

**AN EVALUATION OF EFFLUENT DISPERSION
AND FATE MODELS FOR OCS PLATFORMS**

VOLUME 1: SUMMARY AND RECOMMENDATIONS

**Proceedings of the Workshop
7-10 February 1983
Santa Barbara, California**

**Prepared for
Minerals Management Service
U. S. Department of the Interior
Contract No. 14-12-0001-29122**

**Prepared by
MBC Applied Environmental Sciences, and
Analytic and Computational Research, Inc.**

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Edited by:
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An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms

Volume II: Papers Presented at the Workshop

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PREFACE

The emphasis on leasing and development of offshore petroleum resources by the Minerals Management Service (MMS) of the U.S. Department of the Interior, and the ensuing disposal of drilling effluents resulting from exploratory and production operations, has resulted in increased concerns regarding the effects of these activities on the Outer Continental Shelf (OCS) marine environment. In an effort to better understand the behavior of the disposed materials in relation to the offshore environment, the MMS sponsored a Workshop entitled, "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms." The Workshop was conducted by MBC Applied Environmental Sciences (MBC) and Analytic & Computational Research, Incorporated (ACRI) in Santa Barbara, California, from 7 through 10 February 1983. The objectives of the Workshop were to evaluate the existing mathematical models for dispersion of drilling effluents, to assess the state-of-the-art, and to make recommendations about future directions in the development of these models and research related to the fate of discharges.

The proceedings of the Workshop form the subject of this two volume document. The first volume contains the background and introductory material, evaluation of the selected mathematical models, abstracts of the papers presented at the Workshop, and the conclusions and recommendations of the subgroups and the Workshop panel. The overall recommendations and conclusions are contained in the Executive Summary which is included in both Volume I and Volume II. The complete papers dealing with a range of issues relevant to the discharge of drilling effluents in the OCS environment are reproduced in the second volume. The only exception is a paper presented by Dr. Petrazzuolo (See the Agenda - Appendix A); this paper, or a summary of it, was not received from the authors in time for inclusion in these volumes.

These proceedings do not contain a transcript of the valuable discussions, and questions and answers during the three-and-a-half days of the Workshop. The essential elements of these discussions are reflected in the summary of conclusions, recommendations and subgroup chairmen's reports which are included in Volume I.

Every attempt was made to include representative models from all of the diverse models applicable to the disposal of drilling fluids in the program of the Workshop. If any known model was not included, it was either because a very similar model (possibly an improved version) was included in the program or because the model was not available for review and presentation.

In the Workshop proceedings, the authors and contributors are identified by their name only; their affiliation, mailing address and telephone number is given in Appendix B.

A number of persons contributed greatly to the success of the proceedings. The expert panel which provided overall technical guidance consisted of Dr. Robert C. Y. Koh (Chairman) of the California Institute of Technology, Dr. Lorin Davis of Oregon State University, and Dr. Anthony Policastro of Argonne National Laboratory. The subgroup chairmen, Dr. Robert Ayers, Jr. (Exxon Production Research Co.), Mr. Maynard Brandsma (Consulting engineer), Professor Wilbert Lick (University of California, Santa Barbara), Mr. F. Thomas Lovorn (Lockheed Ocean Science Lab), and Dr. Theodor C. Sauer, Jr. (Exxon Production Research Company), who moderated the group discussions and provided feedback, deserve special mention. All took time out of their busy schedules to summarize the often colorful and wide ranging discussions. In addition, a number of persons devoted their valuable time to application of the models and presentation of papers; this document is primarily a summary of their efforts. Their contribution is acknowledged gratefully and their names appear in the Proceedings where appropriate.

Akshai K. Runchal
Robert R. Ware

Los Angeles, California
July 1, 1983

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EXECUTIVE SUMMARY

THE PURPOSE AND OUTLINE OF THE WORKSHOP

The Minerals Management Service (MMS) of the Department of the Interior, by virtue of the Outer Continental Shelf Lands Act (1978), has jurisdiction over the Outer Continental Shelf (OCS) submerged lands. Among the responsibilities mandated for the MMS under this Act are those to conduct studies to predict, assess, and manage impacts from OCS oil and gas development activities in the marine environment. Other responsibilities include leasing land on the OCS for minerals development, permitting and regulating the development activities, and assessing and monitoring the environmental effects of these activities. One potentially significant impact of the OCS lease process is the discharge of effluents from offshore drilling rigs and production platforms.

Mathematical models, in conjunction with field studies, have played a crucial role in assessing the transport, fate and effect of marine effluents. In particular, models have played an important role in our understanding of the fate of thermal, sewage, and dredged material discharged into offshore waters. However, models for discharge of drilling effluents from OCS platforms are still at a preliminary and largely untested stage. The only part of the mixing process which has been compared with laboratory and field data is the initial descending phase (also called the convective descent phase) of the plume. Our understanding of the later phases in the physical and chemical processes relevant to transport and dispersion of drilling muds, cuttings and formation waters is limited. Further, very little data is available from the OCS environment to validate the models developed so far.

A comprehensive examination of available mathematical models and data would highlight the areas which may require further study. The MMS therefore sponsored a workshop to discuss the strengths and limitations of the available mathematical models for drilling effluent dispersion. The workshop entitled "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms", was held from 7 through 10 February 1983 in Santa Barbara, California. Approximately 100 invited individuals from a wide range of affiliations and

disciplines attended.

The primary objective of the workshop was to survey and consolidate the state-of-the-art knowledge in modeling of the transport and fate of the drilling muds, cuttings and formation waters in the OCS environment. To achieve this objective, a number of models for drilling effluents were identified and standard data sets were developed to assess the model performance in a comparative mode. A number of leading experts were invited to deliver keynote addresses on issues dealing with the physics and chemistry of drilling effluent dispersion. Further, the workshop participants were asked to review the state-of-the-art in their respective fields and to identify the processes related to the physics and chemistry of the discharge plume which are adequately understood and those which require further investigation.

Another objective of the workshop was to educate Federal, State, and local agency personnel in the uses and limitations of the numerical models, compare the uses of and needs for modeling of plumes of discharged materials in relation to the mission responsibilities of MMS and EPA, and to provide feedback from MMS and EPA model users to the scientists involved in developing and testing numerical models.

The total duration of the workshop was three and a half days. Of this period, the first two days were devoted primarily to the technical assessment of the existing information related to drilling effluent discharges. As such, the presentations consisted of the description of the various models and their application to the standard data sets. Presented papers also addressed various aspects of drilling mud discharges. Among the papers presented were those on the review of the existing knowledge, the standard data sets, laboratory experiments in plume behavior, drilling mud composition, sedimentation, resuspension and flocculation processes, EPA modeling needs, and the relationship of biological information needs to modeling of discharges and prediction of pollutant concentrations in the ocean.

During the third day of the proceedings, the participants met in small groups to discuss specific aspects related to modeling of drilling effluent

discharges. The topics of discussion were (1) the near field physics, chemistry and dynamics of a discharged drilling effluent, (2) the dynamic effects of the ambient oceanographic conditions on drilling effluent in the near and intermediate-field, (3) the long-term oceanographic features of the transport and fate of drilling effluents, and (4) the role of models in predicting the behavior of, and assessing the effects of a drilling effluent. These groups also discussed future needs for numerical modeling and related studies. The final day of the workshop was held in plenary session to summarize the group discussions and make recommendations for future directions.

CONCLUSIONS OF THE WORKSHOP

Models And Modeling Methodology

The available models should only be applied for short-term simulation of the transport and fate of drilling effluents. Their applicability beyond a time scale on the order of a day is questionable. The models provide reasonable prediction concerning the behavior of the discharge in the near-field. However, these models remain largely unvalidated with field and laboratory data in the lower densimetric Froude number range encountered with mud and produced water discharges. Most of the models were developed and calibrated for plumes using laboratory data having high initial densimetric Froude numbers. Since such data are not directly applicable to the drilling mud discharges, and because the plume buoyancy has a pronounced effect on near-field dispersion and mixing, separate calibration of the models for low Froude number range is required. After the initial buoyancy and momentum of the mud plume have subsided, the plume enters a passive diffusion phase. This diffusion phase is thought to be the least accurate portion of the short-term fate models.

In general, the predictions of plume behavior from the several short-term models for the standard data sets were in agreement. However, the bottom deposition rates predicted by the models varied by an order of magnitude. The short-term models take reasonable account of the transfer and mixing processes

in the initial dilution and dispersion phases. It should be noted that quite often the bulk of the dilution of discharge occurs during these initial phases.

The processes of flocculation and deflocculation, deposition and resuspension, and wake effects are either missing from the models or are inadequately treated by the existing models. Further, certain initial processes such as predilution in the discharge pipe and separation of the fine particle sizes from the main plume, which have been noticed in field or laboratory studies, are at present poorly understood. The standard data sets tested only the treatment of the jet phase in the mud plume dispersion; the data did not address the passive diffusion phase.

Two methodologies for the long-term predictions (day and longer) are currently available - The deterministic and the probabilistic. Models representing both of these methodologies were presented at the workshop; however none is considered satisfactory for application to the OCS environment.

The deterministic method suffers from the drawback that it requires very detailed synoptic description of oceanographic conditions for accurate predictions. Such data are not likely to be available. Further, this method requires considerable computer resources which may well prove prohibitive for most OCS applications. A deterministic model, with examples of applications to river estuaries, was presented at the workshop (Section 6.3). However such models are judged to be of general predictive utility in the OCS environment because of the requirements of site-specific calibration and high cost.

The probabilistic method does provide a promising alternative but has been poorly explored for OCS applications. The primary advantage of this method is that it can rely upon representative samples of oceanographic data rather than synoptic conditions. It is likely to be much cheaper than the deterministic method. The only model of this kind presented at the workshop (see Section 3.5) employed long-term current averages and did not account for dynamic or time-series effects. The results from such a model thus have limited usefulness.

Field Data

Adequate field or laboratory data for verification and calibration of models is limited. The available field data does not provide the synoptic information on ambient currents, density structure and plume measurements to adequately verify mathematical models. Some laboratory data exist to provide near-field verification of models, but the scope of these data is limited and can at best only provide partial verification of near-field components of the model.

RECOMMENDATIONS OF THE WORKSHOP

Modeling

It was recommended that a feasibility study be conducted to identify a suitable methodology for a long-term model of drilling effluents. It is recognized that such a model would rely heavily on probabilistic rather than deterministic approaches and would require coordination with existing MMS studies in physical oceanography and meteorology. The long-term feasibility study should be multidisciplinary, involving experts in meteorology, physical oceanography, geology, and biology.

Some research effort may be directed towards verification and refinement of short-term models and inclusion of phenomena at present missing from these models. In terms of verification, the models may be tested and improved in modular form (jet phase, convective descent phase, passive diffusion phase) using data from related fields until more laboratory and field data specific to the OCS discharges is available. In terms of refinement of models, it is possible to include the phenomena of plume separation during the initial stage, and pre-mixing of the discharge effluent due to influx of ambient water in the discharge pipe. However, this research effort was recognized to have a lower priority than that related to development of long-term models.

Laboratory Studies

Several processes which may play a significant role in the fate and behavior of discharges from OCS platforms are at present poorly understood. The nature of these processes is such that laboratory investigations would lead to a better understanding of their significance in the long-term fate of the effluents. Of these, the processes of flocculation, deflocculation, sedimentation, and resuspension were identified for priority consideration.

Additionally, the phenomena of interaction of the discharge plume with the bottom, the dilution due to wake effects of the discharge structure, initial separation of certain constituents of the discharge, and initial dilution due to pre-mixing need further investigation.

Field Data

It was recommended that field data be collected for the purpose of validation of short-term models and development of long-term models. This data base should preferably consist of synoptic data relevant to dispersal of drilling effluents in the OCS environment. The data collected should include that pertaining to ambient currents (including statistical parameters), temperature and salinity, natural and artificial sedimentation rates, and sediment transport near the bottom. It was suggested that such a field data effort is likely to be most cost-effective if conducted concurrently with, or pursuant to, the development of a long-term fate model.

1 INTRODUCTION

1.1 OUTLINE OF THE WORKSHOP AND THE PROCEEDINGS

by

Dr. Akshai K. Runchal

INTRODUCTION

A Workshop entitled, "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms" was held at Santa Barbara, California from 7 through 10 February, 1983. The Workshop was sponsored by the Minerals Management Service (MMS) of the Department of Interior. It was organized by MBC Applied Environmental Sciences with technical direction from Analytic & Computational Research, Inc. (ACRI). Mr. Rick Ware of MBC was the the Program Manager and Planning and Logistics Coordinator, and Dr. Akshai Runchal from the ACRI was the Technical Coordinator for the Workshop. The final agenda and the list of participants for the Workshop are included in this report as Appendix A and B, respectively.

The Workshop technical proceedings were overseen and directed by an expert technical panel. The members of the panel were: Dr. Robert C Y. Koh of California Institute of Technology (Panel Chairman), Dr. Lorin Davis of Oregon State University, and Dr. Anthony Policastro of Argonne National Laboratory. The function of the panel was both to advise on the proceedings and to assist in the model evaluations.

For the first two days, the Workshop was primarily concerned with updating the existing state-of-the-art in modeling of drilling effluents. A number of presentations were made concerning the various issues related to the modeling of drilling effluents. These were divided into two categories. The first category dealt with the application of the five preselected models to the standard data sets. The second category dealt with a number of technical and regulatory issues related to the discharge of drilling effluents.

The third day was devoted to the assessments of the material presented and directions for future research efforts. For this latter part, the participants were divided into four subgroups. The topics of discussions for the subgroups were as follows:

SUBGROUP 1: The physics, chemistry, and dynamics of the discharge and near-field of a drilling effluent.

SUBGROUP 2: The dynamic effects of the ambient oceanographic conditions on drilling effluent in the near and intermediate fields.

SUBGROUP 3: The long-term oceanographic features of the transport and fate of drilling effluent, and

SUBGROUP 4: The role of models in predicting the behavior of, and assessing the impacts of, a drilling effluent.

Subgroup 1 was chaired by Mr. Ted Sauer, Jr. of Exxon Production Research Company, the Subgroup 2 by Dr. F.T. Lovorn of Lockheed Marine Science, and the Subgroup 3 by Dr. Robert Ayers of Exxon Production Research Company. Because of the large number of participants in the Subgroup 4, it was divided into two sections; one of these was chaired by Professor Wilbert Lick of University of California, Santa Barbara and the other by Mr. Maynard Brandsma (an independent consulting engineer).

The primary goal of the subgroups was to identify those issues which merited further research and those which were thought to be adequately resolved by existing knowledge. The subgroups were further asked to allocate priority to the identified issues and to make specific recommendations about the state-of-the-art and future directions. Most of the third day of the workshop was spent in subgroup discussions. Near the end of the third day a plenary session was held, and each subgroup chairperson reported on the respective subgroup's findings and conclusions.

The final half day of the workshop was devoted to open discussion, a summary of the proceedings, a presentation of comparative assessment of models, panel recommendations, and identification of future directions in modeling the dispersion of effluents from OCS platforms.

ORGANIZATION OF THE WORKSHOP PROCEEDINGS

The proceedings of the workshop are divided into two volumes. This volume (volume I) contains:

1. the background and introductory material (Chapter 1),
2. the abstracts of the invited review papers on selected issues relevant to modeling of drilling effluents (Chapter 2),
3. the abstracts of the descriptions of the models selected for evaluations (Chapter 3),
4. the description of the standard data sets (Chapter 4),
5. the results of model evaluations (Chapter 5),
6. the abstracts of other papers presented at the Workshop concerning other models and methodologies (Chapter 6),
7. the subgroup discussions and recommendations (Chapter 7),
8. the References (following Chapter 7),
9. the agenda of the Workshop (Appendix A),
10. the list of participants (Appendix B), and
11. the definitions of technical terms used in the proceedings (Appendix C).

The expert panel recommendations, along with the proceedings, are summarized in the Executive Summary of Volume I.

The second volume of the proceedings contains the full-length papers presented at the Workshop. The organization of Volume II is as follows:

1. Invited papers related to a survey of the major technical issues relevant to the discharge of drilling effluents (Chapter 1),
2. A discussion of regulatory issues (Chapter 2),
3. Comments on the relation between physical fate models and biological impact of drilling effluents (Chapter 3),
4. Description of the models selected for evaluation and their application to the standard data sets (Chapter 4), and
5. The contributed papers on other relevant models and methodologies (Chapter 5).

1.2 THE PURPOSE AND BACKGROUND INFORMATION

by

Dr. Fred Piltz

HISTORY OF THE WORKSHOP

The Minerals Management Service (MMS) has the responsibility for leasing oil and gas rights on the Federal Outer Continental Shelf (OCS). This responsibility is delegated by the Secretary of the Interior to the MMS. The MMS also administers the leases after they are awarded by competitive bid to the oil and gas industry. Part of the responsibility of MMS is to make environmental assessments of the effects which oil and gas exploration, development, and production activities may have on the marine environment. These assessments are made by an environmental assessment staff within each OCS region. Assessments are made prior to lease sales in an Environmental Impact Statement (EIS) and prior to exploration or development of the leased tracts in the form of an Environmental Assessment (EA). The subjects considered in these documents range from socioeconomic considerations, such as the growth in community services expected to result from the activity, to the subjects most of us are familiar with: biology, chemistry, and physical oceanography. In concert with the subjects considered in these environmental assessments, a wide range of data are needed and a diverse array of phenomena must be understood to varying degrees. It is the responsibility of the Environmental Studies Program to provide these data and knowledge.

Among the Environmental Assessment Section's many information needs has been an accurate assessment of the fate and effects of the materials discharged during routine oil and gas exploration and development activities. This need led to the Branch of Environmental Studies in MMS (formerly the Bureau of Land Management OCS Program) along with the Environmental Protection Agency (EPA), American Petroleum Institute (API) and other U.S. and Canadian agencies to sponsor a symposium in 1980. The Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings answered many of the informational needs of preleasing and post-leasing assessment but left some questions unanswered and raised some new questions.

The Pacific OCS Region FY 1982 Environmental Studies Plan recognized the needs of the Environmental Assessment staff for more information regarding the behavior of discharges by including a proposed study "Rig Monitoring: Platform Discharge Model and Validation". This proposed study, with other proposed studies, was discussed at a workshop held in Los Angeles in March, 1982 sponsored by the Pacific OCS Office. The workshop focused on long-term environmental monitoring and the participants and scientists on the workshop panel recommended modification of the proposed FY 1982 study. They recommended separating the one study into two with first an evaluation of existing numerical models and modeling to be followed by a later study involving field testing and validation of the model or models. This workshop follows those recommendations, and future work will be strongly influenced by the discussions and recommendations which evolve this week.

ENVIRONMENTAL ASSESSMENT CONCERNS AND QUESTIONS

The following concerns and questions generated in the Environmental Assessment staff subsequent to the 1980 symposium in Florida will provide a perspective for the scope of this workshop and focus attention on some items for discussion.

This workshop's scope includes only the fate of materials discharged from OCS platforms (or other rigs). Concerns and questions regarding the effects or impacts of these materials on the living portion of the ocean are not being ignored either in the environmental assessments or environmental studies. These questions have been deferred as a topic for this workshop in order to efficiently deal with the physical fate of discharges. One of the papers being presented, by Dr. Gary Petrazullo, will in fact give some idea of the considerations being given at this time to the effects and impacts of discharges.

Perhaps the most important question for environmental assessment regarding the fate of discharges in the ocean is "How accurately do the available models predict the behavior of plumes of materials"? Having asked this apparently simple question, one is quickly led to ask what is meant by "accurately"? Over what time periods do predicted and measured plume

trajectories match closely? Under what oceanographic conditions do model predictions match measured plume trajectories? What is close match? A few centimeters? A few meters? Kilometers?

Do model predictions become worse as the ocean bottom is approached by the plume? If this is the case, are topographic features of the bottom then important parameters to consider in model formulation or initial conditions? Do the above considerations come to bear on buoyant plumes as they near the sea surface? How important are the various physical processes in predicting plume behavior? Should sedimentation-resuspension processes be accounted for in the models? Are microscale processes such as flocculation or chemical reactions significant to plume behavior? Which of these processes are important in the near-field and which in the far-field? Are these processes currently modeled? Can they be?

Specifically related to the models were questions of the individual model's limitations. Did some models include parameterization of processes not included in other models? Were some models designed for only negatively buoyant plumes and therefore unsuitable for some types of discharged materials? Did some models require assumptions such as an unstratified ocean whereas other models required no assumptions?

These and other questions were generated among the environmental assessment staff and others outside of the MMS. This gives some idea of the range of topics which came up for discussion during the workshop. The purpose of the workshop was to discuss many of these questions and pursue what future efforts deserve the attention of the MMS Environmental Studies Program.

1.3 THE OBJECTIVES OF THE WORKSHOP

by

Dr. Akshai K. Runchal

One of the objectives of the workshop is to perform a comparative assessment of the existing models for predicting the transport and fate of drilling effluents in the OCS environment. However, and more importantly, the overall purpose of the workshop is not just to evaluate the existing models but the existing modeling methodology and to make recommendations for future directions. The model assessment should therefore be viewed in the light of this overall purpose of the workshop.

In this context the stress should be placed on those methods which currently exist to handle the real-life problems of drilling effluent discharges in an adequate way. In this context emphasis should be placed on the issues of:

- Current variability,
- Current shear,
- Density stratification and variability,
- Flux of particle settlement,
- Resuspension,
- Long-term transport,
- Flocculation and deflocculation,
- Pre-mixing, and
- Initial separation of plume constituents.

A major objective of the workshop is to reach a consensus on which of these issues merit further research and which are adequately handled by the existing models and methodology. Of course, it is also necessary to define model requirements as far the regulatory agencies, the industry and the public are concerned. Once these goals are achieved, we can develop improved models for predicting the transport and fate of drilling effluents.

2. THE ISSUES RELATED TO MODELING OF DRILLING EFFLUENTS

2.1 CHARACTERISTICS OF DRILLING DISCHARGES FROM PLATFORMS

by

Dr. Robert C. Ayers, Jr.

Drilling discharges consist of two basic types; formation solids which are separated from circulating mud stream by mechanical solids control equipment and bulk mud discharges. Information on the composition, rate and quantity of these discharges will be discussed. Over the life of a well 3-6 months) about 1,000 cubic meters (2,000 tons) of material (dry weight basis) will be discharged. Mud additives account for roughly half of this value and formation solids account for the other half.

Drilling mud and formation solids are discharged to the ocean in two ways. They are either discharged beneath the surface through a large diameter (~10 inch) shunt pipe or they are allowed to free fall through the air to the ocean surface.

The behavior of discharged mud has been observed in several field tests. The main plume, containing most of the discharged materials, sinks rapidly. In addition, a secondary plume is formed which is visible from the surface. This near surface plume contains a small fraction of the total material discharged and remains in the water column. Using data from a field test conducted in the Gulf of Mexico it was estimated that the quantity of discharged material in the surface plume was 5 to 7%. In this same study an underwater movie was taken of the mud plume near the discharge source. The movie clearly illustrates the rapid sinking of the main plume and also shows the formation of the surface plume.

2.2 THE PHYSICS AND PROCESSES RELATED TO DISCHARGE OF MARINE EFFLUENTS

by

Dr. Robert C.Y. Koh

The effectiveness of mathematical models requires that (i) the underlying processes are correctly formulated, and (ii) the model results are properly interpreted. The relevant processes are seldom accurately formulated. While such a model is a useful tool in experienced hands, blind acceptance of model predictions often leads to erroneous conclusions.

Formulation of underlying processes involves three steps: (i) identification, (ii) qualitative understanding, and (iii) quantitative formulation. Numerous processes contribute to determine the transport and fate of waste discharged into the sea. These include (i) various phenomena in density-stratified flow, (ii) particulate coagulation, ablation and breakup, (iii) turbulent dispersion and resuspension.

There are principally two methods of discharge: (i) via pipeline and (ii) from a vessel. Drilling mud discharge from an offshore platform is more like discharge from a vessel. In some cases, the mud is allowed to free fall from the elevated tank. In others, a submerged pipe is used. The wake of the drilling platform structure can play a significant (and difficult-to-predict) role in nearfield mixing.

Most wastes may be regarded as a mixture of a liquid and a suspension of solid particles. An important physical property is the bulk density. The discharged waste will sink or rise depending upon whether it is heavier or lighter than the ambient water. Because of the continuous mixing which occurs in the process, this sinking or rising may terminate before the diluted waste reaches the fluid boundary if there is sufficient density stratification in the receiving water. Research in the past two decades has greatly improved the ability to predict this phase of the transport process for those wastes where particulates do not contribute significantly to the dynamics of the mixing process. Following the rise (or fall) the diluted waste would next tend to spread out horizontally and collapse vertically. This gravitational spreading can lead to quite rapid horizontal movements; often much more than

would have been the case without density effects.

The presence of solid particles introduces another family of processes which affect the fate and transport of effluents. One important phenomenon affecting particulates is flocculation. Because of the high ionic strength of seawater, wastes which contain mainly fresh water when discharged into the sea often show a high tendency to flocculate. Fluid shear can not only promote flocculation but also particle breakup. Another process involving particulates is that of deposition and resuspension. Present understanding of these processes is fragmentary.

The effect of particles and density stratification in combination with gravity can also affect the fluid dynamics in the discharge pipeline itself. The discharge may be neither homogeneous across the exit nor steady in time. These inhomogeneities would alter the transport and fate of the discharges.

Beyond the nearfield, transport and further mixing are affected by ocean currents and turbulence, both of which are quite site-specific. Success of modeling in the farfield depends primarily on adequacy of field data. In the longer term, the disposition of the particulates is also subject to periodic redistribution by episodic events such as storms.

2.3 ENTRAINMENT, DEPOSITION, AND LONG-TERM TRANSPORT OF FINE GRAINED SEDIMENTS

by

Dr. Wilbert Lick

Recent work on the settling, diffusion, entrainment, and deposition of fine-grained sediments will be reviewed and synthesized. Particular attention will be given to the dependence of these processes on sediment properties such as particle size. The application of this knowledge to the analysis and numerical modeling of the long-term transport of fine-grained sediments will also be discussed. The discussion will primarily be based on (1) entrainment, net entrainment, and deposition experiments performed on sediments from Lake Erie and also artificial uniform-size, fine-grain sediments, and (2) field data (turbidity) from water intakes as well as from satellites.

2.4 A STATE-OF-THE-ART REVIEW OF MODELING OF DRILLING FLUIDS AND CUTTINGS

by

Mr. Maynard G. Brandsma

Modeling of discharges from drilling rigs is reviewed. The review begins with a summary of drilling rig discharges. Reasons for modeling drilling effluents are discussed along with the view that modeling is an art because of the imperfect nature of the science.

Accuracy of effluent modeling cannot be set in absolute terms. The desired accuracy can only be set in terms relative to the accuracy desired for impact assessment.

Models appropriate for modeling drilling mud discharges and models appropriate for modeling cuttings discharges are named. Mechanisms effecting discharges are reviewed: pre-dilution in the discharge pipe, drilling rig wake effects, flocculation, resuspension, and the effects of heavy, fast-settling particles. Long-term modeling is discussed. Recommendations for field verification of models are made.

2.5 AUTOMATING THE SECTION 403(C) DETERMINATION

by

Dr. William S. Beller

The nation's accelerated schedule for leasing offshore land for oil/gas operations shortened the time available for the Environmental Protection Agency (EPA) to formulate National Pollutant Discharge Elimination System (NPDES) permit conditions. To work within the time allotted, EPA is developing a computer model based on (1) Section 403(c) of the "Clean Water Act", and (2) "Ocean Discharge Criteria", an EPA policy document. A first model is on hand, but improvements are needed, especially in terms of acquiring realistic plume models of the discharges.

2.6 COMMENTS ON THE LINK BETWEEN THE FATES AND EFFECTS MODELS

by

Dr. Ruthann Corwin

The paper comments on the complex and necessary interaction between the physical fate and effects models and requirements of the predicting the biological effects of the drilling effluents. Specific recommendations are made to consider the option of convening a biological and ecological effects workshop with a multidisciplinary panel to consider this interaction. It is recommended that such a workshop should focus on the California offshore environment because it provides a range of oceanographic and bathymetric conditions. The paper points out the need for special consideration of the biological factors, such as vertical migration and the range of sensitivity of species, which must be included in any consideration of adverse effects.

It is pointed out that the benchline information for most marine invertebrates north of Point Conception is presently non-existent. New studies have discovered a range of new species. Many California marine organisms are being investigated for commercial, pharmaceutical and industrial exploitation. The richness and diversity of the species is a special cause for proceeding with due care in considering any industrial impacts.

It is concluded that the validation of short-term plume models is less useful for impact assessments and mitigation proposals than that of the general models which allow for estimation of concentrations, affected volumes and areas, and exposure times over an extended range.

3. THE MODELS SELECTED FOR COMPARATIVE EVALUATION

3.1 THE DRILLING MUD AND CUTTINGS MODELS*

A. THE OOC MODEL

by

Mr. Maynard G. Brandsma** and Mr. Theodor C. Sauer, Jr.

B. THE MODIFIED KOH-CHANG MODEL

by

Dr. Frank Wu** and Dr. Thomas Leung

C. THE KRISHNAPPAN MODEL

by

Dr. B.G. Krishnappan**

D. THE DRIFT MODEL

by

Dr. Akshai K Runchal***

NOTES:

- * The models are identified by the names of the authors/developers.
- ** Denotes the name of the author presenting the model at the Workshop
- *** This model was presented at the Workshop by Dr. Ian Austin of Dames & Moore, Los Angeles.

A. THE OOC MODEL

by

Mr. Maynard G. Brandsma and Mr. Theodor C. Sauer, Jr.

The Offshore Operators Committee (OOC) and Exxon Production Research Company have funded the development of a computer model to describe the fate of offshore drilling mud discharges. The model is an evolution of earlier models for dredged material discharges developed for the U.S. Environmental Protection Agency and for the Army Corps of Engineers.

Drilling mud goes through three phases after its release: descent of the jet material through the water column, dynamic collapse in which the material spreads out on the bottom or within the water column, and passive diffusion when the transport and spreading of the plume are determined more by ambient currents than by any dynamic character of the plume. The dynamic calculations are derived from the Koh-Chang model with numerous changes. The passive diffusion portion of the model is of Lagrangian formulation. It is based on the idea that groups of particles leaving the dynamic plume, and the plume itself, can be represented by many small, independent, Gaussian distributed clouds of material. Each cloud is independently advected, diffused, and settled according to local conditions. The concentration of material at any given point is the sum of the contributions from each cloud.

Model performance has been compared with field studies of mud discharge plumes. Some observed features such as drilling rig wake effects, initial dilutions within the discharge pipe, and early separation of fine solids from the main part of the plume (which forms the observed surface plume) are included in the model. The pipe dilution mechanism proved ineffectual and needs more study. The mechanism which estimates the early separation of fine solids from the plume strongly influences the distribution of material in the water column. Comparison of model results and field and laboratory measurements have shown that the model reproduces several observed features of mud plume behavior. There are, however, some features such as drilling rig wake effects and predilution in the discharge pipe that need to be investigated further.

B. THE MODIFIED KOH-CHANG MODEL

by

Dr. Frank Wu and Dr. Thomas Leung

Mathematical and numerical models were developed describing the behavior of drilling mud plumes. The formulations of these models are based on the model developed by Koh and Chang (1973) for the simulation of dispersion, diffusion, and settling of barged waste disposal. The predictions of the Koh-Chang Model compare very well with the experimental results for the short-term. Verification of the long-term part of the simulation is needed.

The drilling mud plume is assumed to consist of solid and liquid phases. The solid phase is characterized by constituents with various densities and fall velocities. The material is discharged through a submerged nozzle into the ocean. The effects of ambient current profiles, density stratification, variation of diffusion coefficients are incorporated in the model.

The dynamic characteristics of a plume are simulated by the numerical model. The short-term plume simulation includes convective and collapse phases. The long-term dispersion and diffusion equation is solved by the method of moments in the Koh-Chang Model. Brandsma and Divoky (1976) adopted Fischer's (1970) passive diffusion scheme to simulate the long-term phase of dispersion and diffusion. Recently, Leung and Wu (1982) incorporated a resuspension mechanism due to waves and currents into Brandsma-Divoky's long-term passive diffusion model.

The convective descent phase describes the dynamic behavior of a sinking jet. The dynamic collapse phase occurs when the descending plume either encounters the bottom or arrives at the neutral buoyancy stage at which vertical movement is retarded and horizontal spreading dominates. In the long-term phase, the ambient currents and turbulence dominate the transport and spreading of the plume. Transition between phases are accomplished automatically in the numerical model. Special efforts have been made to minimize the amount of input required by the numerical model. Solutions at any phase of simulation are displayed. Graphic output is also incorporated.

C. THE KRISHNAPPAN MODEL

by

Dr. B.G. Krishnappan

The Krishnappan model, originally developed for predicting the dispersion of dredged material when dumped in deep water as a slug, is adopted for predicting the dispersion of drilling muds and cuttings resulting from the offshore drilling platforms in outer continental shelf. The model is based on empirical data and the theory of dimensions. The laboratory experiments on the motion of clouds of uniform size particles in a stagnant water revealed that the motion consisted of two phases: 1) the "entrainment" phase, when the size of the cloud increased, mainly due to the incorporation of the surrounding water into the cloud; and 2) the "settling" phase, when the downward velocity of the cloud coincided with the terminal fall velocity of the individual solid particles constituting the cloud. The theoretical formulation of the entrainment phase was made using the theory of dimensions similar to the approach of Batchelor (1954), who considered the motion of the clouds formed by the "denser fluids" moving in a lighter medium. The settling phase was formulated using a method outlined by Koh (1971).

The motion of the clouds formed by a mixture of solid particles of different sizes and specific weights was formulated using a "superposition" principle. Accordingly, the total behavior is predicted in terms of the behaviors of the fractions, each of which is of a particular size and specific weight. The model allows the fractions to settle out of the main cloud as the vertical downward velocity of the cloud coincides with the fall velocities of the various fractions.

The model, in its original form, was formulated for the case where the material is released as a slug. To apply the model for the case where the discharge is continuous, the latter is treated as a series of slugs. The volume of a slug is computed by the discharge velocity to the vertical downward velocity of the cloud at the location of discharge as predicted by the model. The model is only applicable when the momentum of the discharge is small.

D. THE DRIFT MODEL

by

Dr. Akshai K Runchal

The Drilling Effluent Fate and Transport model, DRIFT, employs a probabilistic approach for predicting the long-term fate and transport of drilling effluents (Runchal 1983). The model is, in fact, a combination of short- and long-term models coupled with the observed occurrence frequencies of the current structure for the specific site under consideration. The observed current pattern is divided into a number of speed and direction categories by depth and horizontal location. Interpolation is employed to obtain values at locations intermediate to those at which the measurements are available. Each of these categories is then assigned a probability of occurrence, and it is assumed that the effluent is under the influence of each of these categories in proportion to its probability of occurrence. For each category, a short-term and a long-term model is then employed and the final results are obtained by the method of superimposition.

For the determination of short-term fate, any of the available models for the formation waters or cuttings may be employed within the framework of the DRIFT model. For the determination of long-term fate, the present version of the model employs a simple transport algorithm incorporating advection, settling and deposition. Other phenomena such as dispersion and resuspension may be included without extensive modification to the framework of the model. At present, the DRIFT model only provides the expected values for the concentrations or travel times and distances for the drilling effluents. The standard deviation may be calculated without substantial modification to the mathematical framework of the model if the variance of the currents is available from the field data. The model has been employed in conjunction with field studies at Lower Cook Inlet, Alaska (Atlantic Richfield Company 1978) and to a data base offshore of California (Austin 1983).

3.1.2 THE FORMATION WATER MODELS*

A. The PDS Model

by

Mostafa A. Shirazi and Lorin R. Davis

B. The DKHPLM model

by

Lorin R. Davis

C. The OUTPLM model

by

Winiarski and W.E. Frick

D. The PLUME model

by

D.J. Baumgartner, D.S. Trent and K.V. Bryam

- * The models are identified by the names of the authors/developers. All of these were presented at the Workshop by Dr. Lorin Davis of Oregon State University.

THE PDS/DKHPLM/OUTPLM/PLUME MODELS

There are several models that have been developed to predict the fate of buoyant jets that do not contain suspended particles. They include simple empirical expressions that approximate plume behavior using dimensionless parameters; integral models that solve the energy, momentum, and continuity equations by integrating over assumed velocity and concentration profiles; and complicated numerical models that divide the receiving body into a large number of grid points and solve the governing equations at each grid point assuming turbulent diffusion coefficients throughout the field. Integral models have been the most widely used because of their simplicity and relative accuracy in predicting the fate of the effluent.

Four different integral computer models were selected for the comparative evaluation at this workshop. They are:

1. the PDS model by Shirazi and Davis that calculates the three-dimensional plume that is caused by the discharge of a buoyant fluid from a rectangular structure at the surface of a large, flowing receiving body,
2. the DKHPLM model by Davis that calculates the plume from a submerged multiple port diffuser discharged into a flowing stratified deep ambient,
3. the OUTPLM model by Winiarski and Frick that calculates the plume from a submerged single port discharge into a flowing, stratified ambient, and
4. the PLUME model by Baumgartner and Trent that calculates the plume from a submerged single port discharge into a stagnant, stratified ambient.

Details of the PDS model can be found in Shirazi and Davis (1974); information on the other three models can be found in Teeter and Baumgartner (1979).

4. THE STANDARD DATA SETS FOR MODEL EVALUATIONS

4.1 A SUMMARY OF THE STANDARD DATA SETS

by

Dr. Akshai K. Runchal

For comparative evaluation of the selected models, a set of five laboratory and field test cases were selected. These consisted of:

1. a jet discharged horizontally in a non-stratified environment,
2. a laboratory simulation of mud dump,
3. a field study of mud dump in the Gulf of Mexico,
4. a jet discharged horizontally in a stratified environment, and
5. a vertical jet into a non-stratified, flowing environment.

The second and third test cases represent the mud discharges under the simulated and real OCS environment, respectively. The other three test cases provide data for comparative evaluation of the initial convective phase of mud discharges under a range of conditions encountered in the OCS environment. It should be remarked that this initial convective phase plays an important role in the physical processes governing the transport and fate of a drilling effluent in the OCS environment.

The pertinent details of these test cases are summarized below. A more complete description is available in the references cited. The laboratory test case, Test Case 2, is also described in further detail in Section 4.2.

TEST CASE 1

This test case is based upon the data of Koester(1974; Experiment #3, Table 4-1, page 36). It consists of the discharge of a buoyant jet into a stationary uniform density fluid. The primary purpose for the inclusion of this test case is to check the dynamic components of the models dealing with the transport of fluid. The available data for comparative evaluation consists of jet centerline trajectory, dilution, isotherm areas, jet half-depth and surface half-width (see Appendix C for definition of technical terms). The salient features of the test case are summarized in Table 1 below.

TABLE 1: SALIENT FEATURES OF TEST CASE 1

1. Jet Discharge Velocity:	1.13 ft/s
2. Jet discharge diameter:	0.106 ft
3. Discharge angle:	0 Degrees
4. Total water depth:	0.67 ft
5. Discharge Location:	0.22 ft from bottom
6. Temperature Difference (Exit - Ambient):	18.4 °F

TEST CASE 2

The second test case is based upon the laboratory simulation of a mud dump conducted at the Oregon State University by Davis and Mohebbi (Section 4.2). The tests consisted of the discharge of drilling muds under controlled conditions in a uniformly moving fluid with density stratification. The available data for comparative evaluation consists of total suspended solids concentrations in the plume with distance and depth, and the jet trajectory. The dimensions of the plume can be deduced from the given data. The simulated test data is summarized in Table 2.

TABLE 2: SALIENT FEATURES OF TEST CASE 2

1. Discharge Velocity:	34.9 cm/s		
2. Discharge diameter:	8 inch		
3. Discharge rate:	256.5 bbl/hr		
4. Density at discharge:	1.184 g/cm ³		
5. Ambient Density:	As given in Figure 1 (Page 29, Section 4.2)		
6. Ambient Velocity:	30.5 cm/s		
7. Mud Composition: (by weight)	8.59% high gravity solids with S.G. 4.2 14.62% low gravity solids with S.G. 2.6. 76.79% water		
8. Mud components and Settling Velocities:	<u>Name of Component</u>	<u>Volume Ratio</u>	<u>Settling Velocity (ft/s)</u>
	High Gravity 1	0.00071	0.043
	High Gravity 2	0.00896	0.008
	High Gravity 3	0.00888	0.0008
	High Gravity 4	0.00566	0.00006
	Low Gravity 1	0.00075	0.030
	Low Gravity 2	0.00981	0.005
	Low Gravity 3	0.01121	0.0005
	Low Gravity 4	0.04482	0.0000000001
	Water	0.90921	-----

TEST CASE 3

The third test case is based upon the field experiments conducted by ECOMAR (1980) under the direction of Exxon Production Research Company. The test case selected consisted of a drilling mud discharge of 275 bbl/hr in the Gulf of Mexico. The available data for comparative evaluation consists of the currents, measured light transmittance, density, water samples at specific locations and a number of other parameters. The test data is summarized in Tables 3 below.

TABLE 3: SALIENT FEATURES OF TEST CASE 3

1.	Discharge Velocity:	36.0 cm/s		
2.	Discharge diameter:	8 inch		
3.	Discharge rate:	275 bbl/hr		
4.	Density at discharge:	2.088 (S.G.)		
5.	Ambient Density:	Per Figure 13 of Ecomar (1980)		
6.	Ambient Velocity:	Per Table 9 of Ecomar (1980)		
7.	Mud composition:	62.0% High Gravity Solids (S.G. 4.2) 8.2% Low Gravity Solids (S.G. 2.6) 29.8% Water		
8.	Mud components and Settling Velocities:	<u>Name of Component</u>	<u>Volume Ratio</u>	<u>Settling Velocity (ft/s)</u>
		High Gravity 1	0.0090	0.043
		High Gravity 2	0.1140	0.008
		High Gravity 3	0.1130	0.0008
		High Gravity 4	0.0720	0.00006
		Low Gravity 1	0.0007	0.030
		Low Gravity 2	0.0097	0.005
		Low Gravity 3	0.0111	0.0005
		Low Gravity 4	0.0443	0.0000000001
		Water	0.6262	-----

TEST CASE 4

This test case is based upon the experimental data of Fan (1967; Experiment #32, Table 1, page 61). The available data for comparative evaluation consists of photographs of the jet, concentration profiles, jet trajectory and extent. The data supplied for model simulations is summarized in Table 4.

TABLE 4: SALIENT FEATURES OF TEST CASE 4

1.	Jet Discharge Velocity:	72 cm/s
2.	Jet discharge diameter:	0.25 cm
3.	Discharge angle:	0 Degrees
4.	Discharge density:	1.0134 g/ml
5.	Ambient density:	1.0013 g/ml
7.	Ambient density gradient:	0.000095 /cm
8.	Jet Reynolds Number:	1,800
9.	Jet Froude Number:	40

TEST CASE 5

The fifth and final test case is also based upon the data of Fan (1967; Experiment #20-12, Table 4, page 117). The available data for comparative evaluation consists of photographs of the jet trajectory and width, and some information about the concentration profiles and dilution. The pertinent details of the input data are summarized in Table 5.

TABLE 5: SALIENT FEATURES OF TEST CASE 5

1.	Jet Discharge Velocity:	208 cm/s
2.	Jet discharge diameter:	0.76 cm
3.	Discharge angle:	90 Degrees
4.	Jet density ratio:	0.146
5.	Jet Reynolds Number:	16,200
6.	Jet Froude Number:	20
7.	Velocity ratio:	12

4.2 A DESCRIPTION OF THE LABORATORY DATA SET - TEST CASE 2

by

Dr. Lorin R. Davis

An experimental investigation was conducted at Oregon State University by Lorin R. Davis and Behrooz Mohebbi to study the fate of drilling mud when discharged into a controlled stratified moving environment. What is presented here is preliminary. The final report on this work is pending.

Experiments were conducted on a 40 foot long towing channel. The water in the towing channel was stratified to simulate the ambient profile shown in Figure 1. The discharge and sample collection systems were towed on rails above the towing channel at a controlled rate to simulate current as shown in Figure 2. An actual drilling mud taken from a well off the coast of California was used in the tests. Discharge and ambient conditions, given previously in Tables 2 and 3, were adjusted to simulate field discharge conditions.

Samples were extracted using the sample suction tubes through the vertical centerline of the plume at various distances downstream of the discharge port in order to obtain plume trajectory and concentration profiles. The extracted samples were analyzed for total solids concentration and composition. Solids concentrations were determined using a mass balance while compositions were determined using a neutron activation analysis of the solids.

Figure 3 shows the results of the total solids composition measurements. This figure shows lines of averaged constant concentration within the suspended plume in mg/gm. It is easy to determine plume size and centerline trajectory as well as cross sectional concentration profiles from this figure. Figure 4 is the same type of plot for the high gravity solids present in the plume (Ba SO_4). By comparing these two figures, it can be seen that there has been very little settling of the high gravity solids relative to the total. This was attributed to the low initial concentration of Ba SO_4 in this mud and that long term diffusion and settling has not yet started in the measurement region of these tests.

EQUIVALENT AMBIENT STRATIFICATION

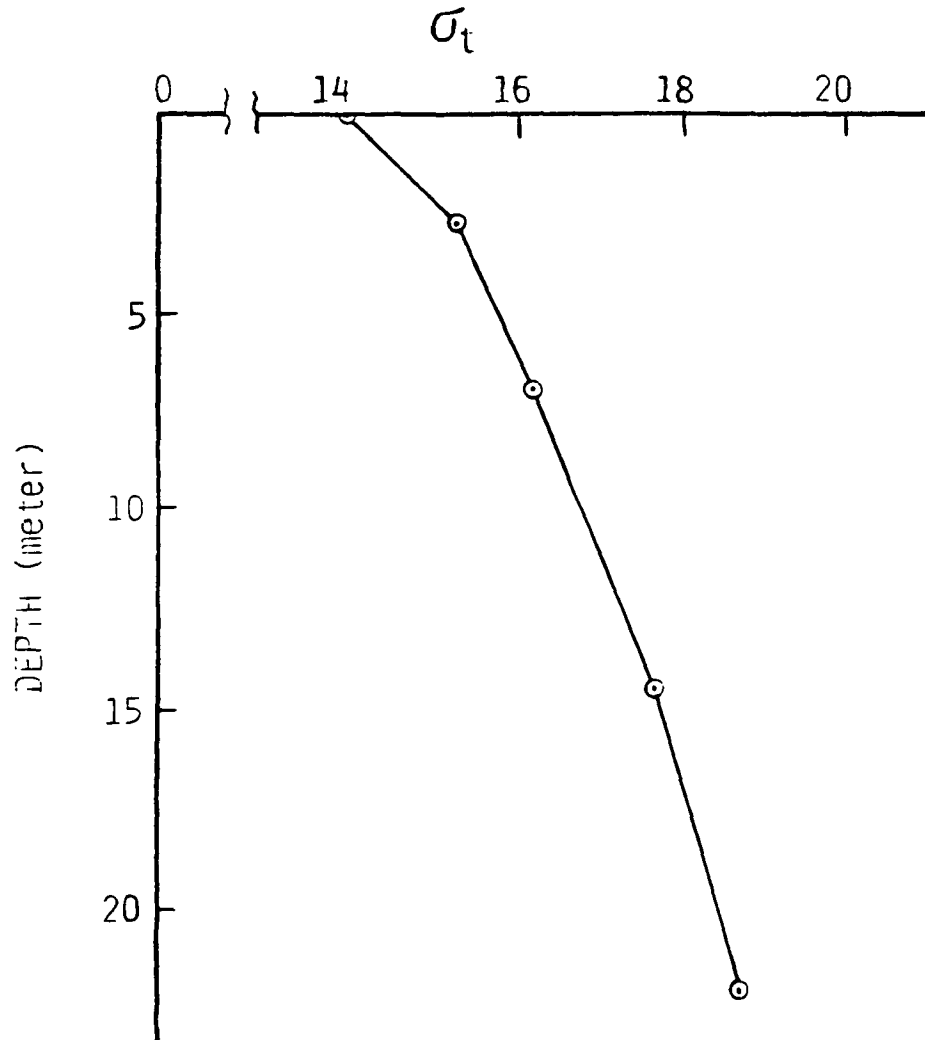


Fig. 1 Simulated Ambient Density Profile

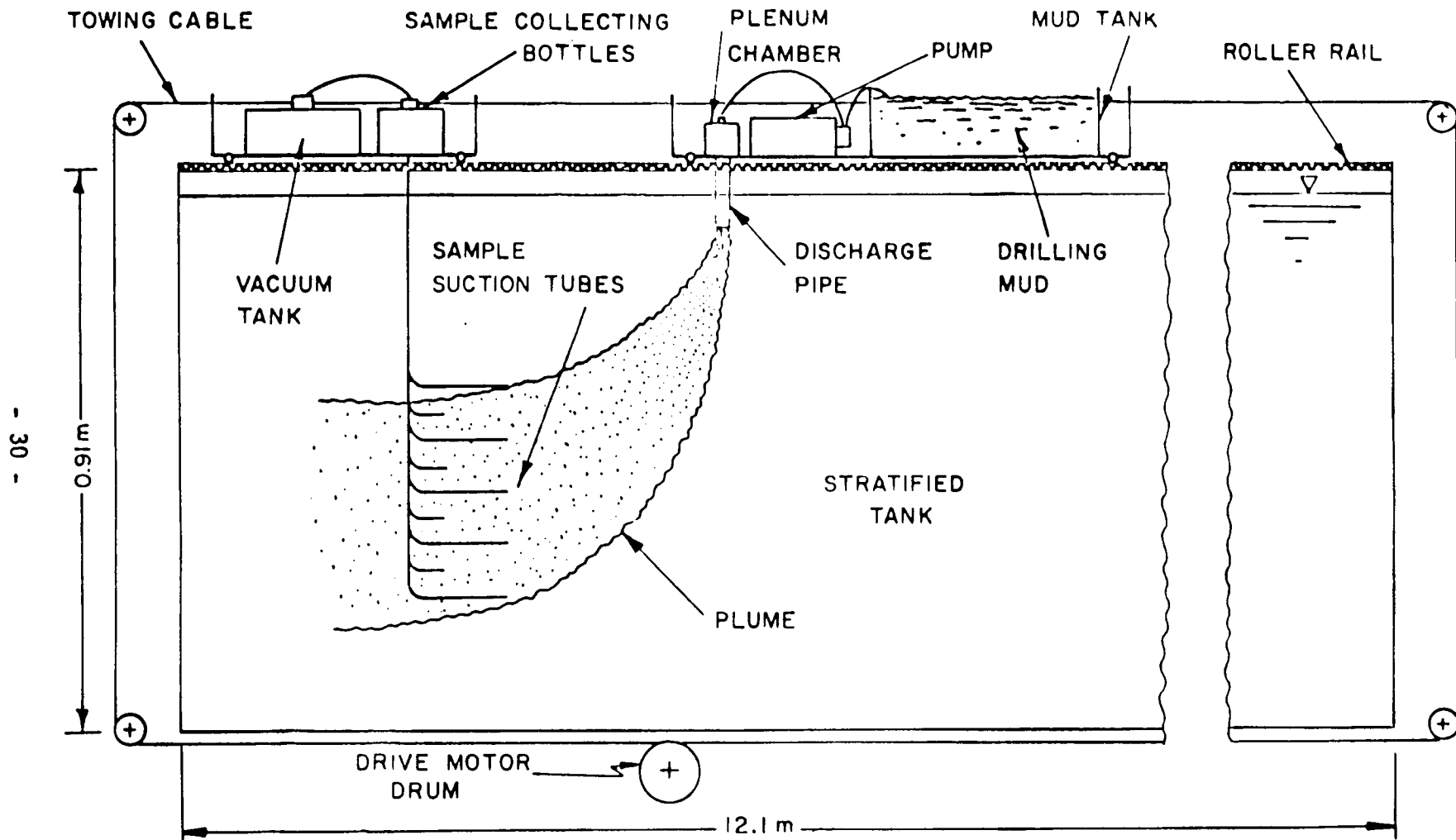


Fig. 2 Sketch of Towing Channel and Mud Discharge and Sample Collection System

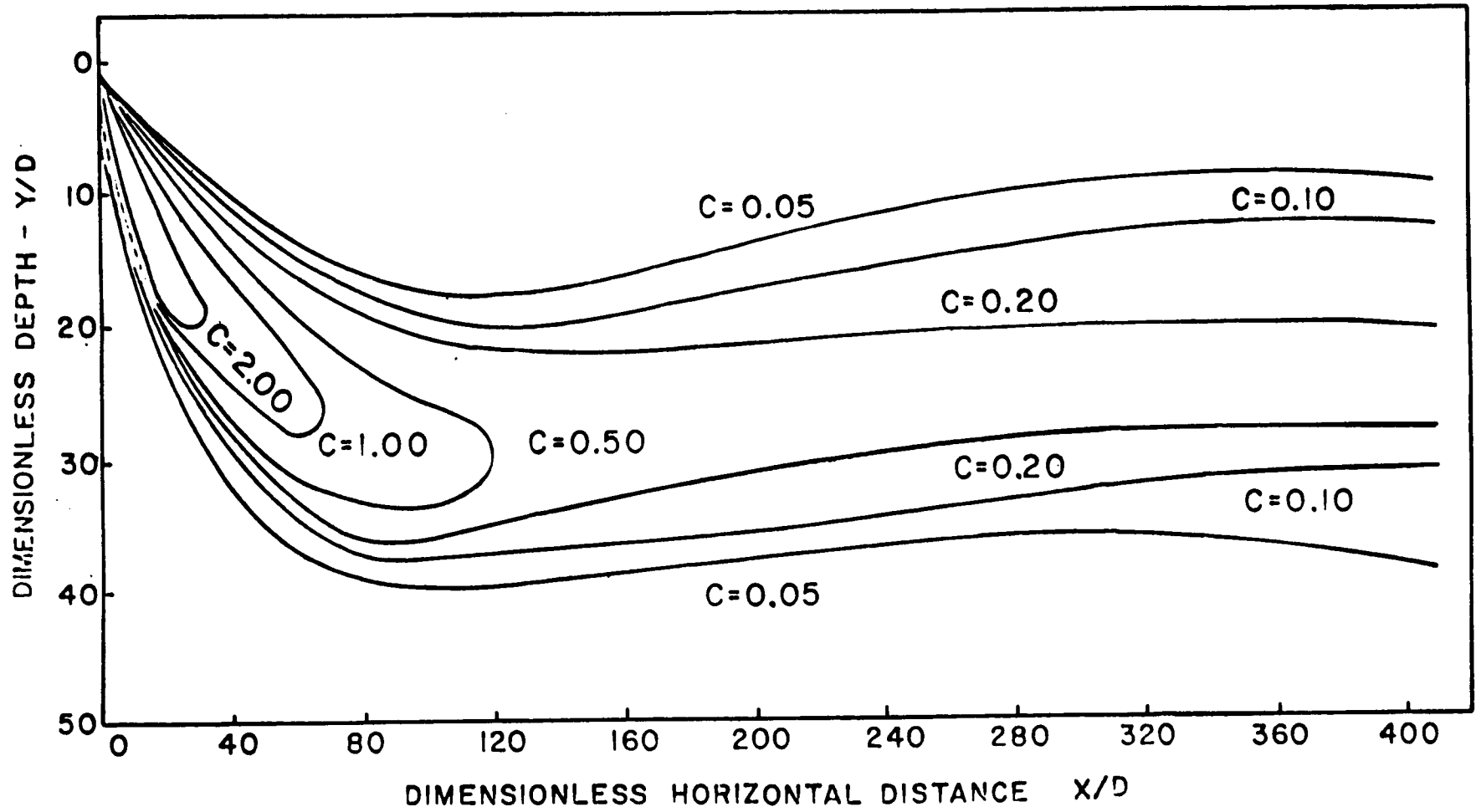


Fig. 3 Contour plot of total suspended solids concentration (mg solids/gr solution)

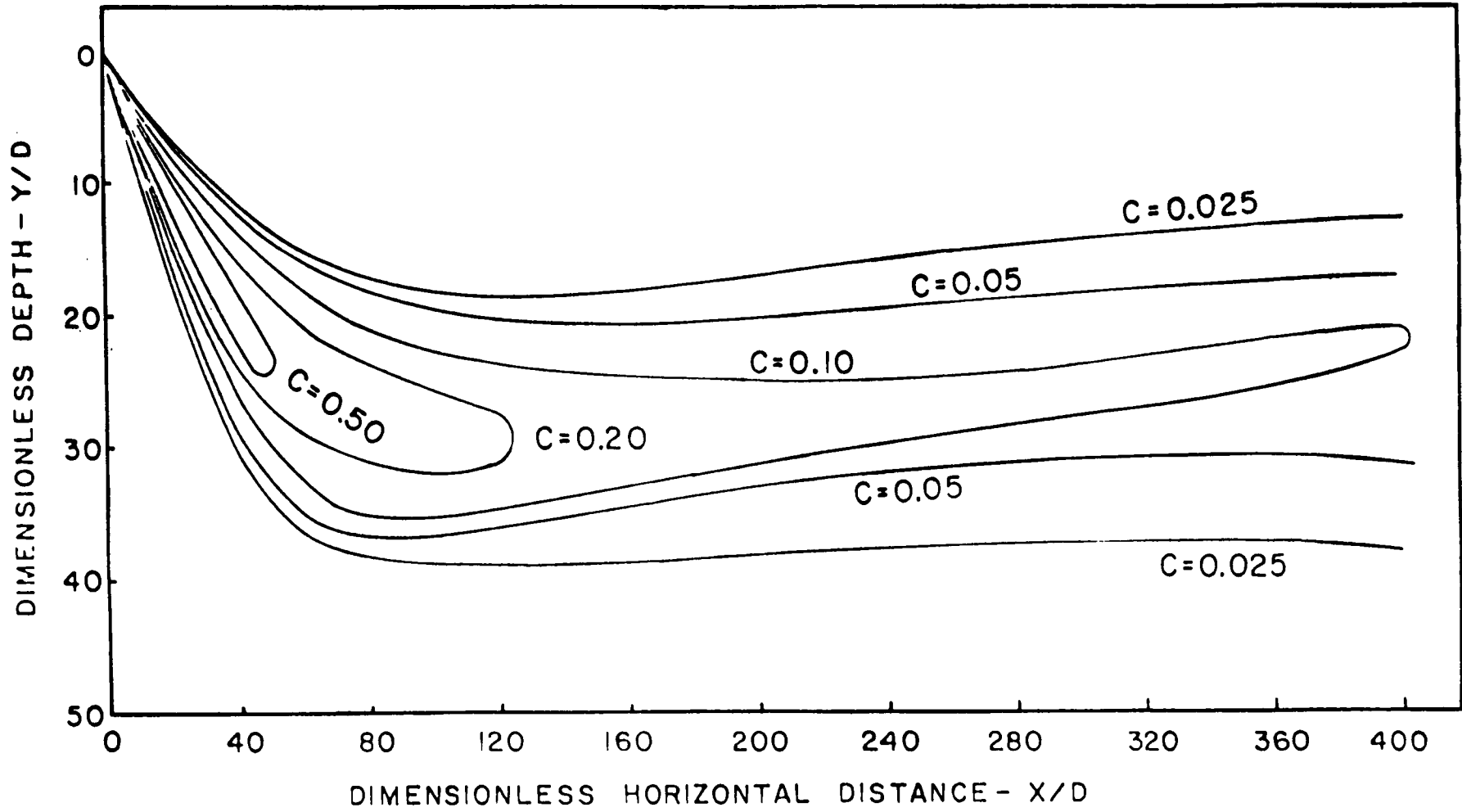


Fig. 4 Contour plot of high gravity solids (BaSO_4) concentration (mg BaSO_4 /gr solution)

5. EVALUATION OF SELECTED MODELS

by

Dr. Anthony J. Policastro

5.1 SUMMARY

The important theoretical features of three drilling mud and cuttings models modified Koh-Chang, OOC, and Krishnappan are reviewed. Differences in the model formulations are presented. Intercomparisons of the models (including those for formation water [PDS, DKHPLM, PLUME, and OUTPLM] are made with the five standard data sets (see Section 4). It is found that:

1. Not all models apply or can run for all five data sets,
2. The OOC model performed best for the most complete data set, Test Case 2,
3. For the ECOMAR (1980) field study case, Test Case 3, there is a factor of 10 and 5 difference in deposited solids between the OOC and modified Koh-Chang models at simulation time of 4320 and 7200 seconds, respectively, after the start of the mud release. This large discrepancy is due to the different treatment of particle settling in the two models.
4. The models remain largely unvalidated with field and laboratory data in the low densimetric Froude number range common to mud and produced water discharges.

New lab data are introduced from Viollet (1977) and Dunn et al. (1982) which can be used for future testing of the models. These data cover the convective descent and dynamic collapse regions of the mud discharge and the near-field portion of the produced water discharge plumes.

5.2 INTRODUCTION

The purpose of this paper is to provide a review of the theory and performance of the short-term fate models presented at this workshop. The first type of models considered (modified Koh-Chang, OOC, and Krishnappan) are those appropriate to mud and cuttings discharges as negatively buoyant sinking plumes. The second type of models (PDS, DKHPLM, PLUME, and OUTPLM) are those applicable to produced water. The latter plumes are usually either positively or negatively buoyant and may interact with either sea surface or the bottom.

The review does not include the DRIFT model. The DRIFT model is essentially a long-term model. None of the five standard test cases (see Section 4) selected for model evaluation provided any information for long-term application or comparison of models. The DRIFT model application presented at the workshop (Austin, 1983) consisted of a generic application to a site offshore of California and did not provide any comparisons with field data. The evaluation of the long-term models must therefore await availability of suitable verification data.

Five standard data sets were defined by the Scientific Panel and were sent to each modeler. Each modeler was encouraged to apply his model to each of the five data sets and present his predictions at the Workshop. The measured plume characteristics as well as measured discharge and ambient data were provided to the modeler. Our purpose here is to provide an intercomparison of the modeler's predictions with the data in order to draw some preliminary conclusions concerning the performance of each model and of the models as a class. Further work is required to provide a more definitive evaluation.

5.3 IMPORTANT PHYSICAL PARAMETERS

The physics of the mud/cuttings and produced water plume dispersal process has been presented in an earlier paper in this Workshop by Dr. Robert Koh (Section 2.2). We review here the three major nondimensional parameters that govern the dispersion and the type of plume that may result from those parameters. The parameters are:

$$F_o = \frac{U_o}{\sqrt{g \Delta \rho / \rho_a} D_o} , \quad K = \frac{U_a}{U_o} , \quad B = \frac{\Delta \rho}{\rho_a} .$$

Here F_o is the initial densimetric Froude number of the discharge, K is the ratio of ambient to initial discharge velocity, and B is the Boussinesq parameter. In the above formulas:

U_o = initial discharge velocity,

D_o = exit port diameter,

ρ_a = density of the ambient ocean at point of discharge

$\Delta \rho = \rho_o - \rho_a$ = difference between density of the discharged effluent and the ambient ocean, and

U_a = ambient current velocity (at location of discharge port).

For the mud cuttings problem, the likely range of these parameters is:

$$0.2 \leq F_o \leq 1.0; \quad 0 \leq K \leq 1.0; \quad 0.15 \leq B \leq 1.0.$$

For the produced water discharge problem, the range is:

$$0.2 \leq F_o \leq 2.0; \quad 0 \leq K \leq 1.0; \quad 0.5 \leq B \leq 1.0.$$

This range in parameters is unique to the mud/cuttings and produced water problems. The plumes are highly buoyant with, in general, strong Boussinesq effects. The Boussinesq approximation will not be valid for these applications. The most similar physical situation is that of natural-draft cooling tower plume (NDCT) dispersion in which $0.4 \leq F_o \leq 1.0$ and $0.0 \leq K \leq 5.0$, but for NDCT plumes $0.9 \leq B \leq 1.0$. Both applications involve significant ambient fluid entering the discharge orifice during discharge.

It should be recognized that data from other plume discharges which do not match the same range in F_o , K , and B as the mud/cuttings or produced-water discharges are not directly applicable to this problem. For instance, much data exist for high F_o , low K , and $B \approx 1$; however, such data should be used with caution in either the calibration or verification process. As will be

noted in more detail later, very little data exist in our range of interest ($F_0 \sim 0.2 - 2.0$, $K \sim 0 - 1.0$, $B \sim 0.15 - 1.0$).

5.4 SUMMARY OF MODEL FORMULATIONS

Both the modified Koh-Chang (Leung and Wu, 1982) and the OOC (Brandsma and Sauer, 1983) models view the dispersion of the mud and cuttings plume as taking place in three phases: the jet, dynamic collapse, and passive diffusion phases. Both models are based on the Brandsma-Divoky model (1976) which, in itself, is based on the earlier Koh-Chang model (1973). In the Brandsma-Divoky model, the one-dimensional integral approach is used to predict the gross plume characteristics in the jet and dynamic collapse regions. Beyond the dynamic collapse region, the plume is divided into many small Gaussian clouds which contain particles (cuttings) of only one size. Each cloud is followed in time with spreading permitted in three dimensions. The concentration at one point at a particular time is computed as the sum of the concentrations at that point from all clouds present. The modified Koh-Chang model is very similar in the dynamic phase to the Brandsma-Divoky model but it has different passive diffusion submodels and incorporates a resuspension mechanism.

The differences between the OOC and the modified Koh-Chang model are outlined below including:

(1) Resuspension: this is not treated by the OOC model since resuspension was thought to be important only in the long term (time scale of months) rather than in the shorter term (time scale of hours and days). Resuspension is treated in the modified Koh-Chang model because it is thought to be important in shallow-water applications.

(2) Lagrangian diffusion phase: The modified Koh-Chang model employs the method of Fischer (1970, 1972); an approximate solution to the convective diffusion scheme. The OOC version was aimed at a scheme that would avoid the requirement in the Fischer method of setting diffusion coefficients to be a function of grid size. The OOC model tracks a large number of puffs individually in three dimensions. The centroid of each puff is tracked and

the dispersion coefficients of the Gaussian distribution for concentration vary in space and time. Use of the Gaussian distribution in the OOC model assumes homogeneous, stationary turbulence.

(3) Impact on the bottom: the modified Koh-Chang model assumes that the normal component of the plume velocity, as it impacts the bottom, drops to zero. The OOC model assumes that 80% of the vertical jet momentum is simply redirected into horizontal momentum along the bottom and the balance is transferred into a collapse impulse (enhancing the lateral spreading after the plume strikes the bottom). The plume impaction phenomenon is largely a pressure effect and is not as simple as either model assumes.

(4) Wake of drilling structure: the OOC model considers this in terms of its effect on the dilution and position of puffs in the passive diffusion phase.

(5) Interaction with water surface: Plume interaction with the surface is not handled in the modified Koh-Chang model; the OOC model treats the surface as a reflecting boundary.

The Krishnappan model is an empirical model based on laboratory data; the data involve the release of a slug of particles without any initial downward momentum into a body of stagnant water. To apply the model, it is required that there be no significant initial momentum. The model simulates a continuous discharge as a series of instantaneous releases. The ambient current can vary with depth but the model does not treat ambient stratification. It is applicable whenever the nondimensional parameter:

$$\frac{2 F_0^2}{3 a_m^2 \beta_m^2 C_0} \leq 1 \quad ,$$

where F_0 is the initial densimetric Froude number, C_0 is the initial volumetric concentration of solids in the discharge, and a_m , β_m are dimensionless constants used in the Krishnappan model.

The above nondimensional number will be less than 1 under conditions of low initial momentum (low F_0) and high initial concentration C_0 . The model applies to discharges of cohesionless particles; in such case, no dynamic collapse region will occur. In effect, then, the Krishnappan model applies to a different type of problem than do the OOC and modified Koh-Chang models.

The models PDS, DKHPLM (recently modified and renamed DKHDEN), PLUME, and OUTPLM may be applied directly to produced water discharges since such plumes are generally positively buoyant and contain no cuttings. These models were originally developed to handle plumes from thermal or waste-water discharges and are applicable as well to the produced water problem. The formulation of each of the models was discussed in the paper by Dr. Lorin Davis in this workshop. The characteristics of the set of models are:

- 1) The models are based on the one-dimensional integral approach in which conservation equations of mass, momentum, and energy are derived. Assumptions are required on the entrainment function and pressure drag force along with similarity assumptions on velocity and temperature (density) across the plume cross-section.

- 2) They treat only the plume rise phase and do not handle the phase of dispersion due to ambient turbulence.

- 3) These models cease to be applicable if plume reaches the bottom of the waterbody or if the depth of the growing plume becomes comparable to the depth of the waterbody. They assume that an infinite ambient waterbody is available to provide mixing.

The author has direct experience with the PDS and OUTPLM models from validation studies over the past several years (Dunn et al., 1975, Policastro et al., 1980). The PDS model applies only to discharges at the surface of a waterbody. For shallow water submerged discharges, it may be applied (only very approximately) by assuming that the discharge is at the surface. Larger surface temperatures (concentrations) should occur for the surface discharge application since less entrainment water is present than for the equivalent submerged discharge. Our validation work with PDS found that:

1. It was one of the two best (of 10) models tested with field and laboratory data,
2. It was accurate to within a factor of 2 in centerline distance to a surface isotherm, a factor of 2 in predicting surface width, and a factor of 5 in predicting isotherm surface areas. The model will perform better for high F_o plumes and for discharges in deep water,
3. Computational difficulties occur often for low F_o jets and for low current cases. Extrapolation methods are recommended in PDS but they are cumbersome to apply. For some problems (low F_o , low current, discharge/current angles greater than 90°), no prediction is possible.

The atmospheric plume version of the OUTPLM model was evaluated by Policastro et al. (1980) with air and water plume field data under low initial F_o conditions. It was one of the three best performing models of the 15 tested. It showed a definite tendency to dilute too rapidly but generally predicted the trajectories correctly. The model could be improved by including a drag force to provide more bending without creating additional dilution.

5.5 RESULTS OF COMPARISON OF MODELS TO THE FIVE STANDARD DATA SETS

Details of the five data sets chosen for model testing were given earlier in these Workshop proceedings. Results of the model/data comparisons are presented in Figures 5 through 10. It may be seen that not all models were applicable or could be run for each data set.

Test Case No. 1 represented a horizontal, submerged discharge into shallow water. From Figures 5 and 6, PDS predictions are excellent. Although not directly applicable to this problem since it is a submerged discharge, PDS performs well apparently due to:

1. The high initial densimetric Froude number for this case ($F_o = 13.2$), and
2. The lack of significant differences (not shown here) in the plume data

TEST CASE No. 1

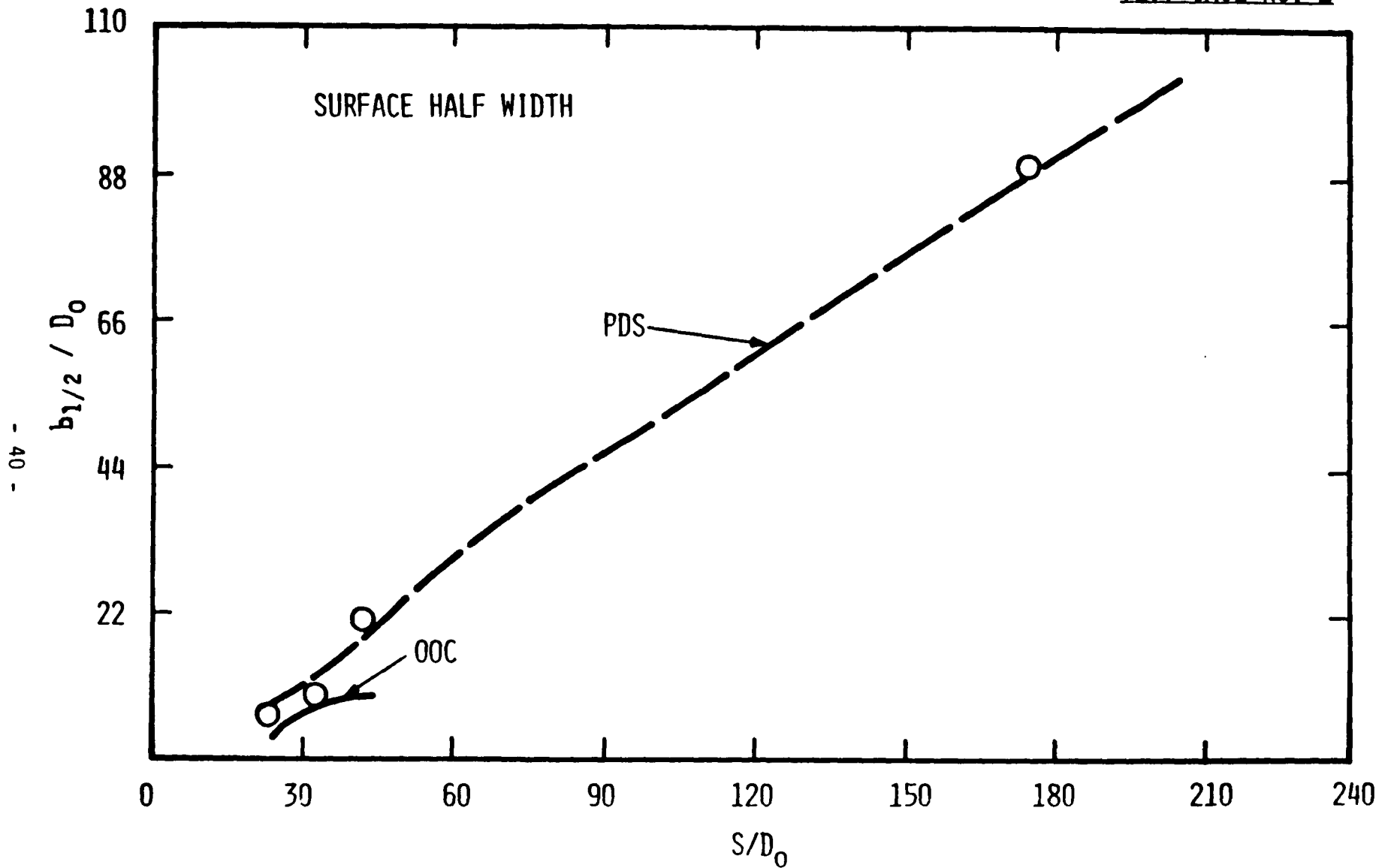


FIG. 5 COMPARISON OF SURFACE HALF-WIDTH OF PDS AND OOC MODELS TO KOESTER DATA, EXPERIMENT No. 3.

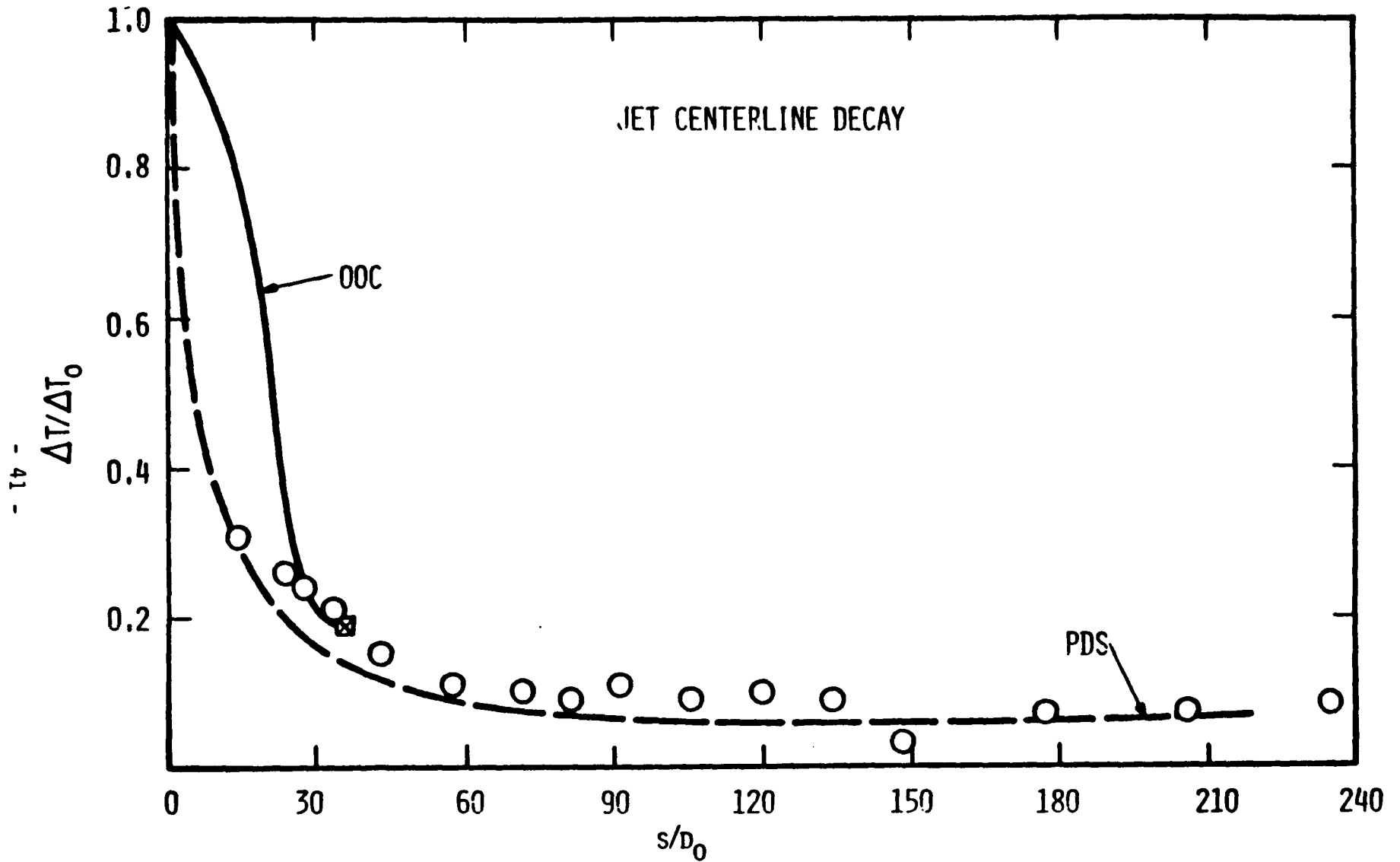


FIG. 6 COMPARISON OF PREDICTIONS OF JET CENTERLINE TEMPERATURE DECAY OF PDS AND OOC MODELS TO KOESTER DATA, EXPERIMENT NO. 3.

themselves (beyond about 20 diameters downstream) for the jet placed at the surface and the jet located in its present submerged position (Koester, 1974).

Thus the discharge at the surface is a fair approximation in this particular case. PDS model performance is typically very good for high F_o discharges in deep water. Performance is usually degraded for low F_o cases.

The OOC model prediction has an unexplainable concave-downward slope to the jet centerline decay curve. This kind of curvature may indicate that insufficient mixing is occurring in the very near field in the model. The OOC prediction terminates at the end of the jet phase. No diffusion phase calculations were made. The modified Koh-Chang model was not run for this case because, in its present form, it is unable to take account of plume interaction with the surface.

Test Case No. 2 refers to the Oregon State University (OSU) Mud Dump Study (Section 4.2) in which high and low density solids were discharged in the laboratory. Convective descent and dynamic collapse regions were observed (see Figures 7 and 8). Models/data comparisons of (a) centerline trajectory, and (b) centerline decay of the average total suspended solids concentrations are given in Figures 7 and 8, respectively. For these data, $F_o = 0.69$ and $K = 0.9$. The OOC model performs very well here in both centerline trajectory and centerline concentration predictions. The difference in predictions between the OOC and modified Koh-Chang Models here (convective descent and dynamic collapse region) is largely due to the different entrainment functions used. Otherwise, the models are very similar in formulation for these two regions. The Krishnappan Model, although plotted in Figures 7 and 8, does not strictly apply since the nondimensional number representing model applicability is 7, and is not less than 1. The OUTPLM model provides a good prediction of trajectory but the predicted dilution is too high; this behavior is consistent with earlier model tests (Policastro et al., 1980). A run of DKHPLM was attempted for this case but the computer code failed to run.

For Test Case No. 3, due to the shear current present during the Ecomar field study, the surface plume and bottom plume moved in directions nearly at

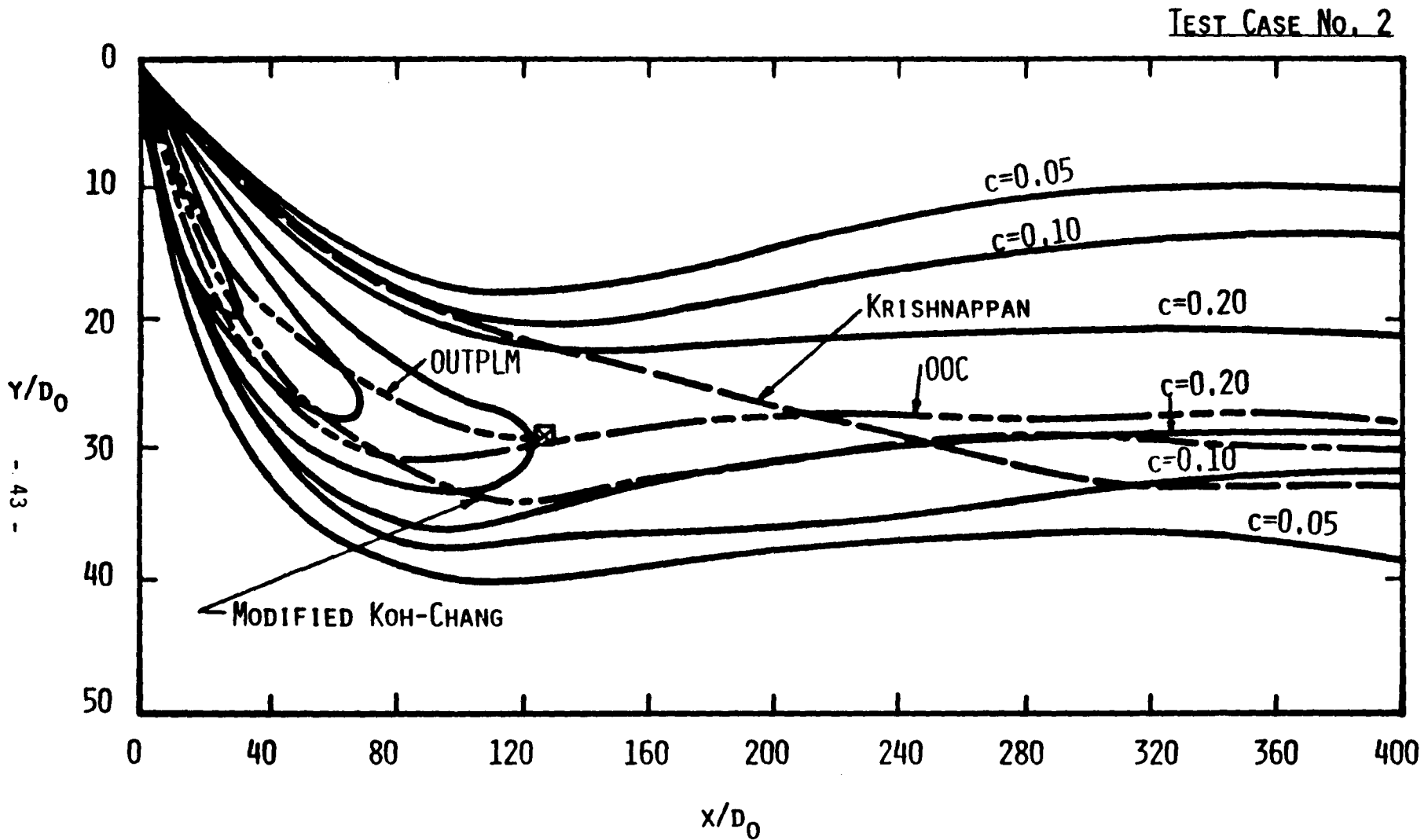
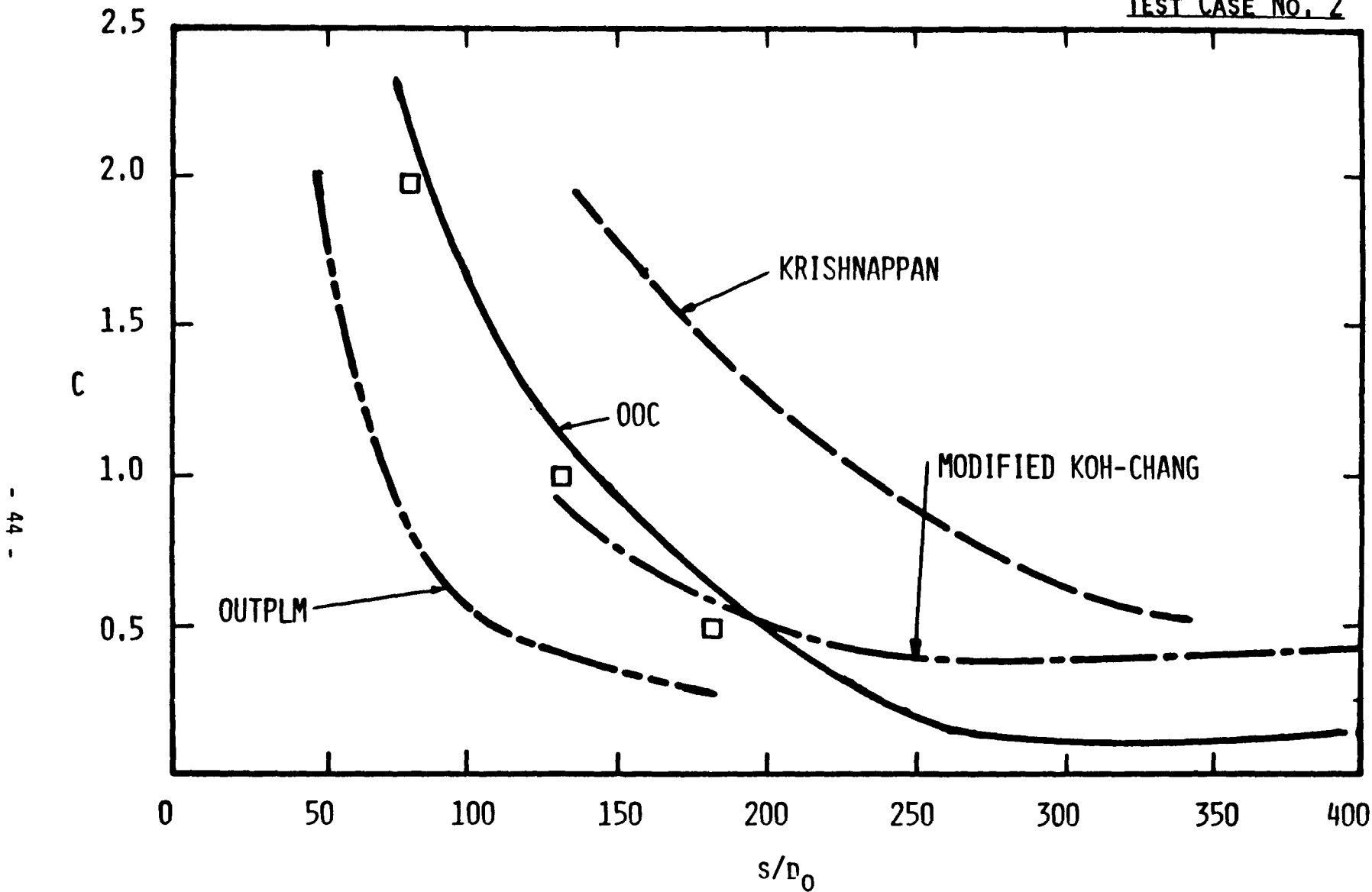


FIG. 7 COMPARISONS OF CENTERLINE TRAJECTORY PREDICTIONS OF KRISHNAPPAN, OUTPLM, OOC, AND MODIFIED KOH-CHANG MODELS FOR OSU MUD DUMP STUDY... ISOPLETHS REFER TO LAB DATA ON AVERAGE TOTAL SUSPENDED SOLIDS CONCENTRATION (MG/G OF SOLUTION).



- 44 -

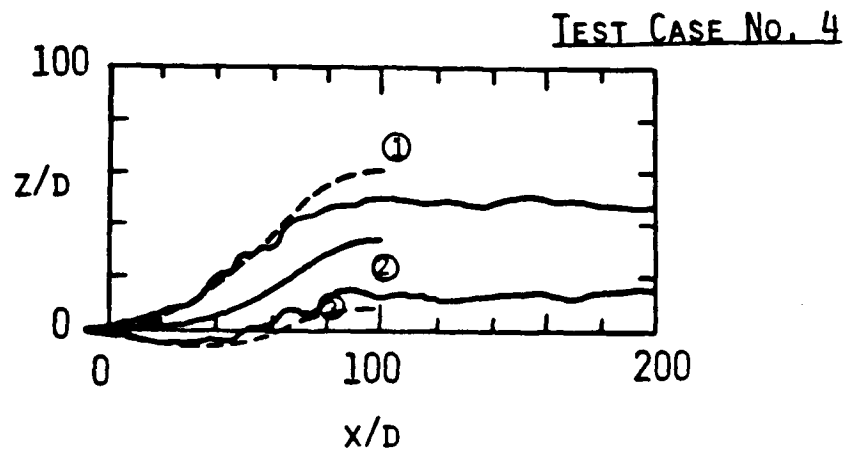
FIG. 8 COMPARISONS OF CENTERLINE DECAY OF AVERAGE TOTAL SUSPENDED SOLIDS (CONCENTRATION NORMALIZED TO INITIAL CONCENTRATION) FOR THE KRISHNAPPAN, MODIFIED KOH-CHANG, OOC, AND OUTPLM MODELS FOR THE OSU MUD DUMP STUDY.

right angles to each other. Only the surface plume was measured. OOC Model predictions for this surface plume are given in Brandsma and Sauer (1983). Unfortunately, no other predictions were made for other models for the upper plume. However, three models predicted the deposition of total solids as a function of time for the lower plume. The Krishnappan model applies in this case since the nondimensional parameter used to determine applicability is 0.3. Unfortunately, no field data exist for comparison. An intercomparison of the three models indicates a wide range in predictions for the amount of solids deposited at the bottom as a function of time. At 4,320 seconds after the start of the dump, the Krishnappan model predicts the solids deposited to be 14 times, and the OOC model to be 10 times, that predicted by the modified Koh-Chang (6,680 lbs). At 7,200 seconds, these ratios are, respectively, 6.3 and 5 compared to the modified Koh-Chang (19,400 lbs). The primary reason for this large discrepancy is the very different treatment of settling of particles in the OOC and the modified Koh-Chang.

For Test Case No. 4, only the OUTPLM, DKHPLM, and PLUME models were tested. Other models either do not apply or were not run. The case involves a horizontal discharge into a stagnant, stratified environment (Fan, 1967). As expected, OUTPLM predicts the maximum centerline location well (Figure 9). The DKHPLM and PLUME Models do not predict a sufficiently rapid rise. No dilution data were measured in this experiment.

For Test Case No. 5, only DKHPLM, and OUTPLM were run. As expected, OUTPLM provides a fairly good trajectory prediction but dilution is too strong (Figure 10). The DKHPLM trajectory bends over too rapidly; predicted dilution is too large. Both models appear to need a revision of the model physics to provide greater bending and less dilution or perhaps a better calibration of the unknown coefficients in the model. The PDS model does not apply and the OOC and modified Koh-Chang Models were again not run with this data set.

It should be kept in mind that we are primarily interested in low F_o jet discharges. Test Cases 1, 4, and 5 represent high F_o data; the result of the model/data comparisons are helpful in estimating model performance but are not definitive since a model can perform well for high F_o data and poorly for low F_o data. For low F_o , plume buoyancy is dominant in dispersion leading to a

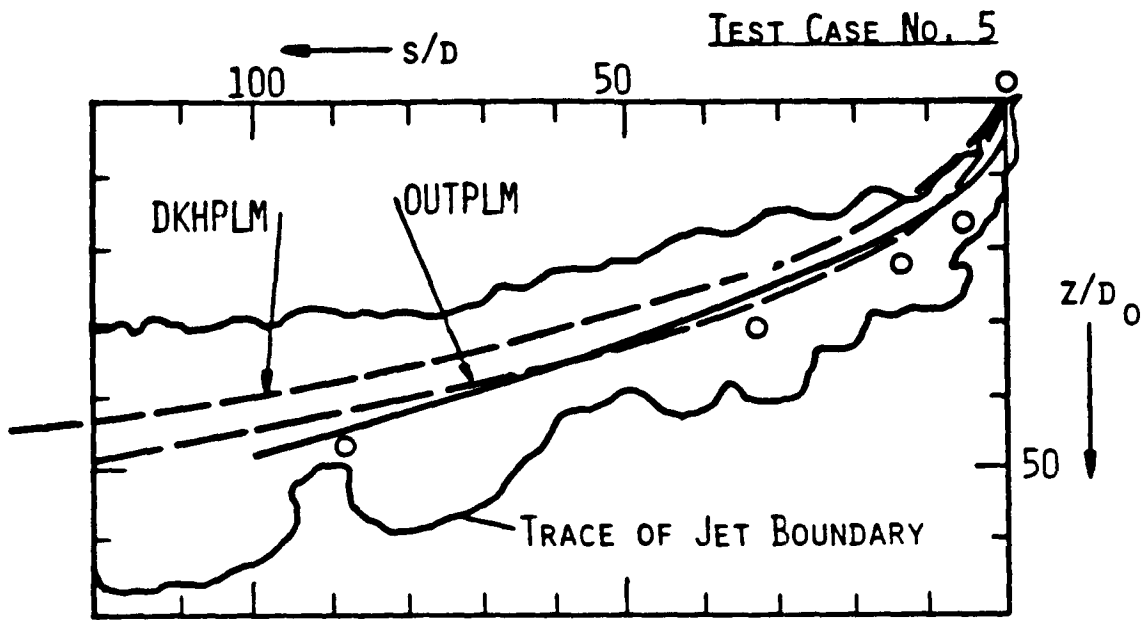


$F_0 = 40, T = 510$ --- $T = \frac{e_0 - e_1}{\left(-\frac{de_a}{dz}\right) D_0}$

POINT OF MAXIMUM HEIGHT AS PREDICTED BY:

- ① OUTPLM
- ② DKHPLM
- ③ PLUME

FIG. 9 COMPARISON OF PREDICTIONS OF POINT OF MAXIMUM HEIGHT OF RISE AS PREDICTED BY OUTPLM, DKHPLM, AND PLUME FOR EXPERIMENT No. 22... HORIZONTAL DISCHARGE IN STAGNANT STRATIFIED ENVIRONMENT.



$F = 20, \kappa = 0.08$

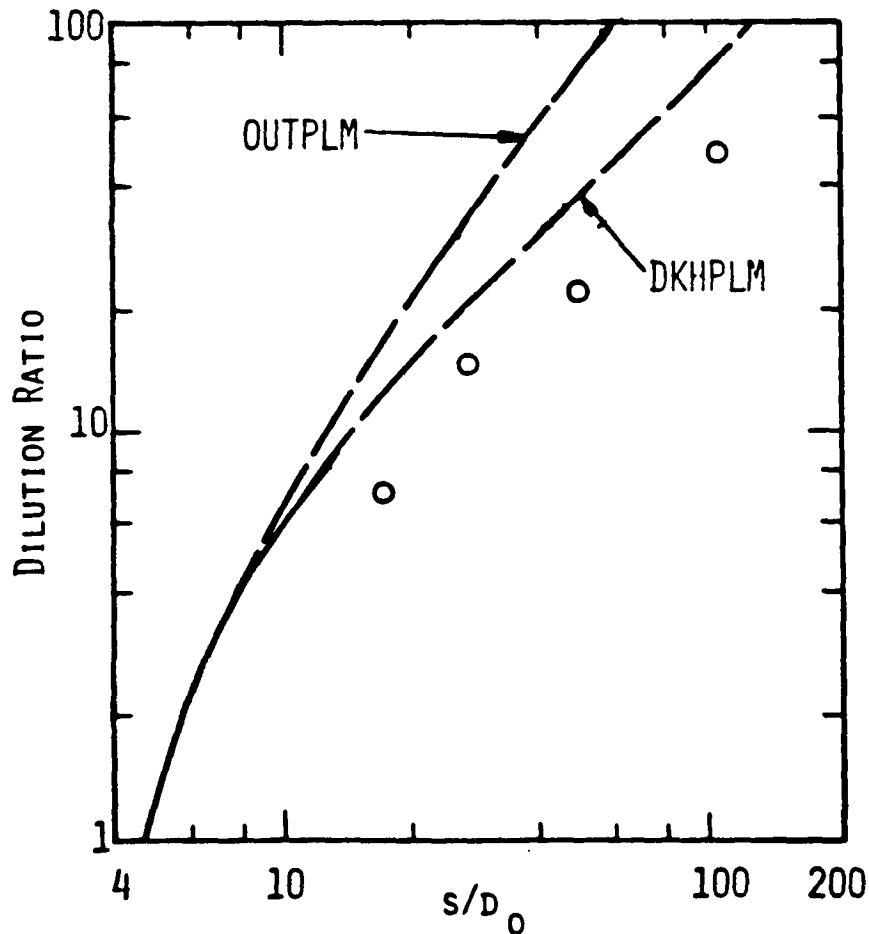


FIG. 10 COMPARISON OF PREDICTIONS OF OUTPLM AND DKHPLM FOR EXPERIMENT No. 20-12 OF FAN (A) (TOP) CENTERLINE TRAJECTORY, (B) (BOTTOM) CENTERLINE DILUTION RATIO ...VERTICAL DISCHARGE IN UNIFORM CROSS-STREAM.

different balance between buoyancy and momentum transfer mechanisms in the plume than for high F_o jets. The presence of a pair of buoyancy-induced counterrotating vortices dominates the mixing for highly buoyant plumes.

Recently, new data have been made available for very low F_o jets (F_o 0.2 - 2.0) discharged vertically in a current. Data are from Viollet (1977) and Dunn et al. (1975). The Viollet data (1977) were taken in a hydraulic flume using a heated water discharge. Ambient current variations were simulated with depth; stratified and unstratified conditions were recorded. Dye was released through discharge port and dye concentrations were measured in the plume. More than 15 data sets exist in our parameter range of interest. These data are good for testing the convective descent and dynamic collapse regions of the jet.

The data of Dunn et. al. (1975) were taken in a cryogenic wind tunnel (using a downward discharge of cold nitrogen gas); uniform, unstratified flow was simulated. Temperature was used as a tracer. The F_o range was 0.2-2.2 and K ranged from 0.3-5.5 (0.3-1.0 is useful in our application). Both data sources covered distances up to 25-30 diameters downstream as part of the near field. Future validation efforts of these models for produced water and mud/cuttings should include these data sources in order to properly evaluate near field trajectory and dilution prediction of the models.

The most uncertain aspect of these short-term fate models is the treatment of the far field where ambient turbulence predominates. This region of dispersion was not addressed with the five data sets chosen for model comparison in this Workshop. It is recommended that any further model evaluation plan include separate evaluation of the jet (convective descent and dynamic collapse) and diffusion phase submodels since separate data do exist for both regions.

6. OTHER MODELS AND RELATED METHODOLOGY

6.1 MODELING THE COAGULATION OF SOLID WASTE DISCHARGE

by

Mr. F.T. Lovorn

Simple sedimentation tests using mixtures of seawater or freshwater and simulated tailings from a research-scale hydrometallurgical processing scheme show that the net vertical flux of the solids is greatly affected by the total solids concentration. The results of the tests, throughout much of the concentration range tested, are consistent with a model in which flux rate is completely determined by simple second order coagulation of fine-grained solids. A comparison of results from a plume dispersion model incorporating coagulation processes indicates an important discharge scale effect. Because of the relationship of scale size to coagulation, settling rates estimated from relatively small scale field test observations may dramatically underestimate the settling rates for a full-scale operation.

6.2 ANALYSIS OF THE DISCHARGE OF DRILLING MUDS IN SHALLOW WATER USING A SIMPLE TWO-DIMENSIONAL MODEL

by

Dr. John Yearsley

The presently available models for predicting the fate of drilling muds have not been designed to deal with the plume interaction with the ocean floor. In many cases this does not present a problem. However, there are large areas in Alaska where drilling may be conducted in waters less than 5 meters of depth. The Region 10 Office of the U.S. Environmental Protection Agency is in the process of writing National Pollutant Discharge Elimination System (NPDES) permits for these sites and, in doing so, needs a method for evaluating the effects of drilling mud discharges to shallow water.

A simple, transient, two-dimensional model which includes horizontal diffusion, advection, and settling was developed for the purposes of making preliminary estimates. Model predictions using a priori estimates of the parameters were compared with available field data from the Gulf of Mexico to demonstrate that the model was a reasonable screening tool. The results of the comparisons suggested that the model did indeed serve its purpose.

6.3 LONG-TERM SIMULATION OF SEDIMENT AND CONTAMINANT TRANSPORT

by

Dr. Y. Onishi and Dr. D. S. Trent

To assess the potential adverse impact of drilling mud and cuttings in a receiving water body, the short- and long-term migration and fate of sediment and contaminants must be evaluated. The long-term behavior of these contaminants is controlled by transport due to water and sediment movements, intermedia transfer such as adsorption/desorption, chemical and biological degradation, and possibly transformation.

We have developed and applied four unsteady sediment-contaminant (both dissolved and particulate contaminant) transport models that include sediment contaminant interactions such as adsorption/desorption, transport, and deposition and resuspension. Among them are the three-dimensional model FLESCOT and the two-dimensional model FETRA. These models calculate time-varying distributions of sediments for each sediment size fraction or type (e.g., sand, silt, clay, or organic matter), dissolved contaminant, and particulate contaminant adsorbed by sediment for each sediment. They also predict changes in bed conditions including bed elevation changes due to sediment erosion and/or deposition, bed sediment size distribution changes, and particulate contaminant distributions within the bed.

The FLESCOT model was applied to the Hudson River estuary in New York to simulate the movements of tidally varying flow, salinity, sediments and a radionuclide. The FETRA model was applied to the James River estuary in Virginia to predict the migration and accumulation of sediments and a pesticide, Kepone. In this study, the model was also used to determine the optimal location of Kepone removal from the river bed and the effectiveness of such cleanup activities in reducing the Kepone levels in the river.

Although these applications of FLESCOT and FETRA models were not specifically made for drilling mud and cuttings, the similarity between mechanisms affecting these cases indicates that these models can be used for the long term migration and fate of drilling mud and cuttings with relatively minor modifications.

6.4 MEASUREMENTS AND OBSERVATIONS OF DRILLING, AND OTHER NEGATIVELY BUOYANT FLUIDS DISCHARGED INTO STRATIFIED AND STATIC SEAWATER

by

Dr. Robert J. Ozretich and Dr. Donald J. Baumgartner

Three computer programs, PLUME, OUTPLM, and DKHPLM (Teeter and Baumgartner, 1979), have been used by EPA and municipalities in determining initial dilutions of sewage discharged into marine environments. The research described in this presentation evaluates the accuracy of the three programs in predicting the centerline dilution, trap depth, and maximum penetration of drilling fluids, and other negatively buoyant fluids discharged downward into stratified and static seawater.

A tank (8' diameter, 4' deep) with a plexiglass window was filled from the bottom with 7 layers of filtered seawater mixed with freshwater, resulting in a linear density gradient within the tank prior to discharge. Samples were taken for gravimetric and/or colorimetric analysis through seven ports extending to the centerline of the photographed plumes. As many as four replicate synopticate samples were obtained through each port by a sequential train of evacuated test tubes incorporating a unique cork-float valve.

In order to use the three programs with the discharge and density gradient characteristics of the experiment, the input parameters were modified while maintaining the densimetric Froude number and the appropriate gradient. The results presented showed: 1) developing plume and the flocculated drilling fluid components "raining" out of the plume once the maximum penetration was reached; 2) σ_t versus depth in the tank indicating the linearity of the density profiles; 3) measured and predicted centerline dilutions; 4) observed versus predicted trap depths and 5) maximum penetrations. The conclusions of this work are: 1) the solid and soluble components of drilling fluids dilute at essentially the same rates within the buoyancy and momentum-dominated initial dilution phase; 2) flocculation occurs rapidly during early plume development; and 3) the computer programs PLUME, OUTPLM, and DKHPLM predict the measured dilutions and plume features to a high degree of accuracy.

6.5 A MODEL OF THE DISPERSION OF MUD DISCHARGED BENEATH
SEA ICE IN SHALLOW ARCTIC WATERS

by

Dr. Richard Miller, Mr. Robert Britch and Mr. Richard Shafer

Since 1979 Sohio Alaska Petroleum Company (Sohio) has contracted with Northern Technical Services (Nortec) for a series of investigations on the effects of discharge of waste drilling fluid in the Beaufort Sea. This program was conducted on behalf of Sohio and a number of other interested oil companies. Major tasks included oceanographic data collection, effluent modeling, bioassay testing, and benthic effects studies. This presentation focuses on effluent modeling.

Below ice disposal tests were conducted at two locations near Prudhoe Bay. Tests included discharge of dyed drilling effluents through holes augered in the sea ice, monitoring of various physical and chemical parameters, and measurement of bottom deposition. To supplement field results, a laboratory model was constructed and time lapse photography was used to record the physical dimensions of the discharge plume under a variety of conditions.

Results from field and laboratory tests showed that the effluent plume acts as a vertical jet which upon bottom encounter behaves as a radial wall jet. The wall jet thickness was found to increase proportionally to the radial distance to the 1.1 power, and velocity was found to be inversely proportional to radial distance to the 1.24 power.

7. SUBGROUP DISCUSSIONS AND RECOMMENDATIONS

7.1 SUBGROUP 1: THE NEAR FIELD PHYSICS, CHEMISTRY, AND DYNAMICS OF
A DISCHARGED DRILLING EFFLUENT

by

Dr. Theodor C. Sauer, Jr.

BACKGROUND

Even though the modeling of the dynamic phases of the nearfield portion of discharges is fairly well understood, a number of important processes need some further consideration and research. These processes or topics of interest, which were discussed in this subgroup, are briefly listed below.

1. Flocculation of solids in the water column,
2. Verification of the collapse phase of the dynamic part of a discharge, both in the water column and near the bottom,
3. Initial dilution of effluent inside the discharge pipe at low Froude numbers,
4. Forced separation of solids from the main plume near the discharge pipe to form the visible surface plume,
5. Drilling rig wake effects, and
6. Discharge of effluent above sea surface.

For each of these topics, the subgroup participants discussed the mechanisms needed to sufficiently characterize these processes. We discussed our experiences, and reviewed experiments and literature we were familiar with in these areas. In some areas we came to a consensus on methods of implementing these processes now in existing models. We also discussed future research needs in these areas and tried to prioritize the processes as to their importance in the modeling effort.

DISCUSSION TOPICS

FLOCCULATION: Probably the most difficult process to characterize fully is the process of agglomeration of fine particles in high ionic strength waters, i.e. flocculation. Flocculation looks to be a continuous process; however, for the time scales of most interest, the flocculation which occurs in the first few minutes of a discharge seems to be the most important. Particles are most concentrated during this time and also encounter the largest ionic strength differences.

Some short-term fall velocity distribution analyses (pipette method) have been conducted that suggest the flocculation process of fine clay-size particles in mud occurs in seawater within a few minutes at dilutions no less than 300 to 1 (a dilution known to occur quickly in a plume discharge). Clay-size particles (< 2 microns) which usually make up at least 30-40% of the total solids in muds is reduced to less than 5%. The clay particles flocculated to a size greater than 10 to 15 microns.

At this time enough work has been done to recommend that fall velocity distribution techniques, such as the pipette method, should use a seawater medium instead of deionized water in doing the analysis. The use of seawater gives a first-order approximation of the mud solid flocculation process occurring shortly after mud solids entrain ambient seawater. It is felt that by working a little more with the technique of determining fall velocities in seawater, a better estimate of at least the short-term phase (minutes) of flocculation can be acquired. Some of the parameters in the technique needing testing are the effects of different dilution ratios, the effects of different mixing rates and times, the effect of different muds, and the change in fall velocity distribution with time during the analysis.

As for longer-term (hours) flocculation processes, research in this area is still valuable and should be continued. Due to the complexity of the problem (i.e. long time scales and large dilution effects), results of any use are not expected for a number of years.

COLLAPSE PHASE VERIFICATION: Refinement of the rate at which a plume spreads upon reaching neutral buoyancy (i.e. the dynamic collapse mechanism) in the short-term dynamic phase of discharge plumes is needed. Coefficients used in the equations that describe the collapse phase have not been verified. Those values selected for coefficients used now are based on laboratory data conducted in 1960 on the spreading of dye from a single dump point source in a stratified medium. Further verification is essential and can be done through controlled laboratory tests using drilling mud, similar to those conducted recently for the jet phase by Dr. Lorin Davis.

INITIAL DILUTION AND FORMATION OF VISIBLE SURFACE PLUME: Both processes, the initial dilution of effluent inside the discharge pipe at low Froude numbers and forced separation of fine solids near the discharge source to form the visible surface plume, are grouped together since both are felt to be influenced by the value of the discharge Froude number.

In the case of initial dilution, the Froude number indirectly indicates the extent to which the interior of the discharge pipe is filled with effluent and entrained seawater during the discharge. Consideration of this process is important in determining the bulk density of the effluent at the pipe exit. The bulk density influences significantly the results of the dynamic phase portion of the discharge. Laboratory studies could be valuable in assessing this situation. Collecting samples at the discharge exit during discharges of different Froude numbers (different pipe diameters, mud densities, and exit velocities) would be recommended and is believed to be relatively simple.

As for the forced separation of fines, the value of the Froude number is felt to be the major cause for separation of material from the main plume to form near surface plume. Field studies seem to indicate that the lower the Froude number, the larger the quantity of material separated. It seems that a visible plume is less likely to form when the intensity (turbulence energy) of the discharge plume itself is great (high Froude number). Other possibilities felt to influence separation of fines beside low Froude numbers were suggested. These are the strength of the ambient current velocity and the turbulence generated by the obstruction of the rig structure. The intensity in a plume (based on Froude number) and the drag effect from ambient currents

are felt to be the major contributors to the separation of solids from the main portion of the plume. These influencing conditions (Froude number and current velocity) could be successfully assessed both together and separately in controlled laboratory tests. Simple experiments where only visual observations are made of discharges at different Froude numbers and current velocities are suggested at first, then perhaps once the important bounds are established, more elaborate quantitative determinations could be conducted.

DRILLING RIG WAKE EFFECTS: The ambient turbulence created by a drilling platform, a semi-submersible, a jack-up, or a development platform in a high current environment may be important in causing the scattering of discharged solids near the discharge source and in forming the visible surface plume mentioned previously. Unfortunately, the intensity of a wake and its decay with distance as it relates to ambient current velocity is not well known.

Estimates of the wake effect could possibly be made by measuring in the laboratory the intensity of turbulence from model rig structures. With a laboratory study, even though direct quantitative relationships between current and structure type may not be possible, at least boundaries could be established in the type of rig structure the current needed to create significant changes in the fate of a discharge. This in itself would be an important piece of information. Possibly, the wake effect from a rig may not be important for many of the conditions which exist in the marine environment.

ABOVE SEA SURFACE DISCHARGES: Discharges of effluent above the sea (free-fall discharges) are felt to cause more of an impact to surface water quality than discharges below the sea surface. Essentially, much of the dynamic phase of the discharge is lost upon impact with the sea surface. A passive phase situation is of primary concern with this type of discharge, and those models which are based on passive-type calculations are most applicable. The type of discharge, either free-fall or subsurface, can be easily controlled by the discharger; only the pipe needs to be shortened or lengthened. The fate of material from such a free-fall discharge can be determined either in the laboratory or field studies.

RECOMMENDATIONS

The important dynamic processes (Topics 1-6) of the nearfield portion of discharges which need some further consideration and research are probably the most easily attainable of any of the other processes discussed in the modeling workshop (except perhaps long-term flocculation). Flocculation is a special problem. A rough estimate of the short-term flocculation process (minutes) can be determined fairly readily; however, a detailed analysis of the entire flocculation process, especially the long-term (hours), would need considerable amounts of time and resources.

Most of the mathematics (physics) describing the dynamic phases of a plume discharge have been developed relatively well. The need now is to do some tuning of the dynamic phase coefficients and to formulate at least some empirical equations which represent the minor processes observed in the field (i.e. separation of fine solids to form visible surface plume). Well designed, controlled laboratory studies are felt to be the best and probably the most likely to succeed means of acquiring information on the dynamic phase processes. A number of laboratories are available now which can do these studies. Most process questions (Topics: 1 through 4) could be answered within a year.

7.2 SUBGROUP 2: THE DYNAMIC EFFECTS OF THE AMBIENT OCEANOGRAPHIC CONDITIONS ON DRILLING EFFLUENT IN THE NEAR AND INTERMEDIATE FIELDS

by

Mr. F.T. Lovorn

BACKGROUND

Applications of numerical and physical models requires input of appropriate parameters and appropriate treatment of the variability of these parameters. This brings into question the field study basis of existing models - are the field studies credible science? Are appropriate methods being used? Is enough known about the effluent itself to say that all the important parameters are being measured? These questions emphasize the need for defining the limitations of a model and then using it only where applicable.

A general appeal was made for better communications among disciplines. Since this work is interdisciplinary in nature, concerted effort for unity and consistency in terminology will greatly improve communication. Defining terms by means of glossaries and providing sufficient information in reports so they can be used by other disciplines would be very helpful.

DISCUSSION AND RECOMMENDATIONS

VELOCITY FIELD: First priority was given to the measurement of the velocity field. At least three spatial/temporal scales were recognized for horizontal variability:

1. Near field where the wake from the platform would affect the plume,
2. Intermediate scale (10-15 km) associated with eddies and mean shears, and
3. Far field where seasonal and interannual variability strongly influence mean flow.

The intermediate scale is particularly important because it is associated

with plume meandering, enhanced dispersion due to shears and transport of pollutant captured by eddies. This is also the scale at which the pollutant may still be detectable. Local bathymetry and estimates of the velocity field based on historical data or a pilot project would have to be considered in developing an adequate sampling plan for this scale.

As is evident from observation of the vertical structure of currents, it is not sufficient to assume a vertically uniform velocity field. Vertical variation in the velocity field will cause various parts of the plume to travel in different directions and speeds as it penetrates down through the water column. Current meters continuously profiling the water column would be the preferred measurement approach, but cost constraints usually dictate continuous measurements at discrete depths. In this case, a minimum of three levels is required - above thermocline, below thermocline, and near bottom. The data collected in any verification study should be compared to historical current data to determine its representativeness. In the absence of historical current data, meteorological and hydrographic data could be used in such an assessment.

The method of characterizing the intermediate scale current regime of an area was also discussed. It was generally conceded that a probabilistic description was most useful. Joint probability distributions of speed and direction at each measurement location would be a minimum requirement. However, the horizontal and vertical coherency of the currents would also have to be accounted for to adequately characterize the three-dimensional current structure.

STRATIFICATION: Ambient stratification affects the plume in a number of ways - trapping level, vertical diffusion, dilution. The pycnocline can also act as a ceiling to resuspended sediment, a level of internal wave activity, and a level of strong current shear. Strategies for discharging drilling muds should consider the relative merits of discharging above or below the pycnocline.

Compared to current measurements, the resolution required for hydrographic data is greater in the vertical than in the horizontal direction.

Data on the intra-seasonal and annual variability of the stratification may be adequate for most plume predictions, although the effects and importance of short-term variability (minutes, hours) has to our knowledge not been addressed. This may be a question that can adequately be addressed in the laboratory.

As with current data, a probabilistic description of the density profile is probably the best approach. Comparison should be made with historical profile data. These data are more likely to be available for a particular area than are current data.

WAVES: The importance of wave effects will depend upon water depth. In shallow water, the wave induced water velocity may initiate sediment resuspension. For near surface discharges, waves may cause hydraulic pumping and periodic currents at the discharge port and breaking waves may affect the dispersion of drilling muds discharged at the surface (air-sea interface).

An estimate of the wave climate for deep water is available for many areas. However, this is inadequate for shallow water due to transformation of the wave field by interaction with the bottom. The location of wave measurements in the vicinity of a drilling muds discharge will depend upon local bathymetry.

RECOMMENDATIONS

1. Determine the intermediate scale circulation. Provide a joint probability distribution for each current measurement location and determine correlations among locations.
2. Measure the velocity field in the platform wake and determine its effect on the Plume.
3. Coordinate field measurements and hydrodynamical modeling to determine the far field, large scale circulation.
4. Determine the inter-seasonal and annual variability of the

temperature/salinity field. Seasons may be defined oceanographically (e.g., upwelling, Davidson Current Regime, etc.). Develop probabilistic description of density profile, pycnocline strength and depth.

5. Determine the effects of short-term variability of velocity and temperature/salinity profiles on the plume.
6. Determine the effects of waves on the discharge jet and plume.
7. Determine the frequency and distribution of those conditions under which sediment resuspension is likely to occur.

7.3 SUBGROUP 3: THE LONG-TERM OCEANOGRAPHIC FEATURES OF THE TRANSPORT AND FATE OF DRILLING EFFLUENTS

by

Dr. Robert C. Ayers, Jr.

BACKGROUND

This subgroup addressed the need for and feasibility of developing a long-term fate model. The discussion centered around the following topics:

1. What do we want a long-term fate model to do?
2. What are the cases of interest?
3. What are the dominant processes?
4. What additional information is needed on dominant processes?
5. How should a model be designed?
6. Is sufficient environmental data available?
7. Is sufficient verification data available?
8. Other questions of interest?
9. Recommendations

DISCUSSION AND RECOMMENDATIONS

Most of the group felt that the need exists for a long-term fate model. However, concern was expressed that it will take a good deal of time to develop and that it should be used with care and the limitations noted. It was agreed that the model should be quite comprehensive being able to predict the concentration of every type of discharged material as a function of time and space. It was decided that biological effects, other than bioturbation, would not be included. The group recognized that other biological mechanisms such as bioaccumulation and biomagnification are important but these were considered to be effects rather than major transport mechanisms. It was also believed that the model should address the fate of the settled material on the bottom. It was the general opinion of the group that the short-term fate models did a fairly good job predicting immediate water column concentrations. The model should be able to handle all coastal and offshore environments as well as all operating conditions such as discharges from platforms and gravel

islands and should also be able to handle exploratory and development drilling.

The group considered the major physical, chemical, and biological processes affecting the physical fate and discussed them in some detail. These processes were advective transport, diffusion, desorption/adsorption, chemical alterations, flocculation/deflocculation, deposition, resuspension, compaction, and bioturbation. It was felt that more information was needed on all of these processes with the exception of advective transport and diffusion. In particular it was believed that more information was needed on resuspension and deposition processes. It was also pointed out that resuspension occurs from other activities such as trawling and the importance of these activities should be investigated.

The group envisioned that the long-term fate model would be a combination of existing models. A short-term fate model such as the OOC model would be used with discharge data and current data to generate the initial conditions. This would yield the initial distribution of material on the bottom. The long-term portion of the model was envisioned to be a combination of both deterministic and probabilistic models. A deterministic model would be used for intermediate term (~ one week) fate and episodic events. A probabilistic model would be used over the longer term.

The group recognized a lack of oceanographic data in some areas for application in the model. There may be enough in Alaska but probably not enough in California. Also the group noted the lack of available verification data. There is some information available from studies conducted in the Atlantic and some from studies conducted in the Gulf of Mexico but very little elsewhere.

The group recommended that MMS contract for a feasibility study to determine whether a long-term fate model could be successfully developed and make appropriate recommendations on how this should be done. This effort would include a sensitivity study to evaluate the importance of the proposed physical processes, a review of possible models, and finally a recommendation on how to proceed.

7.4 SUBGROUP 4: THE ROLE OF MODELS IN PREDICTING THE BEHAVIOR OF
AND ASSESSING THE IMPACTS OF A DRILLING EFFLUENT

by

Dr. Wilbert Lick and Mr. Maynard G. Brandsma

BACKGROUND

Specific questions that were asked and discussed were as follows:

1. What is the purpose of the models?
2. What is the use of models?
3. How are the models to be applied?
4. What models are necessary?
5. How are the models to be verified?
6. Deterministic vs. probabilistic models?
7. What prediction accuracy is needed?

DISCUSSION TOPICS

PURPOSE OF THE MODELS: The purpose of drilling mud dispersion models is the evaluation of effluent discharges by prediction of concentrations of sediment and soluble material in the water column and on the bottom as a function of time and distance from the discharge. Another use of models is in designing mitigation measures by comparative evaluation. It is not clear that biological models are available for use in assessing the impacts of drilling effluents on the biological community. However, the predictions of numerical models of effluent dispersion may be, and are, coupled with toxicity and effects data for the purposes of assessing mud impacts.

USE OF MODELS: Models have a variety of uses. For MMS needs the models may be used to assist in the design of biological and chemical monitoring, and for environmental assessment. For EPA needs they may be used to assist in the automation of permits, and to develop basic understanding of processes important in modeling the transport and fate of drilling effluents.

In addition to the analysis of actual events, models can and should be

used for design purposes and for mitigation of the effects of drilling muds. For example, is it better to concentrate sediments on the bottom at one location or to disperse them over a wide area? This is largely dependent upon the initial release and therefore design of the diffuser and can be investigated by modeling.

It is obvious that the results of models need to agree with field data when available but models are necessary and of most use when field data and other knowledge is not available or is minimal.

APPLICATION OF MODELS: There are two different areas of drilling that should have different treatments. One is the isolated exploratory well. The other is a large group of development wells in a producing area. The subgroup thought the idea of developing a workbook for estimates of drilling plumes was a good one and should be defined as to usage, confidence levels that could be placed in such a document, and what level of effort that would be necessary to produce it. Isolated exploratory wells in non-sensitive areas should be candidates for a workbook type analysis.

Cumulative impacts of a number of development wells are likely to be much higher than a single exploratory well. These areas are candidates for analysis by verified models for plume formation and deposition. If the development area is a near sensitive zone, it is a candidate for analysis by a long term sediment migration model, if a verified model is available.

MODELS REQUIRED: Short term plume models are necessary to predict the plume that forms the initial condition for passive diffusion. Intermediate terms models are needed to predict the initial deposition of sediments on the bottom and concentrations in the water column resulting from the discharge (this is the passive diffusion phase). Long term models to predict sediment migration would be good to have, but a suitable model is not available because the driving mechanisms are not well known.

It was believed that short-term plume models are in comparatively good shape and give reasonable results. This conclusion is subject to further comparisons of the models and field verification. Flocculation was a major

unknown and further understanding and quantification of this process is necessary.

Intermediate-term models are probably adequate as far as the mathematical modeling is concerned. Flocculation and input data such as diffusion coefficients limit the applicability of these models. There is an inherent limitation on the accuracy of the predictions of these models due to the natural variability of currents and other climatic variables. Lack of a quantitative understanding of resuspension and deposition of fine-grained materials (drilling muds) also will limit predictions.

Processes important to the long-term modeling of drilling effluents are not well understood and no valid model is available. Among these processes are those of flocculation, entrainment, and deposition of fine-grained sediments (muds). A better understanding of these is needed before adequate long-term modeling studies can be performed. It is recommended that experimental work on flocculation, entrainment, and deposition be initiated as well as preliminary numerical modeling of the long-term transport of muds which would incorporate this experimental information.

VERIFICATION: For models to be used for evaluation and design, they must be credible. That is, regulatory agencies must be able to defend drilling permit grants/denials. If models are used for this purpose, the best defense of them is to have them verified in the field (preferably more than one case).

DETERMINISTIC VS. PROBABILISTIC MODELS: For the short term, at least in the jet phase, deterministic models are available and useful. For longer times the inherent variability of nature and the increase of errors with time and distance require that we incorporate probabilistic thinking into our deterministic models. The long-term problem is essentially the probability of finding a particular concentration of drilling mud at a particular location given our uncertain knowledge of currents and input data such as particle size, chemistry, etc.

ACCURACY: The accuracy needed in a model predicting the behavior of the effluents is a function of the accuracy to which biological impacts are known.

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APPENDIX A: THE WORKSHOP AGENDA

MINERALS MANAGEMENT SERVICE WORKSHOP:

"An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms"

February 7-10, 1983, Sheraton, Santa Barbara, California

MONDAY - FEBRUARY 7, 1983

0800 Registration
0845 Introduction: Dr. Robert C.Y. Koh, California Institute of Technology
0900 Purpose of the Workshop and Background Information: Dr. Fred Piltz, Minerals Management Service, Pacific OCS Region
0930 Keynote Address - Physics and Processes Related to the Discharge of Marine Effluents: Dr. Robert C.Y. Koh, California Institute of Technology.
1030 Break
1045 Keynote Address - Characteristics of Discharges from Platforms: Dr. Robert Ayers, Jr., Exxon Production Research Company.
1145 Drilling Dispersion and Fate Models and the Standard Data Set: An Introduction - Dr. Akshai Runchal, Analytic & Computational Research, Inc.
1215 Lunch
1345 Modified Koh-Chang Model (Tetra Tech Version): Dr. Frank Wu, Tetra Tech, Inc.
1445 The OOC Model: Mr. Maynard Brandsma
1545 Break
1600 The Krishnappan Model: Dr. B.G. Krishnappan, Canada Centre for Inland Waters
1700 Summary and Close

TUESDAY, FEBRUARY 8, 1983

0830 The PDS/DKHPLM/OUTPLM/PLUME Models: Dr. Lorin Davis, Oregon State University
0930 The DRIFT Model: Dr. Ian Austin, Dames & Moore.
1030 Break
1045 Contributed Paper - Adaptive Environmental Assessment Model of Potential Fate and Effects of Drilling Fluids in the Marine Environment: Dr. Gary Petrazuolo, Technical Resources, Inc.
1145 Lunch
1300 Keynote Address - A State-of-the-Art Review of Modeling of Drilling Fluids & Cuttings: Mr. M.G. Brandsma
1400 Contributed Paper - Entrainment, Deposition, and Long-Term Transport of Fine Grained Sediments: Dr. Wilbert Lick, University of California, Santa Barbara.
1500 Break

- 1515 Contributed Paper - A Model of the Dispersion of Mud Discharged Beneath Sea Ice in Shallow Arctic Waters: Richard C. Miller and Robert P. Britch, Nortec, and Richard V. Shuler, Sohio Alaska Petroleum Company
- 1600 Contributed Paper - Automating the Section 403(c) Determination: William S. Beller, U.S. Environmental Protection Agency
- 1615 Long-Term Simulation of Sediment and Contaminant Transport: Y. Onishi* and D.S. Trent, Pacific Northwest Laboratory
- 1630 Measurement and Observations of Drilling, and Other Negatively Buoyant Fluids Discharged into Stratified and Static Seawater: Robert J. Ozretich and Donald J. Baumgartner, U.S. Environmental Protection Agency.
- 1645 Modeling the Coagulation of a Solid Waste Discharge: Mr. F.T. Lovorn, Lockheed Marine Sciences
- 1700 Summary & Close: Dr. Lorin Davis, Oregon State University
- 1730- MBC and Analytic & Computational Research, Inc. Hosted Wine Reception

WEDNESDAY, FEBRUARY 9, 1983

- 0830 Subgroup Discussions
 Subgroup 1: The Near-Field Physics, Chemistry, and Dynamics of a Discharged Drilling Effluent. Chairman: Mr. Theodor C. Sauer, Jr., Exxon Production Research Company
 Subgroup 2: The Dynamic Effects of the Ambient Oceanographic Conditions on Drilling Effluent in the Near and Intermediate Fields. Chairman: Mr. F.T. Lovorn, Lockheed Marine Sciences
 Subgroup 3: The Long-Term Oceanographic Features of the Transport and Fate of Drilling Effluents. Chairman: Dr. Robert C. Ayers, Jr., Exxon Production Research Company
 Subgroup 4: The Role of Models in Predicting the Behavior of and Assessing the Impacts of a Drilling Effluent. Chairman Section A: Dr. Wilbert Lick, U. of California, Santa Barbara; Chairman Section B: Mr. Maynard G. Brandsma.
- 1030 Break
- 1045 Continue Subgroup Discussion
- 1145 Lunch Break
- 1300 Continue Discussions
- 1400 Subgroup Reports to General Session by Subgroup Chairpersons
- 1530 Break
- 1600 Summary of Model & Methodology Evaluations: Dr. Antony Policastro, Argonne National Laboratory.
- 1700 Summary Remarks

THURSDAY - FEBRUARY 10, 1983

- 0830 Comments on the Link Between the Fates and Effects Models: Ms. Ruthann Corwin, Marin County
- 0900 Summary of Proceedings: Dr. Robert C. Y. Koh, California Institute of Technology.
- 0930 Panel Recommendations
- 1000 Break
- 1030 Future Directions & Final Address: Dr. Fred Piltz, MMS Pacific OCS Region
- 1100 Conclusion of Workshop

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APPENDIX C: NOTATION AND DEFINITIONS

NOTATION

- B the Boussinesq parameter; a measure of the relative importance of the density changes compared to the ambient fluid density ($\Delta \rho / \rho_a$)
- D_o exit port diameter of the discharge
- F_o the initial densimetric Froude number of the discharge; a measure of the momentum of the discharge compared to the buoyancy force due to the differences in the density of the discharged fluid and the ambient ocean ($U_o / \sqrt{\{g \Delta \rho / \rho_a D_o\}}$)
- g constant of gravitational acceleration
- K the ratio of ambient to initial discharge velocity; a measure of the momentum of the jet compared to that of the ambient (U_a / U_o),
- U_a ambient current velocity at location of discharge port
- U_o initial discharge velocity
- ρ_a density of the ambient ocean at point of discharge
- ρ_o density of the discharged effluent
- $\Delta \rho$ the difference between the density of the discharge fluid and that of the ambient ($\rho_o - \rho_a$)

DEFINITIONS

Buoyant Jet: a jet which is heavier or lighter than the ambient into which it is discharged.

Convective Descent Phase: the period during which the behavior of the discharge is strongly influenced by its initial momentum and buoyancy.

Dilution: the ratio of the mass of fluid contained in the jet or plume to fluid discharged at the exit port.

Dynamic Collapse Phase: the period during which the behavior of the discharge is primarily controlled by the buoyancy forces. This usually occurs immediately following the convective descent phase.

Half-depth: the depth of the plume (from the surface of the ambient waterbody) at which the value of the temperature is half that at the surface.

Isotherm: the line connecting points of equal temperature value.

Jet: the discharge of effluent with a relatively high initial momentum (velocity) compared to the momentum of the ambient in which it is discharged.

Passive Diffusion Phase: the period during which neither initial momentum nor buoyancy significantly influence the behavior of the discharge. This phase usually follows the convective descent and/or dynamic collapse phases and the behavior of the discharge is then primarily controlled by the dynamics of the ambient waterbody.

Plume: the state of a jet (or discharge) in which the momentum is negligible compared to its buoyancy.

Surface half-width: the width of the plume at the surface of the ambient waterbody between points (on both sides of the centerline) where the value of temperature is half that at the centerline.

Trajectory: the path followed by the centerline of a jet or plume.



The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.



The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.