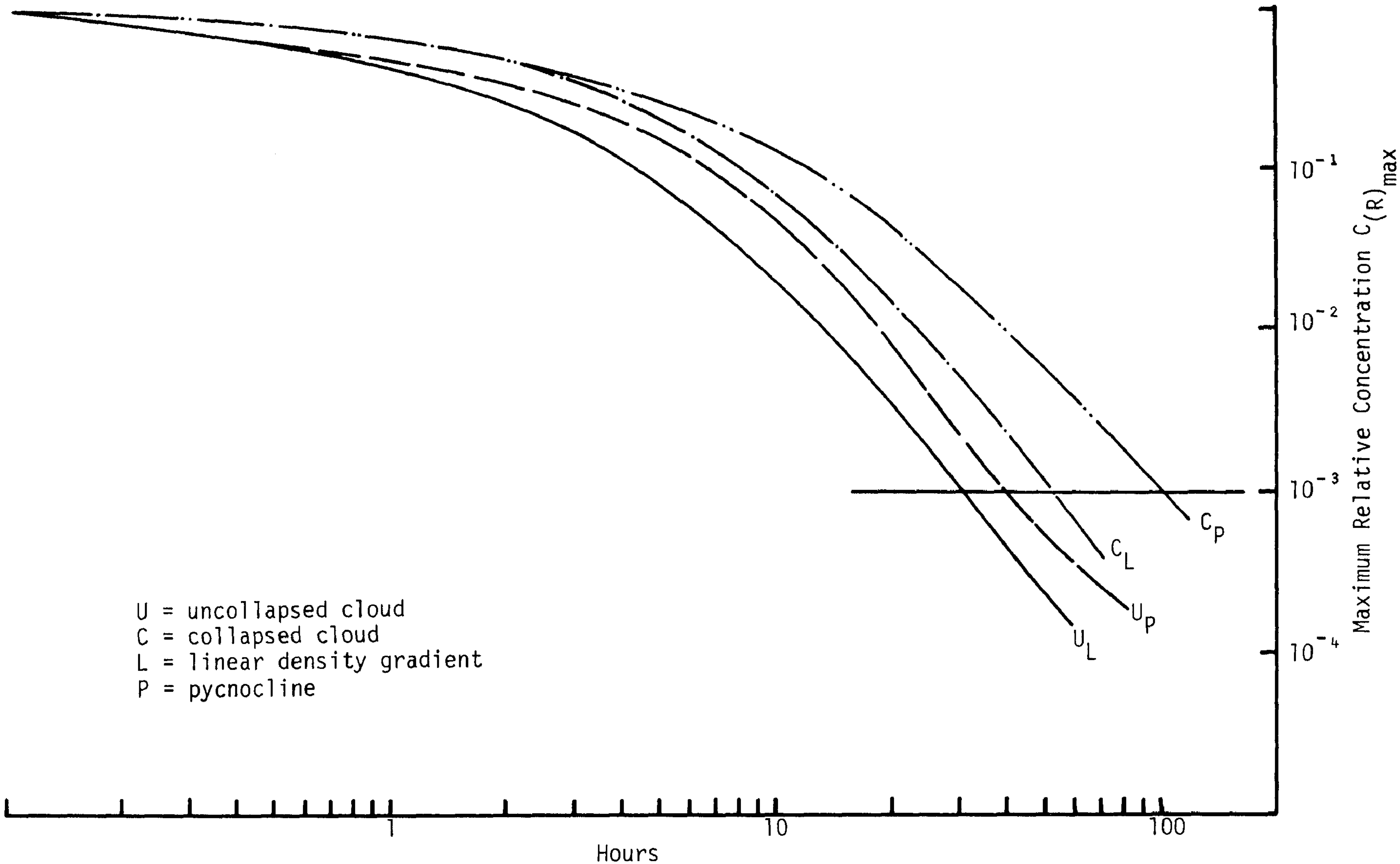


FIG. 14. Maximum Predicted Concentration for Long-term Dispersion Stage

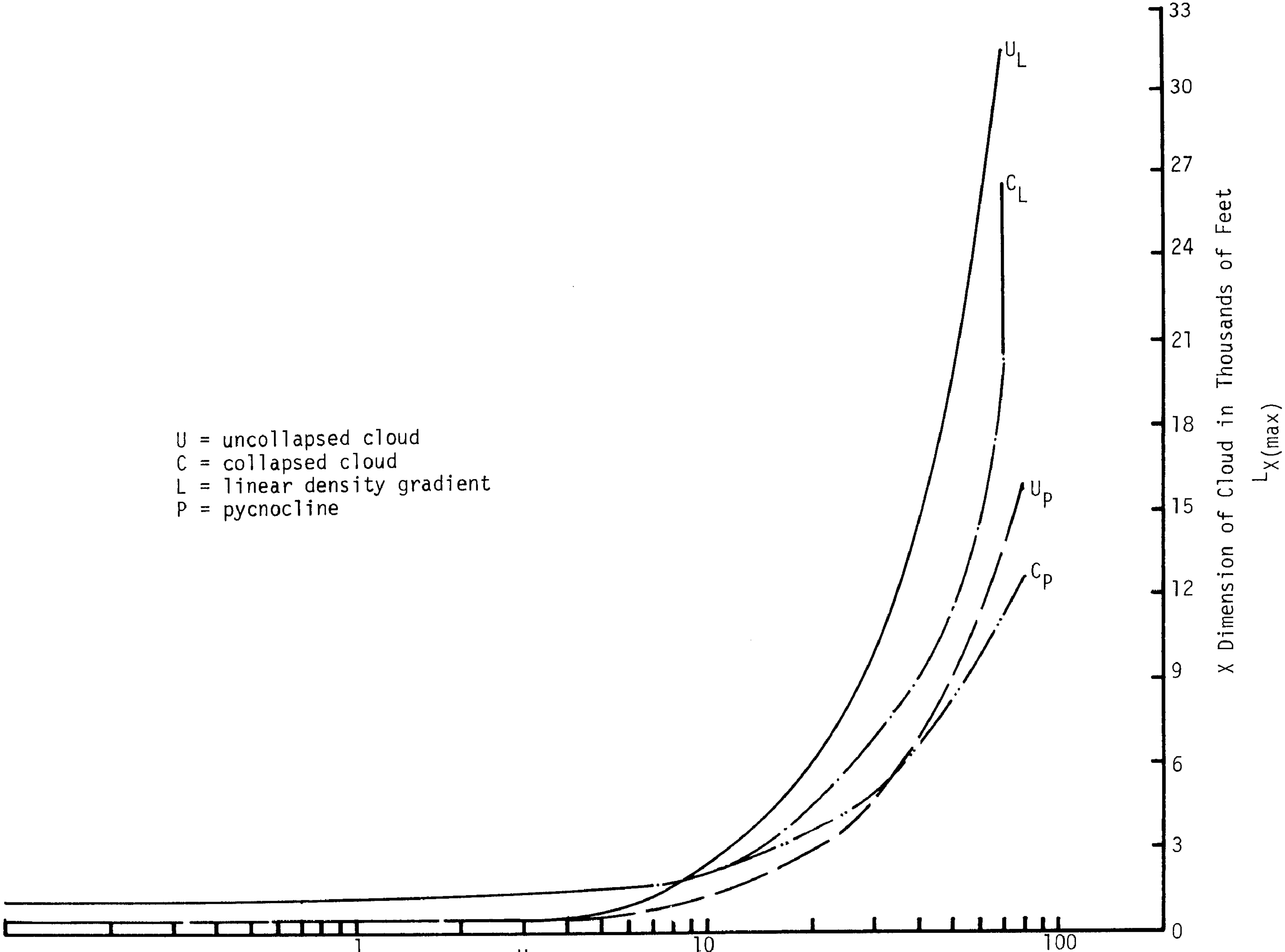


FIG. 15. Predicted X Dimension of Cloud at Level of Maximum Concentration

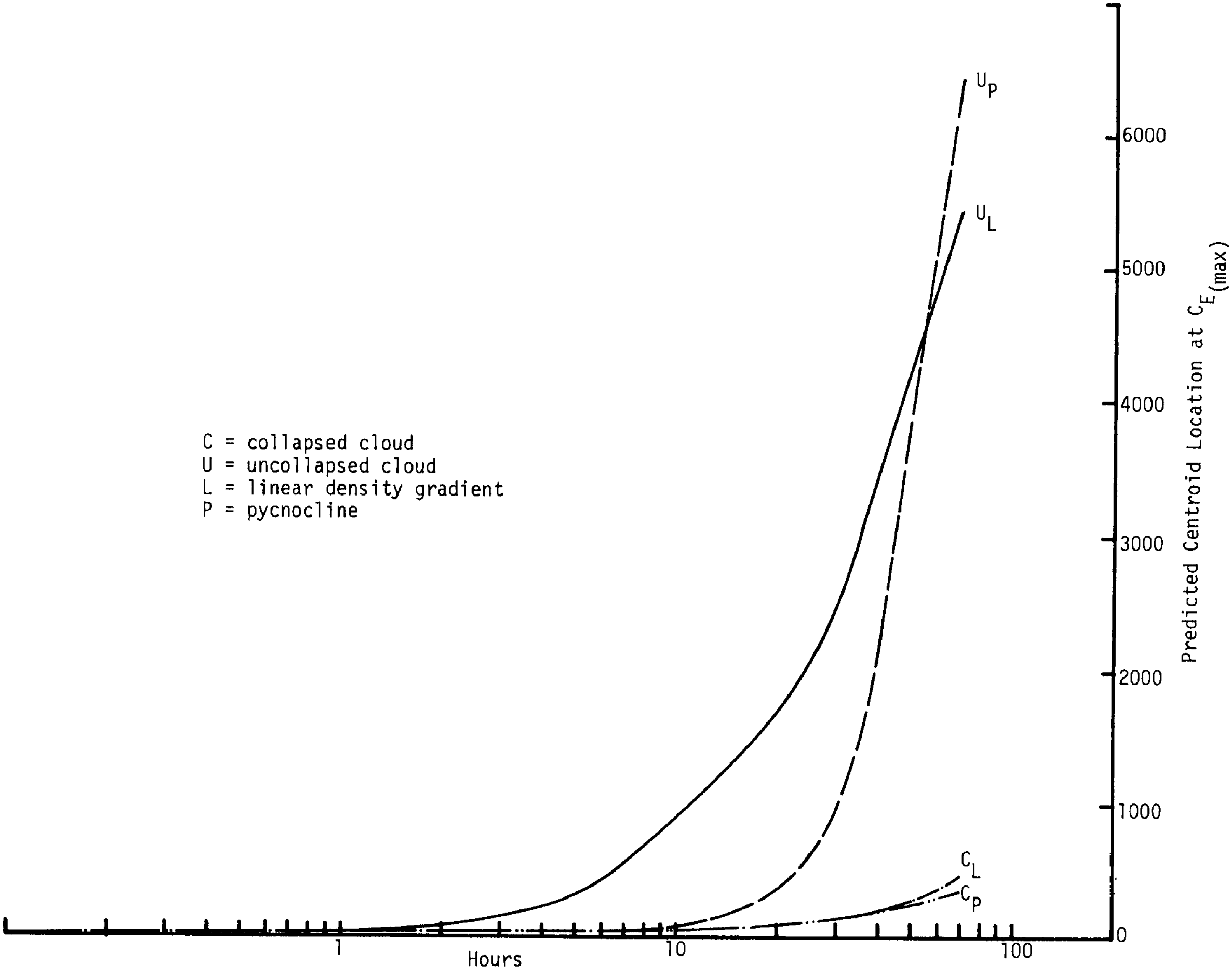


FIG. 16. Predicted Relative Concentration Centroid Location at Level of Maximum Concentration

the time of maximum surface concentration is increased to 70 hours with a resulting reduction in the magnitude of this maximum concentration. The collapsed cloud for the pycnocline case never reaches the surface. The uncollapsed pycnocline cloud does, however, reach the surface at approximately 35 hours but with a much reduced concentration when referenced to the uncollapsed linear case.

The restrictive nature of the pycnocline essentially appears to trap the contaminants and prevent the majority from ever reaching the surface. The maximum concentration for the collapsed cloud in the pycnocline occurred at a depth of approximately 80 feet and reached a maximum of 8.9×10^{-10} at 35 hours decreasing approximately 1/3 in the following 35 hours, thus indicating that for that particular example the surface would have been essentially free of contamination for all time barring any great changes in the boundary or environmental conditions.

The maximum concentration centroid locations (Fig. 16) for the collapsed clouds are found to be relatively stable moving a maximum distance of only 440 feet compared to a 5-6000 foot movement associated with the uncollapsed clouds. The surface concentration centroids follow the same general trend with the centroid locations after 70 hours having moved 6 miles for the uncollapsed clouds and closer to 4 miles for the collapsed cases. These values are both for the case of a linear gradient and therefore represent a different set of extremes, this is necessary because of the failure of the collapsed thermocline case to penetrate the thermocline and reach the surface.

Only one representative cloud dimension is examined and that is L_X the cloud length in the direction of the flow (see Fig. 15). The trend here follows that seen for the maximum concentration-exposure time curves with the cloud length at t=70 hours decreased for either the inclusion of a collapse mechanism or a pycnocline or both. If the conservation of mass is considered, where:

$L = f\ (M/C)$ M = Mass C = Concentration L = Length

This trend can be explained where as shown in Fig. 13 (t=70 hours), the concentration increases with both the inclusion of a collapse mechanism or a pycnocline or both. This relationship applied to the above equation predicts the same trend as was found for the cloud dimensions.

The cloud dimensions are directly determinable only for X, Z directions as the analysis, in its present form, gives only the concentration distribution over two non-rigid boundaries and does not include buildups associated with the cloud reaching the bottom of the surface.

The distributions of concentration with depth at t=70 hours are shown in Fig. 17 for all the cases considered. From this figure the wide variance in surface concentration can readily be realized as well as the variety of profiles that must be considered when these concentrations are being sampled for in the field. This figure probably best typifies the problem at hand and allows a generalization that shows collapse to flatten this vertical distribution. It can also be concluded that the collapse mechanism represents a phenomenon as powerful in its effect on some parameters as the inclusion of the pycnocline over a linear gradient. It is perhaps appropriate here to point out that while the linear uncollapsed cloud distribution appears to overestimate the resulting concentrations it underestimates the possible exposure times by a factor of three. This should not be overlooked as the effects evidenced in marine plants and organisms are dependent on a combination of the two.

A need is clear for research on the collapse mechanisms and the forces which drive it. Emphasis should be placed on the possible entrainment and dilution that may occur during this phase and on the effect of particle settling and its influence on the internal density structure of the cloud.

The deviations that may occur from the neglect of cloud collapse have been shown by this analysis to result in predictions which describe:

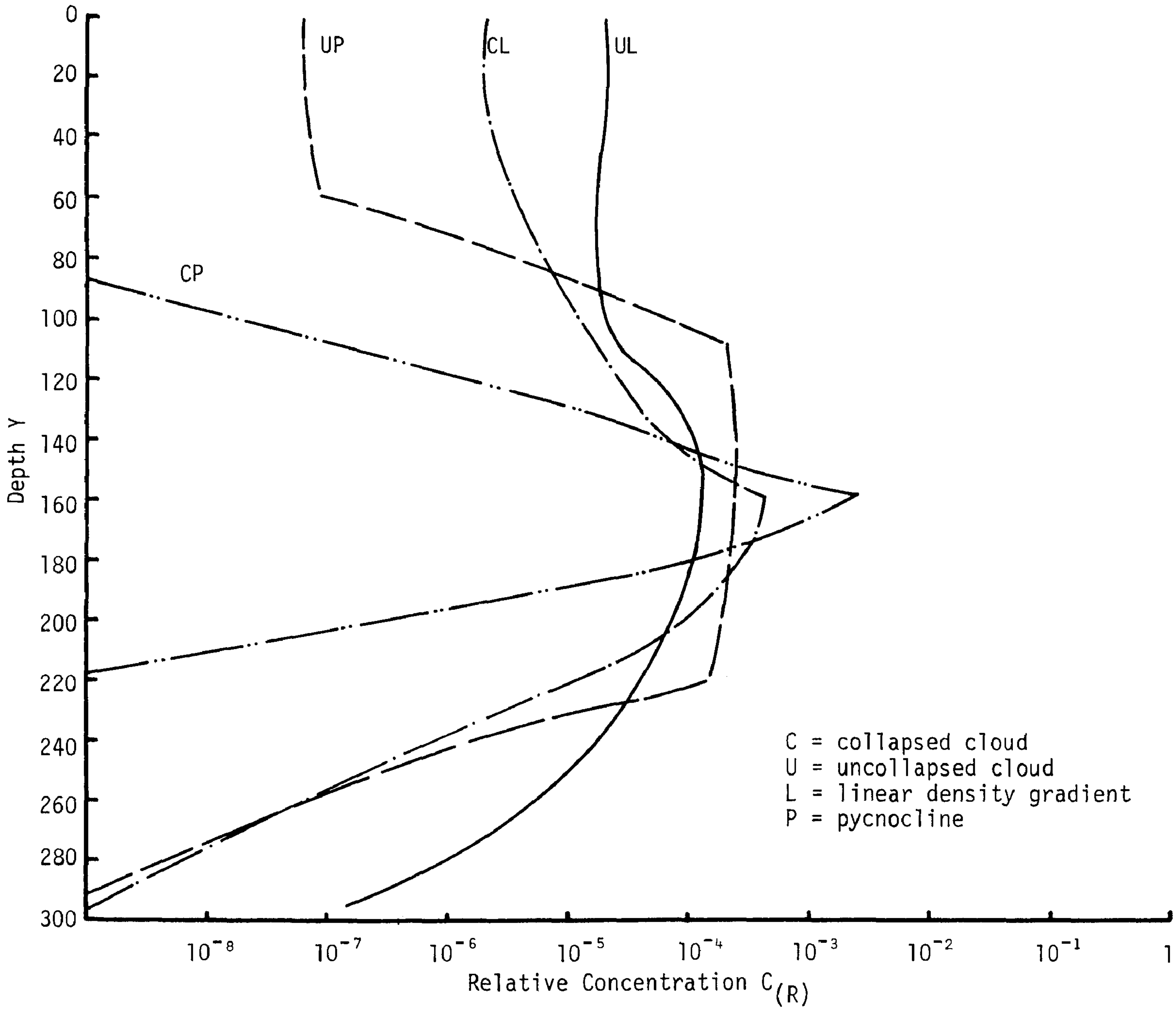


FIG. 17. Concentration Distribution with Depth at T = 70 hours

1. Higher surface concentrations

2. Smaller contaminated surface areas

3. Shorter times to the realization of maximum surface contamination

4. Faster dilution rates for the maximum concentration

5. Larger areas over which the maximum concentration is distributed

For these reasons, the only course of action open at this time is to conduct analyses that assume both cloud stability and collapse providing the maximum and minimum conditions expected. These values are, of course, influenced by the no entrainment collapse mechanism presented herein.

SECTION VII

BARGE CHARACTERISTICS

Wastes are discharged from barges either in bulk or containerized form. Containerized methods have been used for toxic, radioactive, and a variety of industrial wastes as well as the more notorious surplus poisonous war gases. Generally the most popular waste container is the 55-gallon steel drum which can be carried to the site and simply dropped overboard. Reclaimed drums have an expected life of 10 years (90), but this can be extended by filling with a concrete mixture containing the contaminants. Scientists have indicated that the voids in the concrete may result in implosion of the drum and fracture may occur at depths between 100 and 1000 meters.

Two types of barges, towed or self-propelled, employing either pumped or gravity discharges are usually used for bulk disposal. Until recently the self-propelled barge had been limited to the hopper dredge, however, the "Glen Avon," an automated sewage disposal vessel was recently purchased by the city of Bristol, England. It has the following features (91):

1. 900 ton load capacity

2. Maximum speed of 12 knots

3. Discharge time of 15 minutes

4. Low pressure air-gravity discharge system

These characteristics may be compared with those of the Hopper Dredge (Table 6) which operates in the following manner. During the dredging process the bottom material is pumped in a diluted state into hoppers

TABLE 6

SPECIFICATIONS OF CORPS OF ENGINEER'S HOPPER DREDGES*

Name	Length, beam, and depth	Maximum hopper capacity	Maximum draft loaded	Dredge pumps		
				Number	Size	Horsepower
	Feet	Cu. yd.	Ft. in.		Inches	
Essayons ...	525x72x40	8,270	31-0	2	32	1,850
Goethals ...	476x68x36	6,442	29-0	2	30	1,300
Biddle ...	352x60x30	3.060	24-3 3/4	2	28	1,150
Comber ...	352x60x30	3,422	24-3 3/4	2	28	1,150
Gerig ...	352x60x30	3,060	24-3 3/4	2	28	1,150
Langfit ...	352x60x30	3,060	24-3 3/4	2	28	1,150
Harding ...	308x56x30	2,682	20-3	2	20	650
Markham ...	339x62x28	2,681	20-0	2	23	[2]650
Mackenzie...	268x46x22	1,656	21-0	1	26	900
Hains ...	216x40x15	885	13-0	1	20	410
Hoffman ...	216x40x15	920	13-0	1	20	410
Hyde ...	216x40x15	720	13-0	1	20	410
Lyman ...	216x40x15	920	13-0	1	20	410
Davison ...	216x40x15	720	13-0	1	20	410
Pacific ...	180x38x14	500	11-3	1	18	340

* Reference (92)

equipped with overflows. The hoppers can be emptied in 3-15 minutes dependent upon the volume and nature of the material. Generally, relatively fluid materials are dumped quickly whereas sticky clays and certain granular materials may require the washing of the hoppers with large volumes of water, a process known as monitoring.

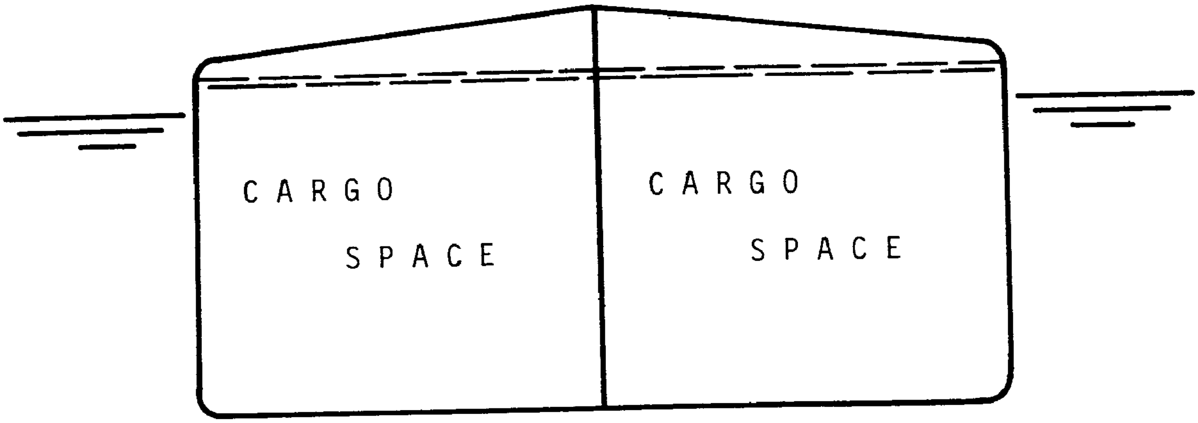
Towed barges are by far the most numerous and are quite variable in characteristics. They range from the simple bottom release mud scow used in small dredging operations to specially designed, automated tank barges for sewage and industrial sludges, toxic liquids and gases, and pressurized liquids. Creeman, (93) in a discussion of the loading, unloading and transport of tank barges illustrates three basic configurations (Fig. 18):

(a) single skin
(b) double skin
(c) double skin with independent containment vessel

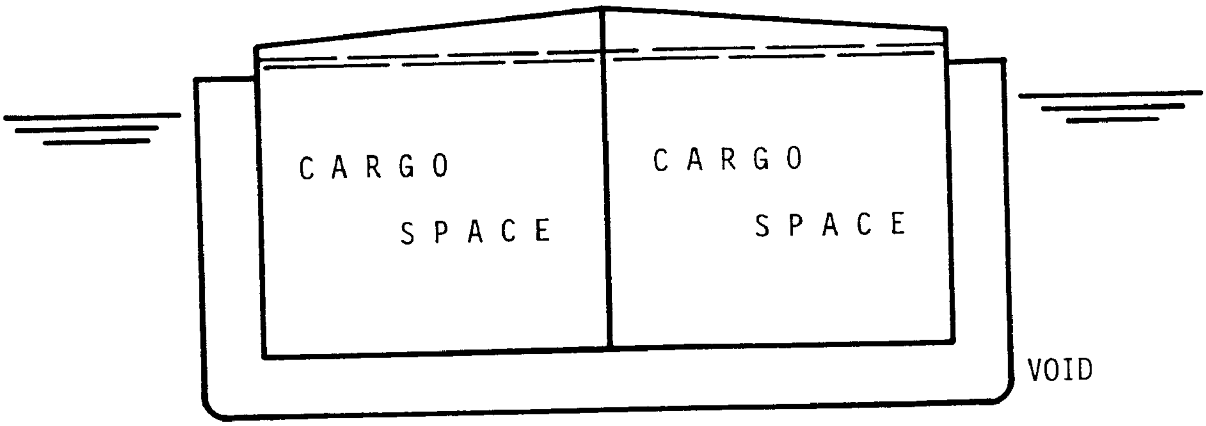
Most petroleum products are carried in single skin barges (a) with poisons, acids and cargos requiring heat or insulation utilizing double skinned (b) vessels. The cylindrical tank barges (c) are generally used to carry liquids under pressure, however, it is not uncommon for pressurized liquids to be transported in double skinned vessels.

Barges can carry large waste loads and discharge the contents quickly. Servizi, et al. (9), reported on a proposed dredging operation that would use 300 cubic yard (approximately 350 tons) bottom dump barges with bottom openings (16 by 65 feet). A self-dumping unmanned 5000 ton barge was described (94) for dumping chemical insecticide wastes at sea at distances not less than 125 nautical miles. All valves, pumps, and other machinery were contained in square tanks that comprised the interior of the 298 foot x 50 foot barge.

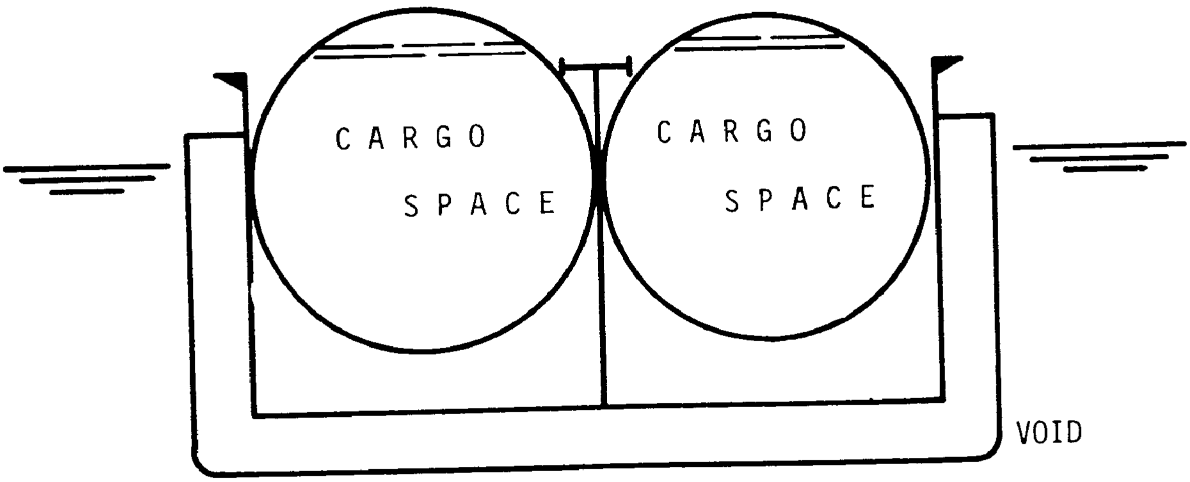
Eberman (95) reported on a deep-sea disposal barge with a rated capacity of 1150 tons in rough weather, and 1300 tons in fair weather. The barge



(A) Single Skin



(B) Double Skin



(C) Double Skin with Independent Cargo Spaces

FIG. 18. Basic Barge Configurations

has six compartments for the cargo, two rows of three each and a loading manifold for pumping the liquid material into any of the compartments. A set of spring-closed check valves on the bottom of each compartment are opened only to permit flow out of the tank when a reduction of pressure occurs on the discharge side of the valve. A vertical turbine pump with a capacity of 2200 gpm against a head of 33 feet discharges through an 8-inch pipe, extending 12-feet below the deck level of the barge. In practice, 4 hours are required to pump out the barge at a pumping rate of approximately 1000 gpm.

The National Lead Company at Sayreville, N. J., uses a barge for the disposal of spent acids and ore washing sludge from a titanium processing plant (96). The system consists of rubber-lined shore storage facilities including dock and dredged harbor and two barges for the transport to the disposal area located 38 miles from the plant dock. The two barges have capacities of 5400 and 3200 tons. The larger barge is used regularly while the smaller one is on a standby basis. The 5400 ton barge is 289 feet long with a 22 foot depth and a load draft of 17 feet and 5 feet when empty. All 8 flat-bottomed waste acid tanks and two cone-bottomed mud tanks are rubber-lined. The disposal operation takes place while the barge is underway at a speed of 8.5 knots. The waste acid is pumped through two 12-inch discharge pipes at the keel level past specially designed skegs approximately 50 feet apart. A load can be discharged in 70 minutes at a rate of 78 tons per minute. The mud is discharged by gravity from the air-agitated cone-bottomed tanks. The smaller standby barge has two 12-inch diameter discharge pipes 43 feet apart at keel depth, which for this barge varies from 15 feet when fully loaded to 6 feet when empty. The rate of discharge has been reported (86, 87) to vary from 16 to 39 tons per minute while being towed at a speed of 6 knots.

New York City barges digested sludge with an automated 6300 ton barge capable of handling cargoes of liquids, acids, or suspended materials. The 226 feet long, 56 feet wide, and 20 feet deep barge is radio-controlled and has an unloading time of 30 minutes.

TABLE 7

BARGE CHARACTERISTICS*

(Tons) Capacity	Type of Waste	Average Depth of Discharge	Discharge Characteristics: Type	Pipe Size	Number Spacing	Towing Speed	Discharge Rate
		Feet		Inches		Knots	Tons/min.
5,400	Iron-acid	10	Pumped	12	2 @ 50 ft.	8.5	78
	Ore washing mud	10	Gravity	-	2 @ 50 ft	8.5	
3,200	Iron-acid	10	Pumped	12	2 @ 43 ft	6.0	16 - 39
5,000	Chem-Insecticides	10	Gravity	-	-	-	-
1,200	Chlorinated Hydrocarbons	12 below deck	Pumped	8	1	6.0	5
1,100	Chlorinated Hydrocarbons	8	Pumped	4	1	6.0	4
8,000	Philadelphia Digested Sludge	-	Gravity	24	8		267
6,300	NYC Digested Sludge	-	-				210
350	Dredge Spoil	17 - 20	Gravity		Bottom dump	-	100 - 200

*Reference (34)

The City of Philadelphia uses an 8000 ton barge for hauling digested sludge with a 2700 ton unit for backup (18, 19, 20, 21). The sludge is hauled approximately 110 miles where it is dumped in 30 minutes through eight 24-inch bottom valves.

Table 7 summarizes towed barge characteristics from the literature readily available on this subject.

Barging Economics

Many factors have been shown to influence the dispersion and dilution of wastes dumped into the ocean. The physical parameters over which some control can be exercised to minimize the effects of waste disposal on the ocean environment are the same parameters which influence the associated costs. These include discharge rate, water, depth, barge capacity and distance to the disposal area.

The literature contains reports on many individual barging operations, few of which include enough information for meaningful comparison. A paper by Gunnerson (3) has summarized the reported costs and presents average disposal costs on a dollar per wet ton basis. These figures are presented in Table 8, and are representative of the following geographic areas: Philadelphia, New York City, Elizabeth, New Jersey, Baltimore, and Washington, D. C.

TABLE 8

REPORTED COSTS OF BARGING OPERATIONS IN $/WET TON*

Waste	Total	Pacific	Atlantic	Gulf
Industrial (a) bulk	1.70	1.00	1.80	2.30
(b) containerized	24.00	53.00	7.73	28.00
Refuse and garbage	15.00	15.00	----	----
Sewage sludge	1.00	----	(.8-1.2)	----

*Reference (3)

To explore and present a method that analyses the towing costs for various barge sizes, sludge quantities and towing distances the following assumptions are made. It is assumed that:

(1) The community owns its own barges and contracts for tug services thus removing the hidden costs of profit and overhead margins.

(2) A standby barge, similar in design to the primary barge, is required. The capacity of this barge is set at 1000 tons.

(3) The availability of tug services is limited to 260 days per year allowing for holidays, strikes, repairs, etc.

(4) Loading costs are included in the operating cost of the facility.

(5) There are three major cost categories, namely:

(a) Capital Costs

(b) Maintenance Costs

(c) Towing Costs

Capital Costs

The capital costs used are based on a figure of $170.00 per ton (14) and represent the purchase of new, specially constructed barges with radio controlled rapid discharge systems. The average discharge time will be taken at 90 minutes.

Service life of ocean going barges varies between ten and twenty years. For this example a barge life of ten years will be assumed for the primary barge and 20 years for the standby barge. Annual costs will be calculated using an eight percent interest rate, equal replacement cost and no salvage value or benefits from depreciation.

Maintenance Costs

Eberman (95) estimated a maintenance cost of $800.00 per trip for a 1500 ton barge making six trips per year or a total yearly cost of $4800.00. This is approximately 12 percent of the annual capital costs of a barge, as described for this example, using the capital cost format itemized. This practice of calculating maintenance costs as a percentage of the annual capital cost is used in the Portland, Oregon area by several firms (95, 97, 33). This approach, where maintenance is independent of both frequency and duration of use, is felt justifiable as salt water corrosion accounts for the major portion of required maintenance and repairs, usually accomplished during one annual dry docking. The capital and maintenance are combined to provide one fixed yearly operating cost. Table 9 shows the distribution of these costs for this example.

TABLE 9

CALCULATED ANNUAL FIXED COST FOR BARGING OPERATIONS

Capacity (tons)	Capital Costs Primary	Capital Costs Secondary	Maintenance	Annual Fixed Cost (Nearest $1000)
1000	25,340	17,330	5.120	48,000
2000	50,680	17,330	8,161	76,000
3000	76,020	17,330	11,202	105,000
5000	126,700	17,330	17,284	161,000

Towing Costs

The greatest amount of variability is expected to occur in the towing costs. This cost can be influenced by discharge rate, tug speed, distance traveled and the existing environmental conditions (i.e., wind, sea state, etc.). Costs in the Oregon, Alaska and Washington areas were found to range between $75.00/hr and $85.00/hr and on this basis an average cost of $80.00/hr was selected as representative of the cost of a tug capable of handling barges up to 5000 ton capacity at an average net speed of six knots. The towing costs on a per trip basis can be calculated from a simple relationship of the following form:

$$C_t = Tc \{\frac{x}{v} + t\} \quad [36]$$

where:

C_t = total towing cost in dollars/trip

Tc = towing charge in dollars/hr

x = round trip distance traveled in miles (point to point)

v = tug speed in miles/hr

t = unloading time in hrs.

From this relationship the total costs per trip can be shown to increase directly with travel time for constant discharge times.

Solving Eq. 36 for various values of (x) reveals a cost/trip mile relationship as given in Fig. 19.

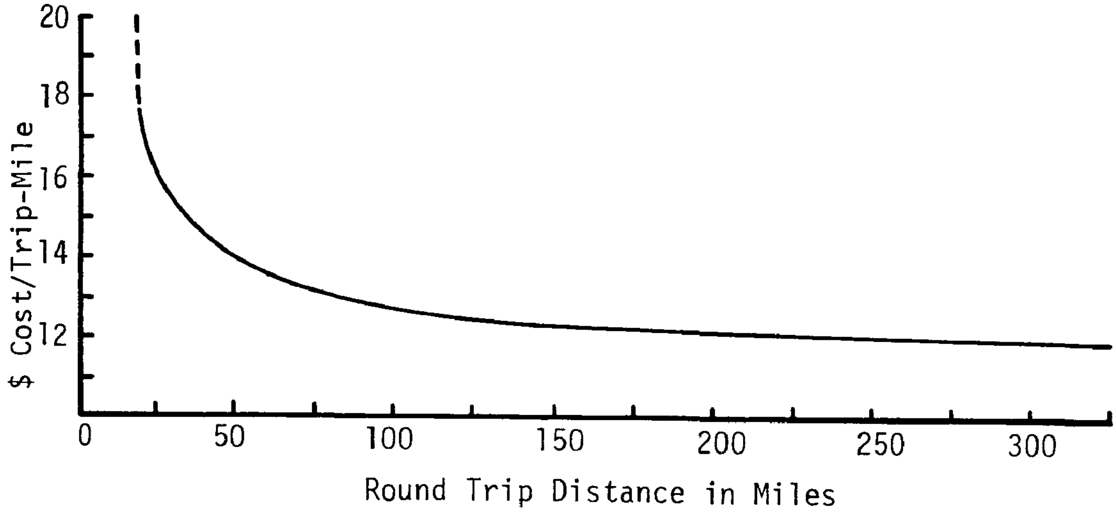


FIG. 19. Cost per Trip Mile as a Function of Round Trip Haul Distance

Assuming a loading time of 3 hrs/ton the limiting number of possible trips for a single barge operation can be determined for the stated tug availability of 260 days/year. These limits are shown for this example in Figure 20.

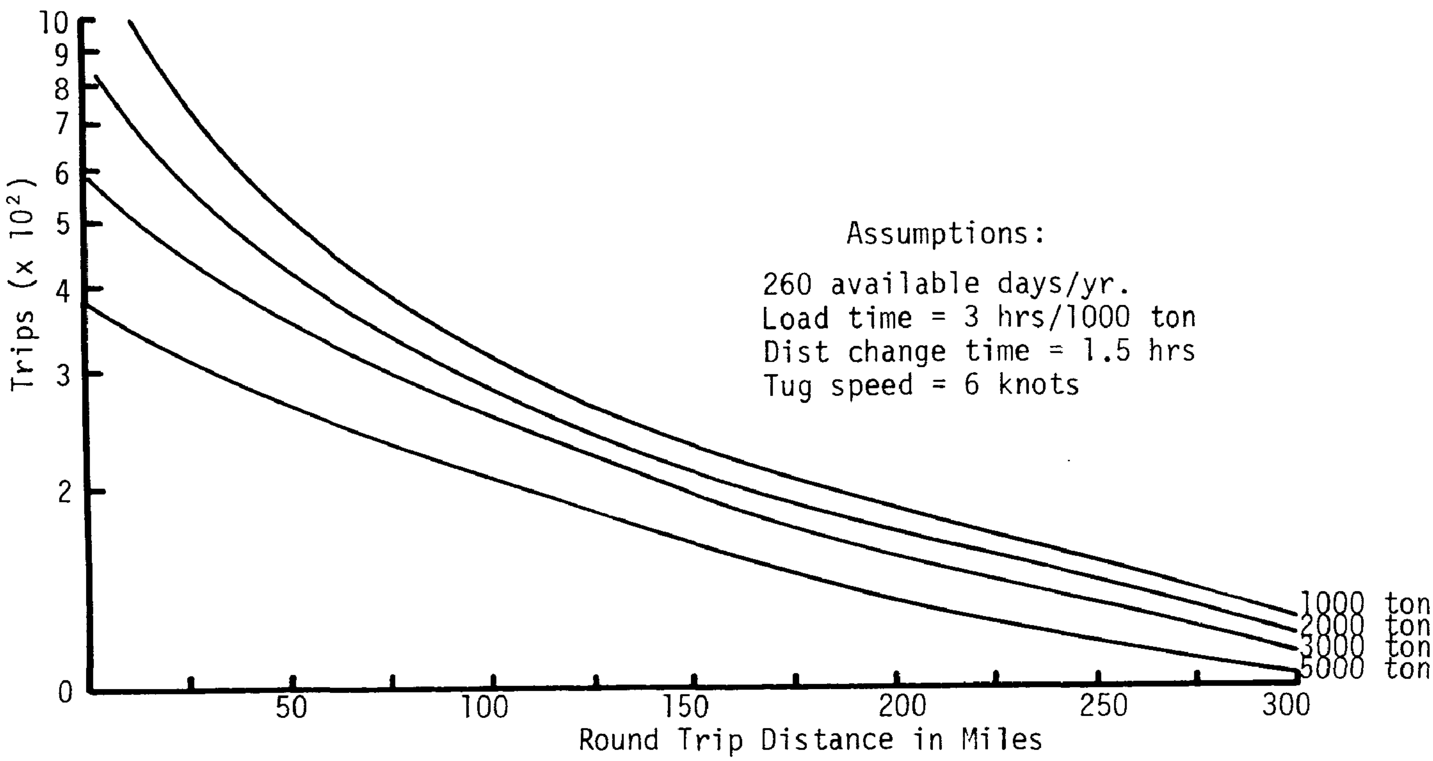


FIG. 20. Limiting Number of Trips per Year for Preset Barge Sizes

The total annual cost (fixed and towing) can be presented by a series of graphs where total annual cost is plotted against the number of trips made in a year for given barge sizes, round trip haul distances, and the total annual tonnage to be disposed of. This method of display (Figs. 21, 22, 23) can provide a method that will aid in the evaluation of alternatives as well as predict the barge size that will accrue the least cost.

This example was not intended to be a black box model that would reproduce the reported costs found in the literature but rather an exercise to expose the controlling variables in barging costs. The relationships and figures presented can be used to determine many factors, for example Fig. 21 for x equal to 20 miles shows a 1000-ton barge to be most economic size for yearly sludge loads that do not exceed 100,000 tons with the 2000 ton barge economically feasible between 100,000 and 300,000 tons and the 3,000-ton barge becoming the cheapest to operate at 600,000 tons/year. These tonnage figures can be related to population of the community if the percent solids and the percent reduction in solids of the process are known. Using 250 mg/l SS, 250 gpd/cap, 10 percent solids and a 33 percent reduction by digestion it can be shown that a population of one million will produce 365,000 tons of sludge per year. If the haul distance were increased to 100 miles round trip, a 5000-ton barge would be necessary to minimize the costs. The additional operating costs incurred when the standby barge is needed are also given in Figures 21, 22, and 23.

The average cost shown in Table 8 for sewage sludges ranged between .8 and 1.2 dollars per wet ton. If an average yearly sludge load of 100,000 tons is assumed with a round trip haul distance of 50 miles, Fig. 23 can be used to calculate the estimated minimum yearly cost and barge size. This results in a barge of 1610 ton capacity making 64 trips per year at a total cost of $117,000 or $1.17/wet ton which is within the average given by Gunnerson.

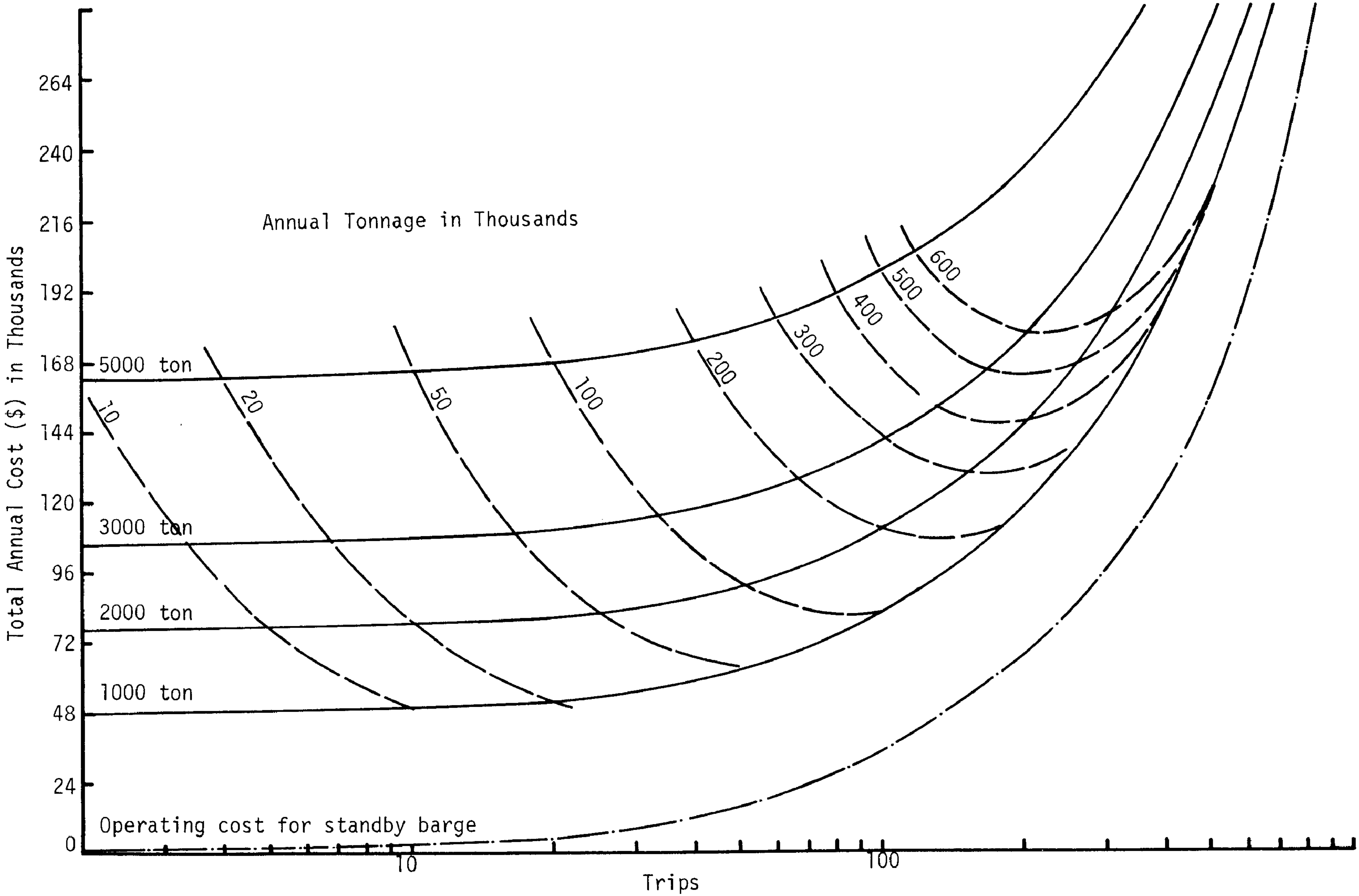


FIG. 21. Annual Operating Costs for Round Trip Haul Distance of 20 Miles

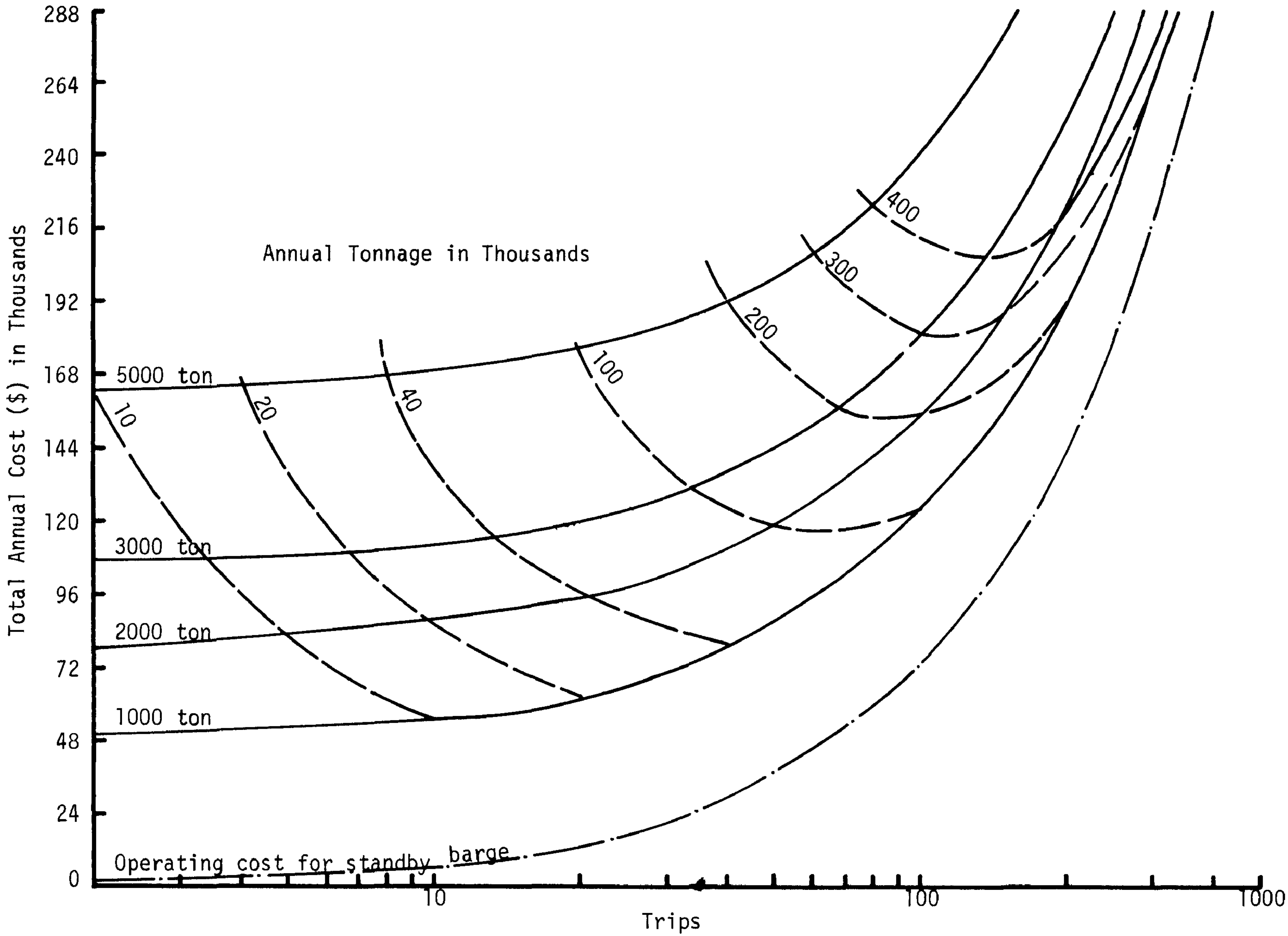


FIG. 22. Annual Operating Costs for Round Trip Haul Distance of 50 Miles

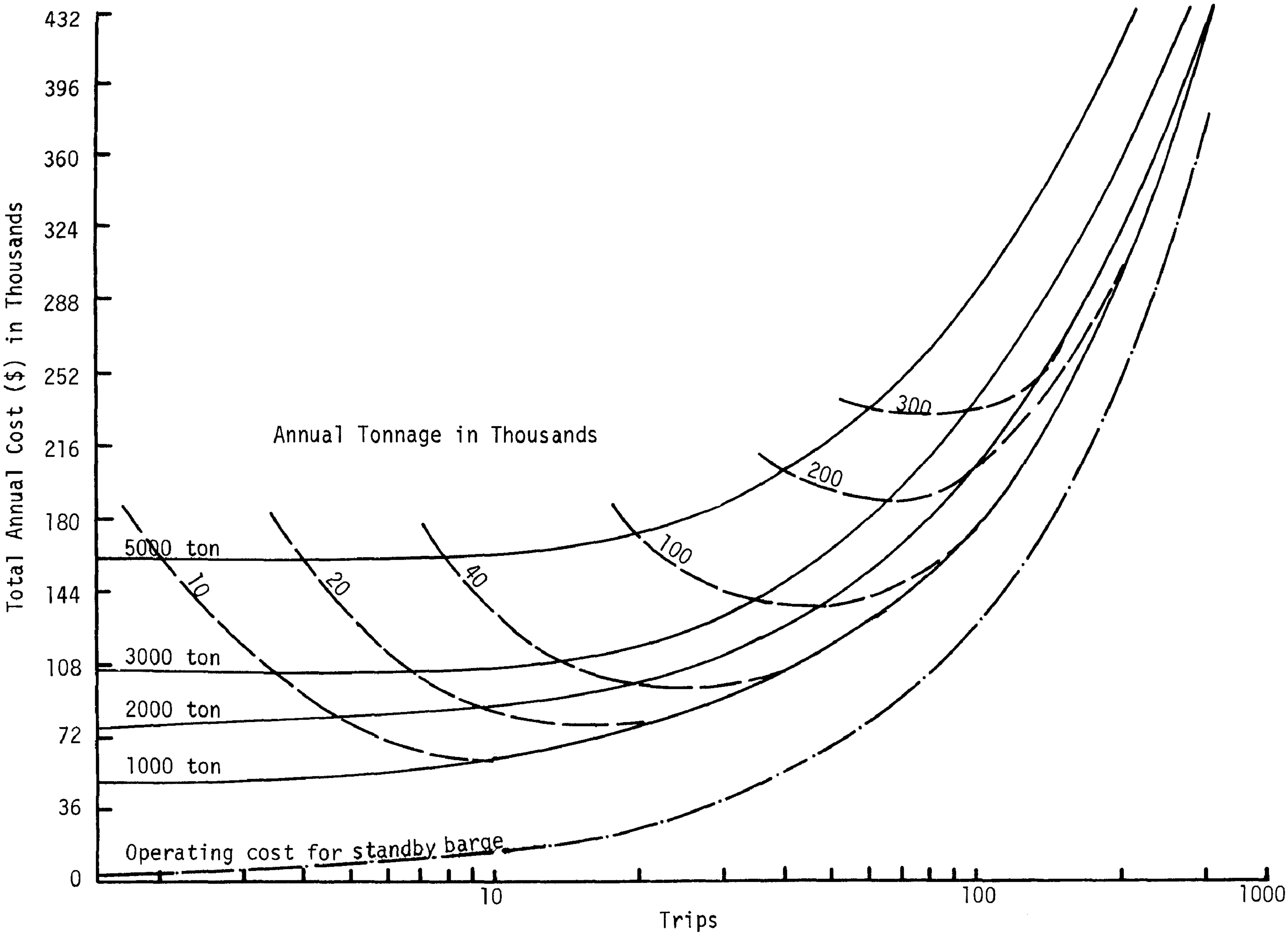


FIG. 23. Annual Operating Costs for Round Trip Haul Distance of 100 Miles

The City of Philadelphia has presented the most complete set of figures (18, 19) and will serve as a test of the validity of this proposed analyses. The conditions are:

(1) x = 220 miles

(2) Barge size = 2700 tons

(3) Sludge load equal to 90 million gallons @ 220 gal/ton

Example Costs are as listed below:

Primary Capital Cost		$68,418
Standby Capital Cost		17,330
Maintenance Cost		10,289
Total Fixed		96,037
Operating Costs		$387,000
	TOTAL	$483,037

This reduces to $5.36/1000 gallon or $1.20 per wet ton again within the average cost/wet ton cited by Gunnerson (3). The operating costs for the Philadelphia operation were given as $3.73/1000 gallons-trip and can be calculated at $4.14 by this method, however the actual average tug speed was 6.35 knots and accounts for the majority of the $0.41 differential shown above.

This approach satisfies the need for a method by which approximate costs of alternative costs of action can be evaluated. The effects of factors such as haul distances, barge sizes, sludge loads, barge speeds, and discharge methods, determined to provide a desired dilution and penetration, can be economically compared allowing the cheapest equivalent combination of design factors to be used to accomplish the desired objectives.

SECTION VIII

USER'S GUIDE

This report has established the fact that ocean dumping is a reality and that it embodies certain risks to the integrity of the marine environment. To this point, little has been said regarding the practical use of this analytical technique. The information derived provides a measure of the dilution, spread and travel or drift of a discharged waste material under various sets of initial conditions and assumptions. These data, if properly interpreted and applied to a particular operation and site, may be used to determine how, when and where a waste should be discharged to preclude violating standards established to protect areas of high marine productivity.

The California Regional Water Quality Board, San Francisco Bay Region, has established such standards and they became effective January 1, 1971. This regulation establishes a protected zone extending seaward approximately thirty three miles. This action was taken to protect the rich marine nursery which extends to the Farallon Islands, and essentially bans harmful waste disposal in this area.

The action taken in California was at this writing the most extensive in the U. S. and may in fact be the forerunner of a more general trend. Without examining the specific considerations given in the establishment of such a boundary, it will be assumed that any discharges made outside this area must be accomplished in such a manner that the protective regulations are in no way violated. Therefore, the basic question is again the one of where, when and how such discharges should be allowed. The approaches and methods outlined in the main text can be used to determine the answers to such questions provided environmental conditions descriptive of the area are known. Seasonal environmental changes may be indicative of the when; dilution, drift and spread, the where; and initial dilution and penetration, the how. These parameters are all interrelated and a continuous set of evaluations will have to be made for each set of conditions used.

The data presented in this report are continuous through the three transport phases for only one set of initial conditions for which the following inputs were used. These are in no way descriptive of any particular operation or geographic area and are used only to explore a use method. These conditions are:

1. Linear density gradient (Table 10)

2. An initial densimetric Froude number of 0.142 based on an initial discharge radius (b_0) of 8 feet and an initial velocity of 0.494 feet per second.

All other conditions are identical to those for the example problem in Appendix I.

From this informational base Fig. 9 can be used to determine the penetration and the dilution that occurs during the convective descent stage. The computer output, as shown in Appendix I, provides a final cloud radius and position both of which may be necessary in either determining the input for the collapse phase or in determining the total extent of the material transport. For this example these parameters are:

Penetration depth (Y_f)	= 159 feet
Dilution (DILN)	= 580
Final radius (b_f)	= 66 feet
Travel in X direction	= 1193 feet

Since the waste cloud reaches a state of buoyant equilibrium both the collapse and long term diffusion-dispersion processes must be considered. The two possible limits are exposed by considering both no collapse and a cloud that undergoes a complete collapse. These values are obtained for a derived value of K_2 given by Equation 11 and subsequent use of Figure 5.

For this example $K_2 \approx 3.8 \times 10^{-3}$ with the collapsed radius equal to 264 feet and an assumed height of 2.06 feet. The collapse time must also be determined from Fig. 5 and used to determine the drift. For the cited K_2 value the time of collapse was 9.4 minutes and for a net current of 0.2 knots gives a drift of 193 feet.

Figures 13, 14, and 15 were constructed for these particular cloud dimensions and therefore can be used to predict the concentration and position as functions of time. The concentrations predicted from this phase of the analysis are relative and assume an initial concentration of unity.

Let us assume that to meet the water quality standards it is necessary to reduce the concentration at the end of the convective descent phase by a factor of 1000. Figure 14 can be used to determine the time for the maximum concentration in the profile to be reduced by this amount. These times are 30 hours for no collapse and 50 hours for complete collapse. Figure 15 gives the final length or diameter of the cloud at this time and only a simple calculation is necessary to determine the drift, assuming of course that the cloud is carried along at the same speed as the current. The total transport can be determined by simply adding together the various components.

	(U_L)	(C_L)
Convective Descent	1193 feet	1193 feet
Collapse Drift	- 0 -	193 feet
Long term		
Drift (U) (t)	36,000 feet	60,000 feet
Spread	5,250	5,750
	42,443	67,036

Conversion to nautical miles gives $U_{(L)} \simeq 7$ miles and $C_{(L)} \simeq 11.0$ miles. The results of this approach predict that for the input conditions and assumptions, discharge should not be allowed within 11 miles of the boundary. The total dilution that has actually occurred during these three transport phases can be shown, assuming a conservative material with no decay to be:

$$D_{final} = \left[C_o \cdot C_{CD} \cdot C_{LT}\right]^{-1} = \left[(C_o)\ (1/500)\ (10^{-3})\right]^{-1}$$

$$D_{final} = \left[2\ C_o \times 10^{-6}\right]^{-1}$$

If we use the San Francisco Bay Protected Zone as an example and apply an additional restriction of 11 miles, some feel for the additional costs involved can be obtained. Assume that before the regulation became effective discharges were made at a point 19 miles off the coast with a total haul distance of 25 miles. The annual tonnage was approximately 100,000 tons and the operation utilized a 2000 ton primary barge with 1000 ton barge held in standby. Fig. 22 can be used to predict an annual cost, including the purchase, maintenance, interest and tug fees of $115,000 or $1.15/ton. The combination of the two additional restrictions increases the haul distance to 50 miles and by Fig. 23 predicts an increase in annual costs of $20,000 with the cost/ton increased to $1.35 representing an increase of 17.4 percent in cost for a 100 percent increase in haul distance.

Hopefully, this exercise demonstrates the potential of analytical approaches of this form. This is certainly only one use and only the first step. Future research and development should refine and improve the overall program limiting the number of assumptions that must be made and making the results more directly applicable to the real world situations.

SECTION IX

BIBLIOGRAPHY

1. "Ocean Dumping: A National Policy." A Report to the President prepared by the Council on Environmental Quality, 45 pages, October 1970.

2. Koh, R. C. Y., and L. Fan. "Prediction of the Radioactive Debris Cloud Distribution Subsequent to a Deep Underwater Nuclear Explosion (U)." A Final Report prepared for the Naval Radiological Defense Laboratory, Contract No. N00228-68-C-0684. 266 pages. October 1968.

3. Gunnerson, C. G., R. P. Brown, and D. D. Smith. "Marine Disposal of Solid Wastes." A paper presented at ASCE Ocean Engineering Conference, Miami Beach, Florida. December 1969.

4. "Investigation of Treatability and Effect on Biota of Dredged Materials from Selected Great Lakes Harbors." University of Wisconsin, U. S. Army Corps of Engineers Contract No. DACW49-68-C-0042. September 1968.

5. Einstein, H. A., and R. L. Weigel. "A Literature Review on Erosion and Deposition of Sediments near Structures in the Ocean." University of California Report HEL 21-6. February 1970.

6. "Dredging and Water Quality Problems in the Great Lakes." Buffalo District U. S. Army Corps of Engineers, Pilot Program Summary, 1969.

7. "Effects on Fish Resources of Dredging and Spoil Disposal in San Francisco and San Pablo Bays, California." USDI Fish and Wildlife Service Special Report. 36 pages. November 1970.

8. Briggs R. B. "Environmental Effects of Overboard Spoil Disposal." Journal of the Sanitary Engineering Division, ASCE, SA3, p. 132-3. June 1968.

9. Servizi, J. N., R. W. Gordon, and D. W. Martens. "Marine Disposal of Sediments from Bellingham Harbor as Related to Sockeye and Pink Salmon Fisheries." Progress Report No. 23. International Pacific Salmon Fisheries Commission, p. 1-38. 1969.

10. Brehmer, M. L. "Turbidity and Siltation as Forms of Pollution." Journal of Soil and Water Conservation. Vol 20, No. 4, pp 132-3. July 1965.

11. O'Connor, B. A., and J. E. Croft. "Pollution in a Tidal Estuary." Effluent and Water Treatment Journal (Brit.). Vol 7, No. 7, p 365-74. 1967.

12. Brown, D. L., and R. Clark. "Observations on Dredging and Dissolved Oxygen in a Tidal Waterway." Water Resource Research. Vol. 4, No.6, p. 1381-84. 1968.

13. Brooks, N. H. "Predictions of Sedimentation and Dilution of Digested Sludge in Santa Monica Bay." Report to Hyperion Engineers, April 1956.

14. Orlob, G. T. "Effects of Digested Sludge Discharge on the Ocean Environment near the City of San Diego Outfall." Report to San Diego Regional Water Pollution Control Board, August 1965.

15. Randall, C. W., and C. T. Koch. "Dewatering Characteristics of Aerobically Digested Sludge." JWPCF. Vol 41, No. 5 part 2, p. R215-238. May 1969.

16. Hinesly, T. D., and B. Sosewitz. "Digested Sludge Disposal on Crop Land." JWPCF. Vol 41, No. 5 part 1, p. 822-830. May 1969.

17. Burd, R. S. "A Study of Sludge Handling and Disposal." FWPCA Publication No. WP-20-4. May 1968.

18. Guarino, C. F. "Sludge Disposal by Barging to Sea." W & SW. Vol 114, p R126-7. November 1967.

19. "Sludge Disposal at Sea." Civil Engineering. Vol 38, No. 8, p. 62-3. August 1968.

20. Baxter, S. S. "Sludge Disposal in Philadelphia." Journal of the Sanitary Engineering Division. ASCE, No. SA6, Vol 85, p 127. November 1959.

21. "Annual Report." City of Philadelphia. 1968.

22. University of Rhode Island. "Progress Report-Systems Analysis for Shipboard Municipal Incineration." Contract No. U. I. 00557-03. 1968.

23. Buelow, R. W. "Ocean Disposal of Waste Material." Transactions, National Symposium on Ocean Science and Engineering of the Atlantic Shelf, Marine Technology Society. Philadelphia, March 19-20, 1968.

24. Beyer, F. "The Spreading of Sinking Pesticides in the Sea." SIW. Vol 27, No. 9, p. 1073-80. September 1955.

25. Hume, N. B., and W. F. Garber. "Marine Disposal of Digested Screened Wastewater Solids." Third International Conference on Water Pollution Research, Munich, Germany, Section III, paper No. 12, 1966.

26. North, N. J. "Ecology of the Rocky Nearshore Environment in Southern California and Possible Influences of Discharged Wastes." International Conference on Water Pollution Research. Pergamon Press, London. p. 247-274. 1962.

27. Carlson, D. E., and C. S. Zichefooze. "Factors Affecting Coliform Reduction in Chlorination of Digested Sludge." Appendix E, Disposal of Digested Sludge to Puget Sound, METRO. Seattle, Washington. July 1965.

28. Brooks, N. H., D. E. Carlson, and R. C. Y. Koh. "Function of Outfall and Dilution in Puget Sound." "Disposal of Digested Sludge to Puget Sound." Submitted to METRO, Seattle, Washington. 1965.

29. Sylvester, R. O. "Sludge Disposal by Dilution in Puget Sound." JWPCF Vol 34, No. 9, p. 891-900. September 1962.

30. Hood, D. W., B. Stevenson, and L. M. Jeffrey. "Deep Sea Disposal of Industrial Wastes." Industrial and Engineering Chemistry, Vol 50, No. 6, p. 885-888. June 1958.

31. Carritt, D. E., et al. "Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters." NAS-NRC Report No. 655. 1959.

32. Joseph, A. B. Sanitary Engineering Conference, Baltimore, Maryland. 1954. USAEC Report. Washington D. C. 1955.

33. Waldichuck, M. "Containment of Radioactive Wastes for Sea Disposal and Fisheries off Canadian Pacific Coast." Proceedings of 1959 Monaco Conference, AEC. Vol III. 1960.

34. Collins, J. C., (ed.). Radioactive Wastes. Wiley & Sons. 1960.

35. Koczy, F. F. "The Distribution of Elements in the Sea." Disposal of Radioactive Wastes. Vol 2, p 189-197. IAEA, Vienna, 1960.

36. Issacs, et al. "Disposal of Low Level Radioactive Wastes in Pacific Coastal Waters." NAS-NRC Report No. 958. 1962.

37. U. S. Coast and Geodetic Survey. "Sea Disposal of Low Level Packaged Radioactive Waste." C&GS Project No. 10.000-827.

38. Pneumo Dynamics Corporation. "Survey of Radioactive Waste Disposal Sites." Technical Report ASD 4634-F prepared under Contract AT(04-3)-331 for AEC. p. 131. 1961.

39. Pneumo Dynamics Corporation. "Sea Disposal Container Test and Evaluation." Technical Report under AEC contract AT(04-3)-367, p. 132. 1961.

40. Mauchline, J. "The Biological and Geographical Distribution in the Irish Sea of Radioactive Effluent from Windscale Works, 1959-60." United Kingdom Atomic Energy Authority, Harwell. p. 70. 1963.

41. Preston, A., and D. F. Jeffries. "The Assessment of the Principal Public Radiation Exposure from, the Resulting Control of, Discharges of Aqueous Radioactive Waste from the United Kingdom Atomic Energy Authority Factory at Windscale, Cumberland." Health Physics. Vol 13, No. 5, p. 477-85. 1967.

42. Sabo, J. J., and P. H. Beckosian, editors. "Studies of the Fate of Certain Radionuclides in Estuarine and Other Aquatic Environments." PHS Publication. No. 999-R-3. 1963.

43. Purushothaman, K. and E. F. Gloyna. "Radioactivity Transport in Water; Transport of ^{85}Sr and ^{137}Cs under Induced Clay Suspensions." Report ORO-490-13, Environmental Health Engineering Research Laboratory, University of Texas, Austin, Texas. 1968.

44. Chia-Shun Shih, and E. F. Gloyna. "Influence of Sediments on Transport of Solutes." Journal of the Hydraulics Division, ASCE, Vol 95, HY5, p. 1347-67. July 1969.

45. Tenny, M. W., and T. G. Cole. "The Use of Fly Ash in Conditioning Biological Sludges for Vacuum Filtration." JWPCF. Vol 40, No. 8 part 2. August 1968.

46. Deb, P. K., A. J. Rubin, A. W. Launder, and K. H. Manuy. "Removal of COD from Wastewater by Fly Ash." Proc. 21st Ind. Waste Conference, Purdue University, Ext. Service 121, 848. 1966.

47. O'Viatt, C. A. "The Effects of Incinerator Residue on Selected Marine Species." Proceedings of the Annual North Eastern Regional Anti-Pollution Conference, July 22-24, University of Rhode Island. 1968.

48. Rogers, B. A. "A Progress Report on Studies to Determine the Effects of Suspended Solids on Marine Fishes With Special Reference to the Effect of Finely Divided Incinerator Residue on Selected Species." Department of Industrial Hygiene, Harvard School of Public Health, p. 24, 1968.

49. Mahoney, J. R. "Feasibility for Ocean Based Solid Waste Disposal." Harvard University, School of Public Health, Department of Environmental Health Services, 7 pages, 1968.

50. Kinsman, B. Wind Wave. Prentice Hall, Englewood, N. J. 1965.

51. Weigel, R. L. Oceanographical Engineering. Prentice Hall. Englewood, N. J. 1964.

52. U. S. Navy Hydrographic Office. "Atlas of Surface Currents, North Atlantic Ocean, 1947a." H. O. Publication 571, First Edition. 1947.

53. U. S. Navy Hydrographic Office. "Atlas of Surface Currents, Northeastern Pacific Ocean, 1947b." H. O. Publication 570, First Edition. 1947.

54. U. S. Navy Hydrographic Office. "Atlas of Surface Currents, Northwestern Pacific Ocean, 1950." H. O. Publication 569, First Edition. 1950.

55. Montgomery, R. B. "Fluctuations in Monthly Sea Level on Eastern U. S. Coast as Related to Dynamics of Western North Atlantic Ocean." J. Marine Research. Vol. 1, p. 165-185. 1938a.

56. Ippen, A. T. (ed.). "Estuary and Coastline Hydrodynamics." McGraw-Hill Book Company, New York. pp. 558. 1966.

57. Morton, B. R., et al., "Turbulent Gravitational Convection from Maintained and Instantaneous Sources." Proc. Royal Society Academy. Vol 234, p. 1-23. 1956.

58. Baumgartner, D. J., R. J. Callaway, G. R. Ditsworth. "Disposal of Aluminum Process Wastes in the Ocean." Working Paper No. 64, Pacific Northwest Water Lab, FWQA, Corvallis, Oregon. March 1968. (Reprinted December 1969)

59. Glover, R. E. "Dispersion of Dissolved or Suspended Materials in Flowing Streams." Geological Survey Prof. Paper 433-B, USGPO, Washington, D. C. 1964.

60. Glover, R. E. and C. R. Daum. "Behavior of Dissolved and Suspended Materials in Flowing Steams." Seventh Hydr. Conf. Proc., Iowas Inst. Hydr. Research, State Univ. of Iowa. June 1958, p. 133-142.

61. Ketchum, B. H., C. S. Yentsch, and N. Corwin. "Some Studies of the Disposal of Iron Wastes at Sea." Woods Hole Oceanographic Institution. Reference 58-7, 17 pp., unpublished manuscript, 1958.

62. Carter, H. H. and A. Okubo. "A Study of the Physical Processes of Movement and Dispersion in the Cape Kennedy Area." File Report under the U. S. Atomic Energy Commission Contract Report No. NYO 2973-1, Chesapeake Bay Institute, The Johns Hopkins University. 1955.

63. Okubo, A. "A Review of Theoretical Models of Turbulent Diffusion in the Sea." Journal Oceanographic Society-Japan. 20th Anniversary Volume, p. 286-320. 1962.

64. Okubo, A. "Some Remarks on the Importance of the Shear Effect on Horizontal Diffusion." Journal Oceanographic Society-Japan. Vol 24, p. 2460-69. 1968.

65. Okubo, A. and M. J. Karweit. "Diffusion from a Continuous Source in a Uniform Shear Flow." Limnology & Oceanography. Vol 14, p. 514-520. 1969.

66. Partheniades, E. "A Summary of the present knowledge of the Behavior of Fine Sediments in Estuaries." MIT Hydrodynamics Lab., Tech. Note No. 8. June 1964.

67. Task Committee on Sedimentation, Sediment Transportation Mechanics: Suspension of Sediment, Progress Report, ASCE Journal of Hyd. Div. Vol. 89, No. HY5, Part 1. September 1963.

68. Schmidt, Wilhelm. "Der Mussemaustausch in freier Luft und verwandte Erscheinungen." Probleme der Kosmischen Physick, Band 7, Haulburg, Germany. 1925.

69. O'Brien, M. P. "Review of the Theory of Turbulent Flow and its Relation to Sediment Transportation." AGU, pages 487-91. April 1933.

70. Sutherland, A. J. "Entrainment of Fine Sediment by Turbulent Flows." Calfornia Institute of Technology, Report No. KH-R-13. June 1966.

71. Shields, A. "Anwendung der Aehnlichheist-smechauik und der Turbulenzforschung auf die Geschiebebewegung." Mitt. der Preusss. Versuchsanstalt fur Wasserbau und Schiffbau, Berlin. 1936.

72. White, C. M. "The Equilibrium of Grains in the Bed of a Stream." Proc. Roy. Soc. Vol 174A, pp. 322-34. 1940.

73. Vanoni, V. N. "Trans. of Suspended Sediment by Water." Trans. ASCE. Vol. 111, pages 670-133. 1946.

74. Anderson, A. G. "Distribution of Suspended Sediment in a Natural Stream." Trans. AGU. pages 678-683. 1942.

75. Kada, H. and Hanratty, T. J. "Effects of Solids on Turbulence in a Fluid." AICHE Journal. Vol 6, No. 4. December 1960.

76. Rouse, Hunter. "Elementary Mechanics of Fluids." John Wiley & Sons, Inc. New York. Pages 245 and 348. 1946.

77. Vanoni, Vito. "Some Experiments in Transport of Suspended Load." Trans. AGU. 1941.

78. Householder, M. K. and V. W. Goldschmidt. "Turbulent Diffusion and Turbulent Schmidt Number of Small Particles - Part I." ASCE Nat. Meeting Preprint 692. Chattanooga, Tenn. May 1968.

79. Householder, M. K. and V. W. Goldschmidt. "Turbulent Diffusion of Small Particles in a Two-Dimensional Free Jet." Purdue University Technical Report No. FMTR-68-3. September 1968.

80. Singamsetti, S. R. "Diffusion of Sediment in a Submerged Jet." J. Hydraulics Division, ASCE, Hy 2, pp. 153-168. 1966.

81. McNoun, J. S. and P. N. Lin. "Sediment Concentration and Fall Velocity." Proc. Second Midwestern Conference on Fluid Mechanics, Ohio State University. pp. 401-411. 1952.

82. Ahmadi, G. and V. W. Goldschmidt. "Dynamic Simulation of the Turbulent Diffusion of Small Particles." Appendix E, Interim Annual Report, FWPCA Project No. 16070 DEP. November 1969.

83. Diaschishin, A. N. "Dye Dispersion Studies." Journal Sanitary Engineering Division, ASCE, Vol 89, No. SA1. January 1963.

84. Abraham, G. and W. D. Eysink, et al. "Full Scale Experiments on Disposal of Waste Fluids into Propeller Stream of Ships." Reprint Rome FAO Conference. December 1970.

85. Schlichting, H. "Boundary Layer Theory." McGraw-Hill Book Company, 6th Edition, pages 692-695. 1968.

86. Redfield, A. C. and L. A. Walford. "A Study of the Disposal of Chemical Waste at Sea." NAS-NRC Pub #201. 1951.

87. Ketchum, B. H. and W. L. Ford. "Rate of Dispersion in the Wake of a Barge at Sea." Trans. AGU.. Vol 33, No. 5, pp 680-684. October 1952.

88. Pearson, E. A., P. N. Storrs, and R. E. Selleck. "Some Physical Parameters and Their Significance in Marine Waste Disposal." In Pollution and Marine Ecology, T. A. Olson and F. J. Burgess (Editors) Interscience Publishers. New York. pp. 297-315. 1967.

89. Webster, C. A. G. "An Experimental Study of Turbulence in a Density-Stratified Shear Flow." J. of Fluid Mechanics, Vol 19, pp. 221-245. 1964.

90. Fulkerson, Frank B. "Transportation of Mineral Commodities on the Inland Waterways of the South Central States." U. S. Department of the Interior, Bureau of Mines, Infor. Circular 8431. 1969.

91. "Sewage Disposal Vessel is Highly Automated." Ocean Industry. Vol 5, No. 2, pages 55-56. February 1970.

92. Mauriello, L. J. and L. Caccese. "Hopper Dredge Disposal Techniques and Related Development in Design and Operation." Symposium No. 3 - Sedimenatation in Estuaries, Harbors and Coastal Areas, Misc. Publ. 970. U. S. Department of Agriculture, Paper No. 65, pp. 598-613.

93. Creelman, W. A. "Pollution Control in the Barge Transportation of Bulk Liquids." JWPCF. Vol 41, No. 11, Part 1, pp. 1879-1885. November 1969.

94. Anonymous. "At Sea About Chemical Wastes." Chemical Week.. pp. 133. October 14, 1967.

95. Eberman, J. W. Sewerage and Industrial Wastes. Vol 28, No. 11, pp. 1365-70. November 1956.

96. Peschiera, L. and Freihers. "Disposal of Titanium Pigment Processing Wastes." JWPCF. Vol 40, No. 1. January 1968.

97. Waller, Robert. "Deep Sea Disposal of Drummed Wastes." E. I. du Pont de Nemouis & Company, Inc., La Porte, Texas. March 1968.

SECTION X

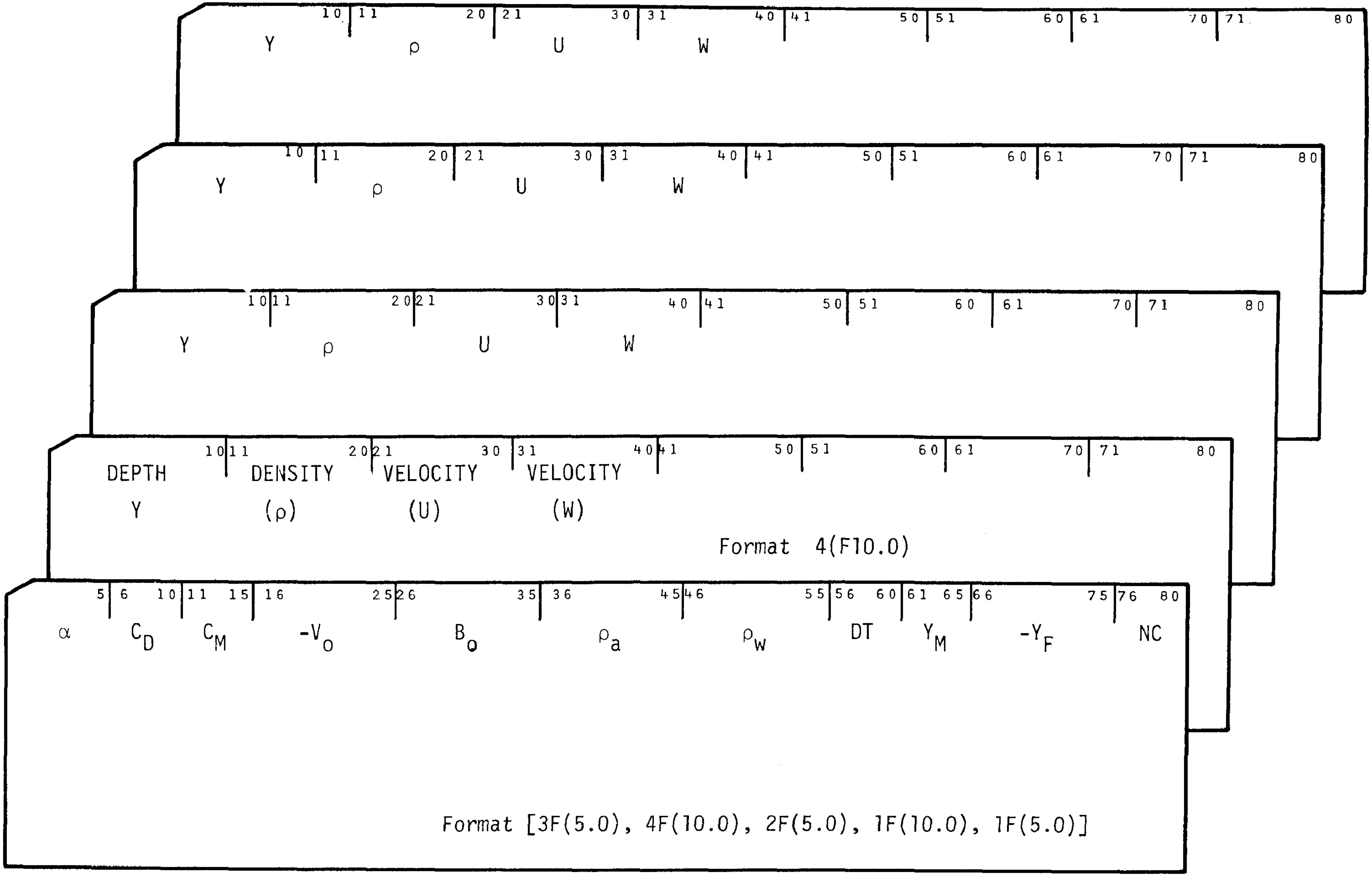
APPENDIX I

This section is intended to be used as a guide for program use, the input requirements for the convective descent stage analysis are presented as they are to be entered on the program control card. The program is currently in conversational mode; however card input requirements will be identical:

PROGRAM CONTROL CARD:

FORMAT: 3F (5.0), 4F (10.0), 2F (5.0, 1F (10.0), 1F (5.0)

COLUMN	DESCRIPTION
1-5	entrainment coefficient (α)
6-10	drag coefficient (C_D)
11-15	added mass coefficient (C_M)
16-25	initial discharge (V_o) (enter as a negative quantity in Ft/sec)
26-35	initial radius of the cloud (B_o)
36-45	initial density of the receiving body in gms/cc (ρ_a)
46-55	initial density of waste sludge or slurry in gms/cc (ρ_w)
56-60	time increment for internal integration (use 0.033 for printout intervals between 5 and 20 feet) (DT)
61-65	print out interval....incremental depths at which solution printout is desired (Y_m)
66-75	maximum water depth in feet....entered as a negative quantity (Y_1)
76-80	number of steps to be entered in the environmental profiles (see discussion in following section) (NC)



APPENDIX I: Convective Descent

DATA CARDS

There should be one card, at least for each depth where a change in any of the environmental parameters occurs plus one additional card descriptive of a point one interval above the waters surface which maintains the same gradient as the first interval below the surface. The program assumes a linear gradient between entered points; therefore, in areas where the changes are rapid, closely spaced points should be entered on either side of the profile change. These cards must be ordered so that the deepest point is read first proceeding upward to a point one increment above the water surface. Values must be entered for all terms on each card. The total number of cards or steps used to describe the profile must be entered in columns 76-80 on the program control card.

Data Card Format: 4(F 10.0)

COLUMN	DESCRIPTION
1-10	Depth of point...entered as a negative quantity when below the water surface
11-20	Density in gms/cc at the depth entered in columns 1-10
21-30	Net horizontal velocity in X direction at depth entered in columns 1-10
31-40	Net horizontal velocity in Z direction at depth entered in columns 1-10

The output from this analytical phase itemizes the control values entered, prints the environmental profile and presents the convective descent solutions in tabular form. The output symbols are defined as follows:

SYMBOL	DESCRIPTION
T	Descent time in seconds
Y_f	Penetration depth in feet
X	X position of the cloud center in feet
Z	Z position of the cloud center in feet
B	Cloud radius in feet
V	Cloud velocity in ft/sec
BETA	Density disparity
DILN	Dilution of the cloud

The following example problem is provided as a sample of the input and output for the Convective Descent Analyses portion.

Initial Conditions:

α = .167

C_D = .250

ρ_s = 1.075 gms/cc

Y_f = 500 feet

C_m = 1.25

V_o = 1975 ft/sec

DT = 0.033

b_o = 4.00 ft

ρ_a = 1.025 gms/cc

Y_m = 10.0 feet

Density profiles are given for the case of linear gradient (Table 10) and a strong pycnocline (Table 11-13). The output is shown in Tables 12 and 13. A discussion of this example is given in the main portion of the text.

TABLE 10

Linear Density Gradient [16 steps]

Y	ρ_a	U	W
-500.0	1.029850	0	0
-300.0	1.028510	0	0
-250.0	1.027925	0	0
-200.0	1.027340	1.0000	0
-150.0	1.026755	2.5400	0
-100.0	1.026170	2.8800	0
- 65.0	1.025749	3.0620	0
- 60.0	1.025691	3.0880	.0370
- 50.0	1.025584	3.1400	.1075
- 40.0	1.025467	3.1920	.1950
- 30.0	1.025350	3.2440	.3750
- 20.0	1.025233	3.2960	.7050
- 10.0	1.025116	3.3480	1.3150
- 5.0	1.025058	3.3740	1.7000
0	1.025000	3.4000	1.7000
50.0	1.024420	3.6600	1.7000

TABLE 11

Strong Pycnocline [23 steps]

Y	ρ_a	U	W
-500.0	1.028900	0	0
-300.0	1.028500	0	0
-250.0	1.028400	0	0
-200.0	1.028300	1.6000	0
-150.0	1.028200	2.5400	0
-100.0	1.028100	2.8800	0
- 65.0	1.028030	3.0620	0
- 60.0	1.028020	3.0880	.0370
- 56.0	1.028001	3.1088	.0655
- 55.0	1.028000	3.1140	.0725
- 54.0	1.027400	3.1192	.0795
- 53.0	1.026800	3.1244	.0865
- 52.0	1.026200	3.1296	.0935
- 51.0	1.025600	3.1348	.1005
- 50.0	1.025000	3.1400	.1075
- 49.0	1.025000	3.1452	.1077
- 40.0	1.025000	3.1920	.1950
- 30.0	1.025000	3.2440	.3750
- 20.0	1.025000	3.2960	.7050
- 10.0	1.025000	3.3480	1.3150
- 5.0	1.025000	3.3740	1.7000
0	1.025000	3.4000	1.7000
50.0	1.025000	3.6600	1.7000

TABLE 12

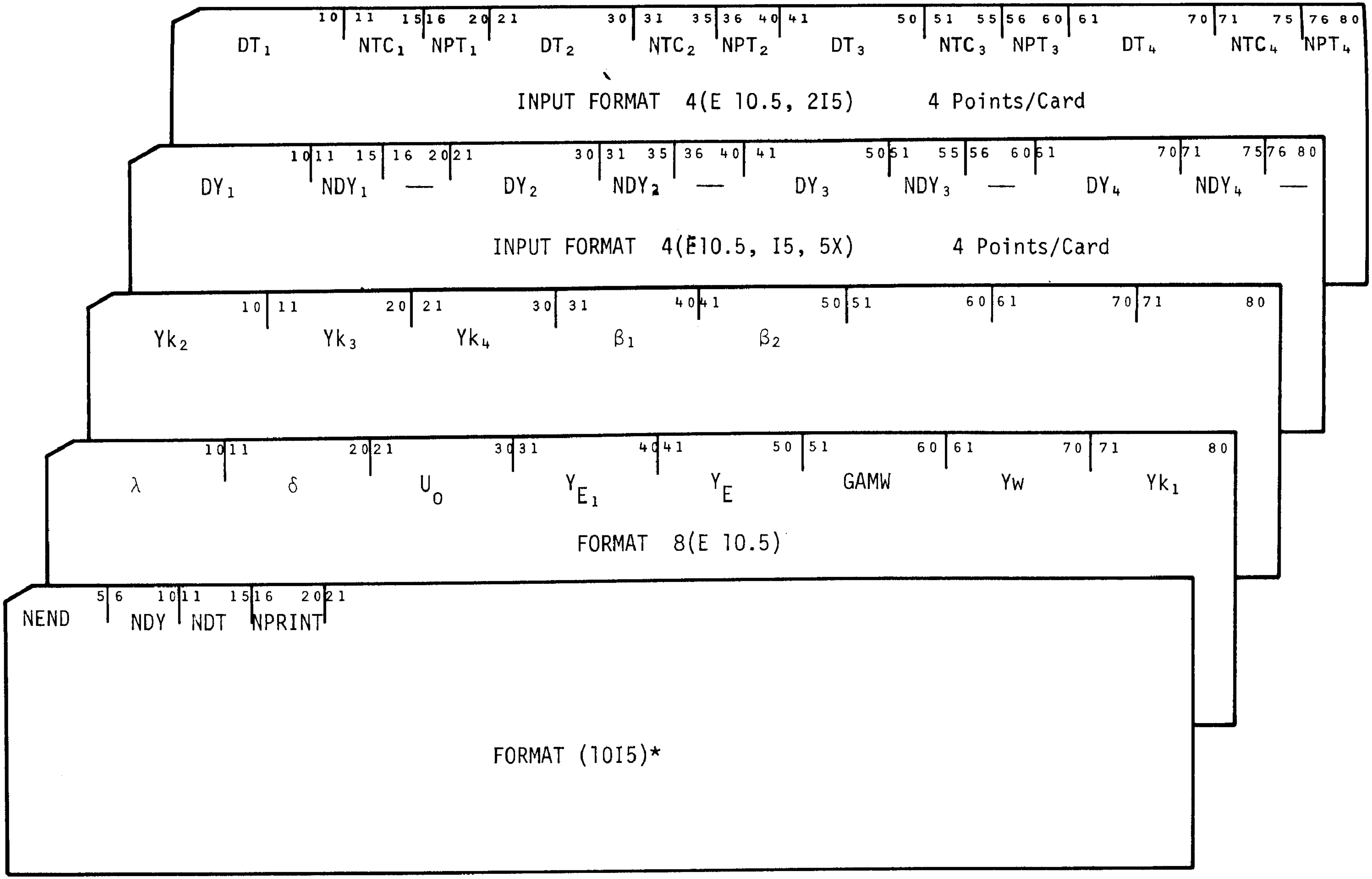
Linear Profile Convective Descent Output

T	Y	X	Z	B	V	BETA	DILN
3.3	-6.61	4.43	2.22	5.705	-1.931	-0.0171812	2.90
5.2	-10.04	8.28	4.08	6.403	-1.838	-0.0121227	4.10
11.1	-20.10	22.78	10.06	8.312	-1.531	-0.0054572	8.97
18.3	-30.07	41.37	15.66	10.192	-1.263	-0.0028725	16.54
27.1	-40.13	64.42	20.57	12.121	-1.047	-0.0016150	27.83
37.4	-50.02	91.64	24.63	14.059	-0.877	-0.009434	43.42
50.1	-60.11	124.65	28.11	16.089	-0.731	-0.0005364	65.08
65.2	-70.13	163.89	30.94	18.188	-0.598	-0.0002732	94.01
84.0	-80.11	212.01	33.28	20.398	-0.469	-0.0000936	132.61
109.1	-90.07	275.66	35.38	22.868	-0.326	.0000332	186.86
155.4	-100.02	390.83	37.85	26.516	-0.114	.0001145	291.32
189.7	-101.84	474.87	39.07	28.942	.000	.0001061	378.79
372.0	-92.51	915.34	41.97	43.740	-0.000	-0.0000280	1307.58
554.4	-95.40	1354.46	42.78	59.066	.000	.0000106	3219.89

TABLE 13

Strong Pycnocline Convective Descent Output

T	Y	X	Z	B	V	BETA	DILN
3.3	-6.62	4.43	2.22	5.705	-1.932	-0.0172300	2.90
5.2	-10.05	8.28	4.08	6.403	-1.841	-0.0121896	4.10
11.1	-20.14	22.78	10.06	8.317	-1.539	-0.0055622	8.99
18.2	-30.04	41.05	15.57	10.180	-1.282	-0.0030334	16.48
26.7	-40.00	63.34	20.33	12.081	-1.083	-0.0018147	27.55
36.7	-50.02	89.67	24.28	14.021	-0.929	-0.0010084	43.07
57.5	-59.35	144.01	29.62	16.557	.003	.0013284	70.93
91.9	-50.19	233.16	35.35	20.053	-0.003	-0.0016155	126.00
118.1	-54.94	300.97	38.70	22.573	.001	.00105910	179.70



APPENDIX II: Long Term Dispersion

APPENDIX II

Both the input and output for the long term dispersion stage analyses are normalized, dimensionless, values. There are two basic input control cards and three or more output and program control cards as shown on the face sheet of this Appendix section.

The input controls are entered in accordance with the following format and normalization scheme:

Format 8(E 10.5)

Column	Symbol	Normalization	Reference Fig.
1-10	λ	$hA/K_{y(1)}\ b_o$	
11-20	δ	h/a_o	
21-30	U_o	$U_s h^2/K_{y(1)} b_o{}^{2/3}$	
31-40	YE_1	Y/h	25
41-50	YE	Y/h	25
51-60	GAMW	$W_{(max)} h^2/K_{y(1)} b_o{}^{2/3} YW$	25
61-70	YW	Y/h	25
71-80	YK_1	Y/h	26
Card #2			26
1-10	YK_2	Y/h	26
11-20	YK_3	Y/h	26
21-30	YK_4	Y/h	26
31-40	BETA 1	$K_{y(y)}/K_{y(1)}$	26
41-50	BETA 2	$K_{y(y)}/K_{y(1)}$	

The initial conditions which must be known, all of which are defined and described in the text, are:

a_o = Y dimension of cloud at end of collapse period [ft]
b_o = X dimension of cloud at end of collapse period [ft]
h = depth of cloud center at end of convective descent stage [ft]
$U_{(s)}$= max x velocity component [ft/sec]
W = max z velocity component [ft/sec]
$K_{y(1)}$= vertical diffusion coefficient used to describe mixed layer [ft^2/sec]
A = dissipation parameter usually assumed as a constant [$ft^{2/3}$/sec]

The program will accept velocity and vertical diffusion coefficient profiles only when they are normalized as shown in the following diagrams:

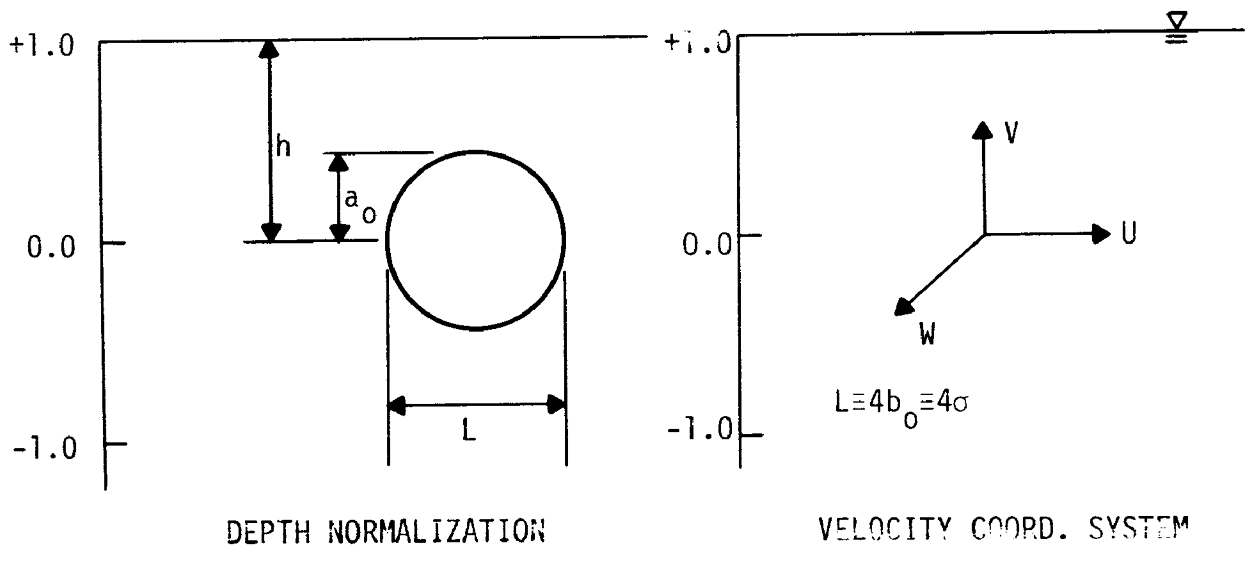


FIG. 24. Coordinate System and Depth Normalization

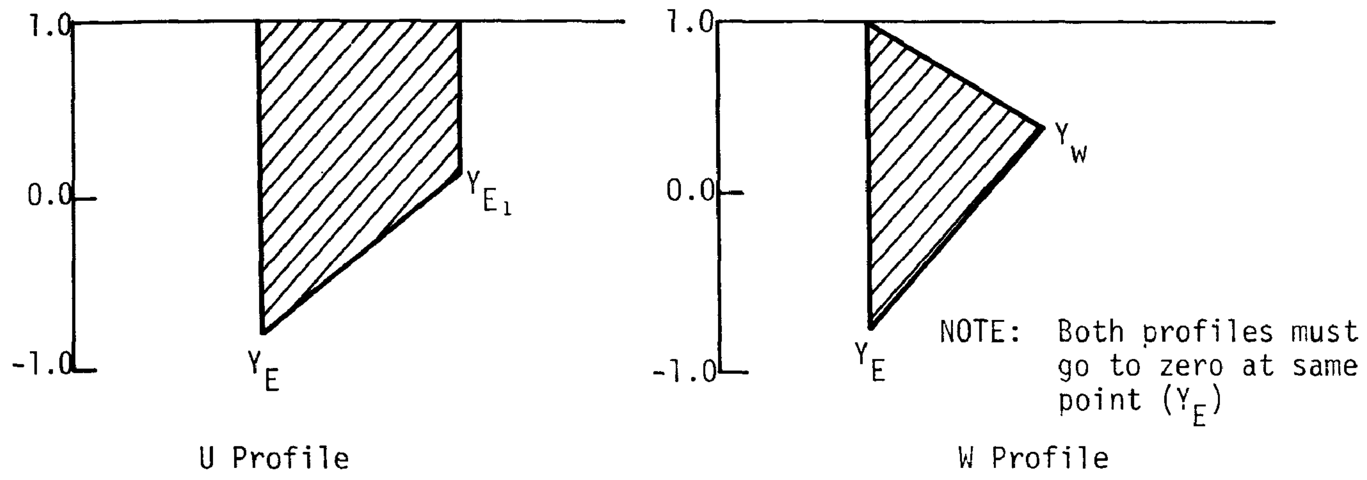


FIG. 25. Velocity Profile Normalization

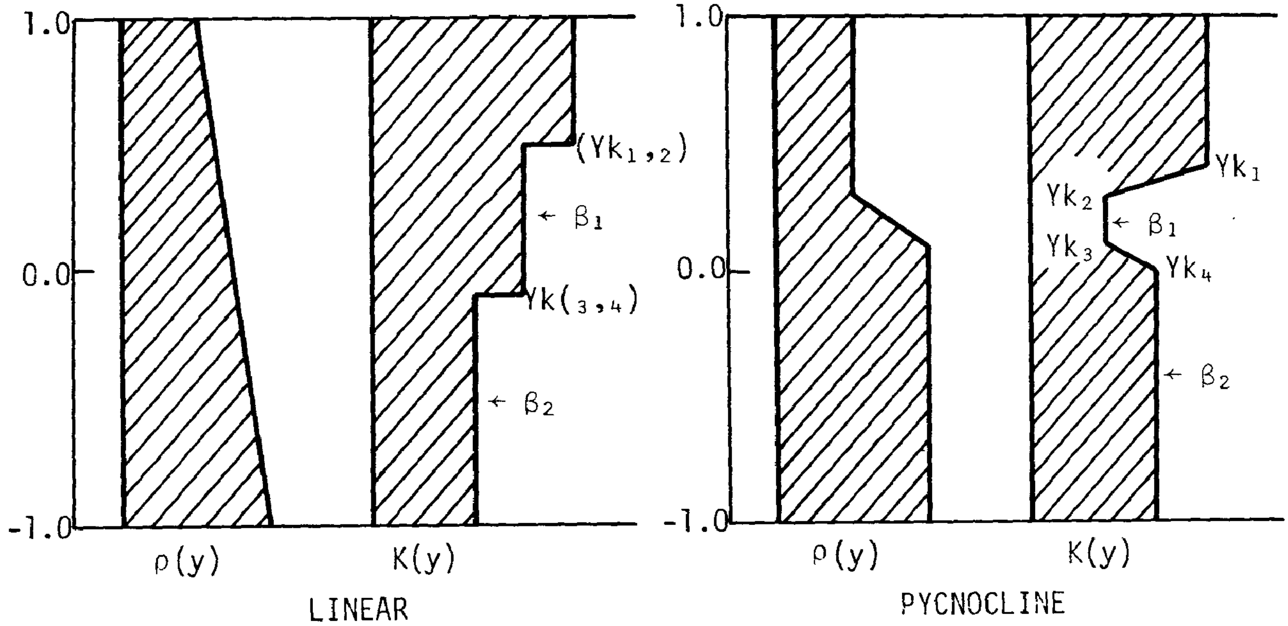


FIG. 26. Vertical Diffusion Coefficient K(y) - Normalization Method

The vertical diffusion coefficient profile relates the decrease in vertical diffusion with increasing density to the magnitude of the $K_{(y)}$ value with depth.

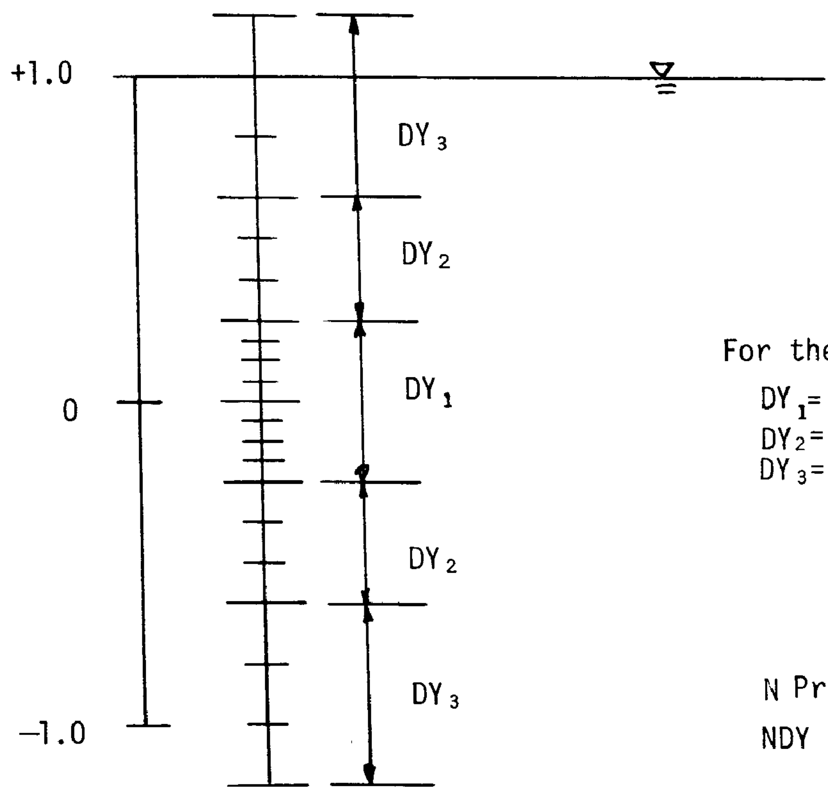
A normalized depth and time grid system must be established for program output control. The depth grid should include one interval above and below the normalized depths of ($\pm$ 1.0). The grid is defined as follows:

$DY_{(i)}$ = size of the individual step

$NYC_{(i)}$ = number of steps of that size

NDY = total number of step size changes

NPRINT = number of Y grid points established between but including ($\pm$ 1.0) N print = $[(\Sigma\ NYC_{(i)})-1]$



For the examples used:

$DY_1 = .063$ $NYC_1 = 8$
$DY_2 = .126$ $NYC_2 = 6$
$DY_3 = .185$ $NYC_3 = 6$

N Print = 19
NDY = 3

FIG. 27. Depth Normalization

The time grid is normalized as follows:

$$t' = \frac{K_{y(1)}t}{h^2}$$

solving this equation for t'=1.0 will allow real time choices to be selected for output. The output will then, using the plotting subroutine, plot the distribution of concentration with depth at the requested times.

The time grid utilizes symbols similar to those of the Y grid namely:

$DT_{(i)}$ = size of individual normalized time stop
$NTC_{(i)}$ = the number of steps of that size
NDT = the number of step sizes used
$NPT_{(i)}$ = the number of steps required to reach the requested output time

The summation of $[(DT_{(i)})(NTC_{(i)})]$ should equal 1.0.

If output is desired at normalized times .01, .1, 15 and 1.0 the steps could be arranged as follows:

Example 2

Step change (i)	$DT_{(i)}$	$NTC_{(i)}$	Σ Nor. time	$NPT_{(i)}$
1	.001	10	.01	10
2	.002	45	.10	45
3	.005	80	.50	80
NDT 4	.010	50	1.00	50

The output from this program is also in normalized form and uses the following symbols:

T = time

C_{oo} = total concentration of material in XZ plane

$I(C_{oo})$ = integral of C_{oo} over the depth

X_o = X centroid location

Z_o = Z centroid location

C_{max} = Max concentration in XZ plane

Y = normalized Y (as given by grid)

$\sigma_x \sigma_x \sigma_{xa}$ = standard deviations of the concentration distribution

These values can be denormalized as follows:

(1) The horizontal dimensions of the cloud $L_{(i)}$ where $L_{(i)} = 4b_o\sigma_i$ where i = x,z

(2) The cloud centroid locations in X,Z where:

$CE_{(x)} = bX_o$ $CE_{(z)} = bZ_o$