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PERFORMANCE AND COMPATIBILITY ANALYSIS OF OIL WEATHERING AND TRANSPORT-RELATED MODELS FOR USE IN THE ENVIRONMENTAL ASSESSMENT PROCESS

FINAL REPORT

AUGUST 1990

BDM/SEA-90-0024-TR

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FOREWORD

This Performance and Capability Analysis of Oil Weathering and Transport-Related Models for Use in the Environmental Assessment Process Final Report is submitted by BDM International, Inc., 16300 Christensen Road, Suite #315, Seattle, Washington 98188, to the Office of Oceanography and Marine Assessment, Alaska Office of the Ocean Assessments Division, National Ocean Service, National Oceanic and Atmospheric Administration, Anchorage, Alaska.

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ABSTRACT

OCSEAP has developed and verified, through both field and laboratory work, a suite of models to study the transport, effects, and fate of oil spills for use in the Alaskan OCS. Each model addresses a particular aspect of an oil spill and is currently designed to be executed independently. The objectives of this study are to analyze four specific oil spill models and to recommend modifications allowing their sequential or integrated use in defining the fate of an oil spill. The four models are the Coastal Zone Oil Spill (COZOIL) Model, the Circulation and Oil Spill Trajectory Model (also referred to as the Coastal Sea Model System or the Circulation/Trajectory Model), the Oil Weathering Model, and the Oil/Suspended Particulate Matter (Oil/SPM) Model. While each of these models addresses certain aspects of an oil spill, they individually fall short of the ultimate goal -- to predict the fate of an oil spill. This project consisted of a comprehensive review of the model characteristics and physical assumptions incorporated into existing models and a study of how they can be effectively combined to support environmental assessment using microcomputers. Eight oil spill scenarios were considered. A study of the applicability of the models to each of these scenarios suggested methods for coupling the models and led to an organized approach for model synthesis.

Redundant model features and missing model features were identified. Various methods for combining the computer codes were compared. These were limited to three sets of the following tasks:

Task 1- Development of Input/Output Software

Task 2- Combined Oil Spill Model Development

Task 3- Addition of Missing Features

Task 4- Acquisition of Databases

A low cost task set is to develop the I/O software with simple architecture, combine the existing oil spill models in the simplest manner, and prepare a database, without addressing the missing features. An intermediate task set is to develop menu-driven I/O software, combine the four oil spill models around the Circulation/Trajectory model, and prepare a database, again without addressing the missing features. The top of the line task set is to develop menu-driven 1/0 software, develop a new integrated oil spill model, add code to address the missing features, and to prepare a database. It is recognized, however, that the final selection will depend strongly upon the desired applications of the combined code and the funds available.

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SECTION I
INTRODUCTION

A. OBJECTIVE

The overall goal of Alaskan Outer Continental Shelf (OCS) pollutant transport studies is to describe the trajectory of an oil spill as well as the amount and persistence of the spilled oil on the sea surface, in the water column, and on the sea bed along the spill trajectories and at landfalls. The objectives of this study are to determine the feasibility of meeting this goal by analyzing four oil spill models and to recommend modifications allowing their sequential or integrated use in defining the fate of an oil spill. The four models are the Coastal Zone Oil Spill (COZOIL) Model, the Circulation and Oil Spill Trajectory Model (also referred to as the Coastal Sea Model System or the Circulation/Trajectory Model), the Oil Weathering Model, and the Oil/Suspended Particulate Matter (Oil/SPM) Model. While each of these models addresses certain aspects of an oil spill (surf interaction, transport in the open ocean, weathering, and interaction with suspended particulate matter), they individually fall short of the ultimate goal -- to predict the fate of an oil spill. This project provides an intermediate step in the process of synthesizing the four models and developing a combined oil fate model.

B. BACKGROUND

For more than a decade the Outer Continental Shelf Environmental Assessment Program (OCSEAP) has performed and sponsored studies to develop knowledge and understanding of transport, effects, and fate of oil spills in the marine environment, including Arctic conditions. The first of these studies, entitled "The Transport and Behavior of Oil Spilled In and Under Sea Ice," began in 1978 with Dr. Max D. Coon and Dr. Robert S. Pritchard as Principal Investigators. This study, documented in Coon and Pritchard (1979), involved the calculation of trajectories of oil spilled on the ice in Prudhoe Bay using buoy data and a computer model.

Computer models for simulating the transport and fate of spilled oil in the marine environment are important tools in environmental assessment. OCSEAP/MMS-sponsored studies have developed and verified, through both field and laboratory work, a suite of models for use in the Alaskan OCS. All of the models were designed and developed individually over a period of years using a variety of scientific approaches, methodologies, and levels of detail. Each model addresses a particular aspect of an oil spill and is currently designed to be executed independently. The ideal case, however, would be to use them in an interactive manner, sequentially or in combination, to simulate the anticipated spill scenario.

The scope of the combined oil spill fate model is illustrated in Figure 1, Oil Spill Fate, which shows a three-dimensional perspective of an offshore and a nearshore oil spill. On the open ocean, an oil spill disperses by a combination of processes: evaporating into the atmosphere, sinking to the ocean floor, and moving to another location. Sea ice, an important feature of the Alaskan OCS, is shown in the vicinity of this spill. The second spill shown in Figure 1 depicts an oil spill near shore, where some of the oil reaches kind. Predicting the fate of an oil spill is an important yet difficult task.

c. APPROACH

The E3DM technical approach to this project consisted of a comprehensive review of the model characteristics and physical assumptions incorporated into existing models and a study of how they can be effectively combined to support environmental assessment using microcomputers. Eight basic oil spill scenarios were considered. These scenarios are combinations of nearshore/offshore, ice/no ice, and surface/subsurface spills. A study of the applicability of the models to each of these scenarios suggested methods for coupling the models and led to an organized approach for model synthesis.

The computational features that BDM characterized included the source code (e.g., lines of code, programming language); compilation and execution requirements (host hardware and operating system); required inputs and outputs; identification of numerical algorithms; and model documentation. The scientific attributes that BDM studied include physical and chemical assumptions; inputs and outputs; numerical methods of solution; constraints on inputs and outputs; resolution; and boundary conditions.

D. OVERVIEW

For ease of understanding, the report has been organized into six sections. Section I provides an introduction and background to the project, Section 11 describes the characteristics of each model, Section III compares the models, Section IV discusses model integration, Section V describes recommendations for modifying and linking the models, and Section VI provides conclusions, followed by complete bibliographic references for the works cited in this report.

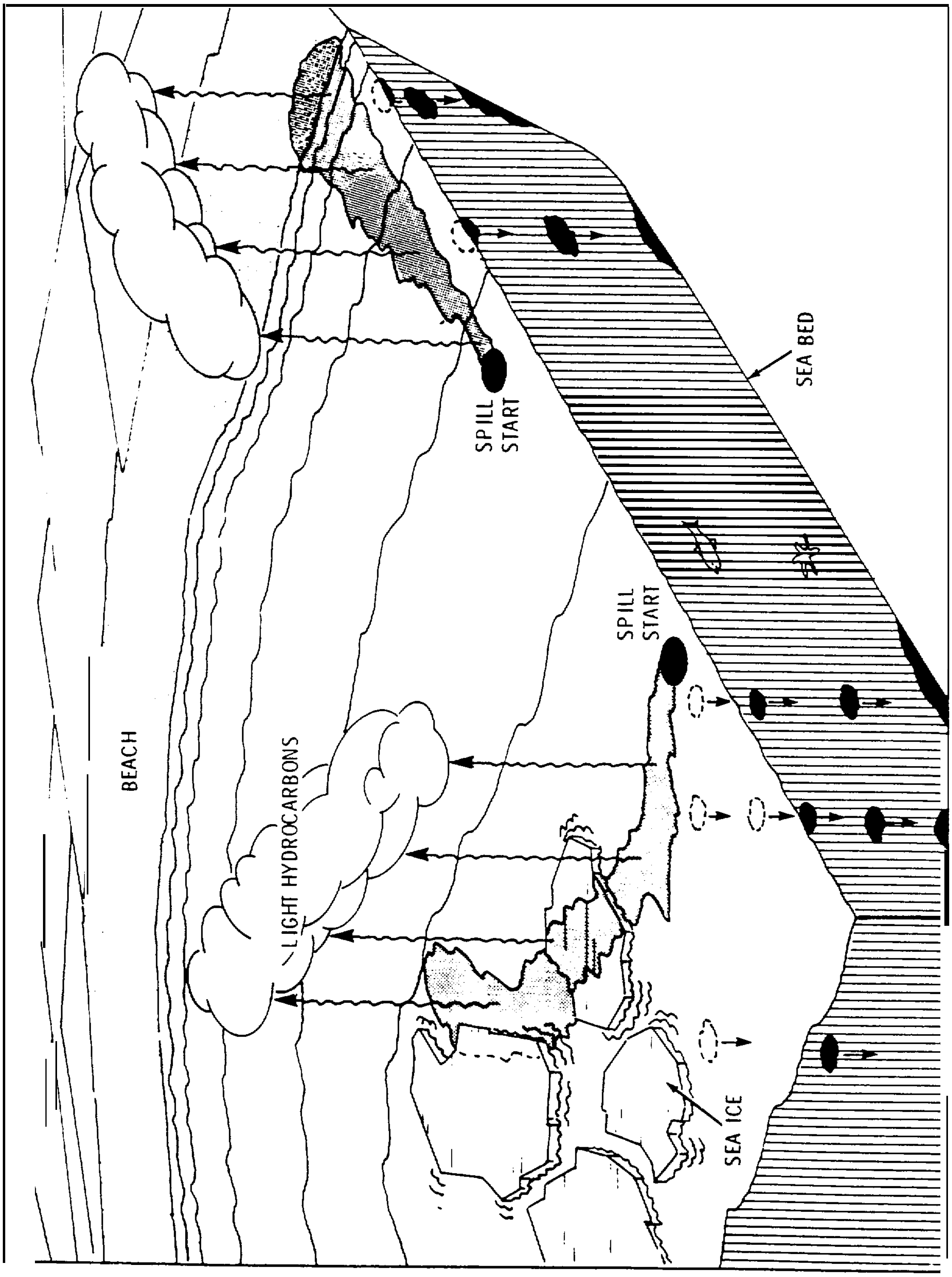

Figure 1. Oil Spill Fate

In Section II, each model is first described in terms of what it does, how it does it, what inputs are required from the user, and what outputs are produced. The physical and chemical attributes of the model are described, including assumptions and limitations of the model, and the physical laws and principles that apply. Next the computational features of the model are described, including the mathematical aspects, the numerical methods used, size of time steps and grid spacing. Section III, Comparison of Models, presents and interprets tables that concisely summarize the important features of each model and compare the most important characteristics of each model. Section IV considers the oil spill scenarios, redundant and missing model features, and viable structures for combining the models. Section V provides a basis for selecting a structure for the combined oil fate model, while Section VI summarizes our conclusions for the program.

SECTION II
CHARACTERIZATION OF MODELS

A. COASTAL ZONE OIL SPILL MODEL

1. Model Description

The COZOIL Model, developed by Coastal Science and Engineering, Inc., was designed to predict the time-varying distribution of oil introduced into a domain separated into three partitions: the nearshore, the surf zone, and the coast. The coast can include gravel and sand beaches, rocks, tidal flats, lagoons, and permafrost bogs. This model was intended to run in close coordination with outputs from an open ocean trajectory model; it is however capable of operating independently as well. A typical simulation run consists of initializing the model domain with a specific grid system, shore type, topography, and physical characteristics and then introduces oil into the system either on the surface (as if a slick were approaching the shoreline) or subsurface (as if a pipeline had failed). The amount of oil in each of the three partitions is then calculated and followed by time stepping through changing environmental conditions, nearshore wave and current conditions, and surface and subsurface oil weathering conditions. The model was written in FORTRAN and is capable of running on a microcomputer. An earlier version (the Smear Model) was documented by Kana et al. (1986); the Coastal Zone Oil Spill Model was documented by Reed (1987).

The COZOIL Model tracks multiple, discrete batches of oil (spinets) in the three partitions. A spinet is a portion of an oil spill having uniform thickness and weathered state. The COZOIL Model is a deterministic model of a shoreline approximately 30x 300 km using a grid size of about 10 x 10 km, and time steps of 3-6 hours for up to 90 days.

The input parameters define the study area location and physical properties (bathymetry, topography, sediment size, beach slope, and shoreline type), environmental data (wind fields, current fields, air temperature, water temperature, ice cover and movement, water surface elevation, and SPM in the water column), and the oil spill (oil type, mass, diameter, and location).

The output parameters define the spatial distribution of oil droplets and oiled particles. For each coastal segment, the oil mass, thickness, weathered state, and location (surface or buried) are provided. The surface spinets are defined in terms of location, mass, weathered state, thickness, and areal extent. The mass of oiled SPM and oil droplets in the seabed is determined as well as the concentration of oiled SPM, SPM, and oil droplets in the water column.

2. Physical and Chemical Attributes

a. **Hydrodynamics**

Wind is constant over the study area. The user can either prescribe a deterministic wind for each spinet, or run the model in a stochastic mode in which wind speed, direction, and air temperature for each spinet are drawn from a statistical distribution.

Waves at the offshore boundary of the model domain are either specified or computed from the wind at the option of the user. As the bottom shoals, the waves are transformed by refraction and diffraction. In the surf zone, the waves steepen and break, thus undergoing further modification. Refraction, diffraction, wave height, and phase transformations are calculated according to a published linear wave propagation model (RCPWAVE from the Corps of Engineers Coastal Engineering Research Center (CERC)). Wave runup (the vertical height above still water level to which incident waves will run up a beach) and wave setup (the vertical average wave height above still water arising from wave radiation stress) are calculated from empirical formulas derived from CERC data.

For the offshore region, currents are the sum of a simple sinusoidal alongshore tidal current and a time-dependent, depth-averaged current that depends on the wind. In the surf zone, the wind-driven current is supplanted by an along shore wave radiation stress current. The latter is taken from a empirical CERC formula. Since the wind-driven current is not applied in the surf zone, onshore wind-driven transport is balanced by an offshore volumetric flux. This can transport oil entrained in the water column away from the surf zone.

b. **Oil Spill Models**

Thin (sheen) slicks are ignored. Spreading is radial, representing a balance among gravitational, viscous, and inertial forces, except in the surf zone, where wind stress in the onshore direction can counteract the tendency to spread, thus elongating the slick. Wave action is not directly incorporated into the transport models. Mass transfer rates for up to 15 constituents of the oil in a spinet are calculated using standard vapor transfer equations.

The user is given a choice of two algorithms for entrainment (dispersion) of oil into the water column. In both the mass transfer rate varies as the square of the wind speed. In one, it is also proportional to the inverse time exponential, while in the other it varies directly as the mass and inversely as a term involving interracial tension, dynamic viscosity, and slick thickness. There is no reason given for presenting both algorithms. Entrainment is the same in the offshore and surf zones.

The slick is advected with a velocity that represents the sum of 3% of the wind speed, the tidal and wind-driven currents, and the wave radiation stress current. Oil that is entrained at the surface is distributed randomly vertically under the slick, then advected by the interpolated horizontal current, and diffused randomly as well. The model downplays the importance of entrained transport, and it is not clear from the description how depth-dependent concentrations are accounted for in the overall oil mass balance. Advection in the surf zone is dominated by the wave radiation velocity, which is ignored elsewhere. It is worth noting that alongshore currents from wind transport setup/setdown (downwelling/upwelling) are not considered, nor are changes in beach water level from such effects taken into account.

An oil slick in contact with the shoreline will deposit oil according to the ratio of the spinet radius (in the onshore/offshore direction) to the exposed beach face, if an empirical holding thickness has not been exceeded. This criterion holds for the foreshore, between the near low water level and the beach berm, and backshore, from the berm to the cliff, vegetation, or dune line. Oil deposited on a beach section from different times or different spinets adds its characteristics to the oil already present in a weighted average sense.

Oil from a surface deposit can penetrate into underlying sediments following Darcy's Law, a common approach to calculating groundwater movement. Oil which has penetrated into sediments above the water table can be removed by beach erosion, for which an empirical equation is written. Oil in the beach groundwater system is removed each tidal cycle according to a simple mass flux equation involving the specific yield and porosity of the sediment. This oil is partitioned into water-accommodated and adsorbed phases.

Waves breaking on a contaminated beach tend both to enhance penetration into the groundwater and to resuspend oil particles, washing them back into the surf zone. An empirical mass removal rate equation describes this process, with partitioning between groundwater and surf zone return determined by constant coefficients. Oil on a beach inundated by a rising tide is refloated and mixed with an existing spinet, if one is present.

Oil which has been emulsified into an oil/water mousse and deposited on a beach face may be released from the mousse according to a simple first-order process. The suggested time constant results in an emulsion half life of 12 hours on land.

3. Computational Features

None of the documentation accompanying the COZOIL Model discusses the numerical methods employed in the model. Behavior offshore, outside the surf zone, is modeled using concepts developed by previous investigators who are identified in the references. A modified version of RCPWAVE, developed by the U. S. Army Corps of Engineers, is used to model wave behavior. Inside the surf zone some of the concepts used are said to be lacking "strong empirical evidence for values of the necessary parameters."

B. CIRCULATION AND OIL SPILL TRAJECTORY MODEL

1. Model Description

The Circulation and Oil Spill Trajectory Model, developed by Applied Science Associates, is designed to calculate the hydrodynamics, wind, ice, and oil spill trajectories and fates for Alaskan coastal waters. The Circulation Model generates, or takes from its program libraries, wind, sea ice, and surface wave forces. From that information, the Oil Spill Trajectory Model calculates the oil spill trajectory and predicts its fate, including drifting, spreading, evaporation, dispersion, emulsification, and subsurface transport. Spills of any hydrocarbon release, from crude oil to refined products, can be simulated. Documentation is provided in Spaulding et al. (1988).

The Circulation Model is a three-dimensional spectral hydrodynamics model based on the solution, in spherical coordinates, of the conservation equations for water mass, density, and momentum using the Boussinesq and hydrostatic assumptions. The model generates surface velocity vectors for tidal currents and residual currents at each grid point in the modeled domain for each season. Fleet Numerical Oceanographic Center (FNOC) data sets and other historical data are used to assemble a wind field coincident with the simulation period. Oil spill trajectories are then simulated from the hydrodynamic model results by superposition of wind-induced, tidal, and residual current drift, Wave-generated transport is not directly modeled; spill trajectory and emulsification include only wind-induced factors. Model components were implemented in FORTRAN and developed on a minicomputer.

The hydrodynamics model was used by Spaulding et al. (1987) to predict wind-forced circulation in the Bering and Chukchi Seas, Two model resolutions were used: a coarse grid model (0.25 degrees latitude by 0.6 degrees longitude) and a fine model which had double this resolution. Isaji and Spaulding (1978) applied this model to the calculation of the M2 and K1 tidal elevations and currents in the northwestern Gulf of

Alaska. The M2 and K_1 constituents are generally representative of the semidiurnal and diurnal tides, respectively. Schwiderski's global tidal models (1979, 1981) provided the input boundary conditions. A grid resolution of 0.2 degrees latitude and 0.35 degrees longitude (about 20x 20 km) produced good results.

The user must set up a grid for the study area, and either provide data on wind, ice, and type of oil spilled, or use data from the program libraries. Final model output is the trajectory, material balance data, and cell-by-cell location of the spilled oil.

2. Physical and Chemical Attributes

a. Hydrodynamics

Forces applied to the ice and upper ocean by the wind provide the primary source of energy for moving oil near the surface. The Circulation Model uses the marine surface winds at 19.5 m above sea level from the U. S, Navy Fleet Numerical Oceanographic Center (FNOC) to estimate this driving force for Alaskan waters. Orographic effects are added based on the literature and nearshore buoy and land station wind records. The FNOC model predicts the global winds on a 2.5 degree grid at 6 hour intervals. Historical wind fields are available from 1976 until the present from this model. Waves play a role only indirectly through pararneterization of Stokes drift in the wind drift rule (3%) and in the entrainment process.

Currents are calculated with a three-dimensional numerical model that solves conservation equations for momentum, salt, and heat (energy) using an equation of state that depends on salinity. The fully three-dimensional model is used only in a diagnostic mode to solve once and for all for the baroclinic currents implied by the archived hydrographic data. Tides, wind-driven barotropic, and sea-surface elevation currents are solved for using the depth-averaged (two horizontal dimensions) version of the model. This was used to model currents in the Bering Sea (Spaulding et al., 1987).

b. Ice Mechanics

For areas where internal ice stress and boundary effects are not important, a free-drift model for ice mechanics is used. The model is not described in the documentation, nor is there a description of the method used to couple the free-drift and hydrodynamics models. It appears that this model is not actually coupled but instead is an independent model that is not used in oil spill trajectory simulations. The model is steady-state and accounts for Coriolis and tilt accelerations, applied air stress, water stress, and bottom drag effects. The water drag is estimated from a two layer model: a quadratic drag law is used for the top two meters, and the bottom log-layer allows an increase in eddy viscosity.

For areas where free-drift is not appropriate, a viscous constitutive law is used. Ice velocity is described by the momentum equation that includes inertial, Coriolis, and tilt accelerations, applied air stress, water stress, and ice stress divergence. Ice compactness and thickness satisfy the conservation laws for a two-component model. Climatological ice growth rates are included.

The water stress is described as following a quadratic drag law. This drag law and the drag coefficient were developed to relate water drag to the ice velocity relative to current beneath the mixed layer. This approach, if actually used, would ignore the mixed layer structure potentially available from the hydrodynamic model. Turning angle is not included in the description.

The full ice model requires that either ice velocity or traction (the shear force component from the internal stress) be specified around the boundary. The report does not describe this boundary condition.

c. Oil Spill Models

Oil spill drift, spreading, evaporation, dispersion (entrainment), emulsification (mousse formation), and subsurface transport are included in the oil spill trajectory and fate model. A spill is represented as a set of oil spinets, each of which is assumed circular. The rate of release of spinets describes the oil spill release rate. This feature allows a continuous spill to be approximated and can describe a variety of large-scale forms, rather than just circular ones. Arbitrary shapes to the oil slick and patchiness are modeled by combining individual spinets. The Trajectory Model is limited to tracking 25 spinets simultaneously. Oil spill trajectories are calculated by accumulating (or integrating) motions, which include effects of tidal currents, density-induced net transport, and a wind-driven velocity.

In the absence of ice, the wind-driven velocity of the oil is assumed to be the sum of a barotropic current caused by sea surface gradients generated by the wind and an Ekman transport due to the direct action of the wind stress acting on the sea surface. Ekman transport is modeled as 3% of the wind velocity turned through a deflection angle. The deflection angle ranges from 25 degrees at low wind speeds to zero at winds of 20 m/s or more.

In the presence of ice, the wind-driven velocity of the oil is the sum of ice velocity and oil velocity relative to the ice. When the relative speed is below a threshold value, the oil is trapped and moves with the ice. In free-drift, wind-driven surface currents are neglected, and the ice velocity is assumed to be 3.3% of the wind velocity deflected 35 degrees to the right. The text suggests that in full ice coverage, the ice is assumed immobile. In partial ice coverage, when ice stress is important (typically north of St. Lawrence Island), the fully coupled ice-hydrodynamics model is used to describe the ice motion. Although the fully coupled ice-hydrodynamic model can be used, the report leaves some question as to whether or not it has actually been used.

Tidal currents are comprised of a tidal residual, and semi-diurnal (M_2) and diurnal (K_1) components. The vertically averaged hydrodynamics model is used to predict one cycle of tidal motions. The residual is estimated by integrating these motions over a tidal cycle.

Density-induced or residual current is estimated using the three-dimensional model in a diagnostic mode, i.e., with the density field determined from the NOAA/NODC climatological salinity and temperature data set. The steady-state current balancing the density field is determined for winter and for summer.

Wind-driven barotropic currents are the sum of Ekman transport due to the direct action of wind stress on the sea surface (modeled by the 3% rule) and the vertically averaged wind-driven current. Note the same two dimensional model is used for both the tidal and barotropic calculations. Representative wind fields, predominant wind patterns in the Beaufort Sea and Gulf of Alaska, and storm events in the Bering and Chukchi Seas are all used to develop oil trajectories.

When ice concentration is less than 30%, an open water spreading model is used where the gravity and viscous forces are in balance (after initial inertial forces diminish, and before surface tension becomes dominant). The rate of increase of oil surface area is proportional to area to the power 1/3 times the ratio of volume to area to the power 4/3.

Under ice, oil is trapped by under-ice roughness. Trapped volume per unit area is linear with ice thickness. The diameter of a spinet is determined by assuming it circular, and with thickness given by the trapped volume per unit area. According to the documentation, the SAIC model is used.

According to the documentation, the SAIC evaporation model for open water is used (Payne et al., 1984a). Oil is characterized by fractionation cuts determined by true-boiling-point distillation (TBP). Identical first order kinematics is used, with mass-transfer coefficients dependent on wind speed and Schmidt number.

The Trajectory Model accounts for oil under fast or pack ice, where loss by evaporation is prohibited. If the ice subsequently retreats, the oil begins to weather. In ice concentrations above 30%, the open water evaporation rate is linearly reduced, and above 90'% it ceases.

According to the documentation, the mousse formation algorithm of Mackay et al. (1980) is used; according to the computer code, the SAIC model is used.

Although the documentation claims to use the same emulsification model as doesSAIC, it is not obvious from the models presented and described. The documentation describes the rate of increase of fraction of water in oil to be proportional to wind speed (plus one) squared times a linear function of the amount of water in oil. The linear function contains an empirical constant. The report also presents equations for estimating viscosity corrections due to emulsification, evaporation, and temperature. It is not apparent where the viscosity is used.

The fraction of a surface slick that can be dispersed into the water column by breaking waves is proportional to wind speed to power two, and decays exponentially with a two day time constant. Alternately, theSAIC formulation (Mackay et al., 1980) may be used. It is also proportional to wind speed squared, and produces similar dispersion rates. Dispersion is prohibited under ice or in broken ice if compactness exceeds 30%. This feature appears to differ substantially from the SAIC model, where dispersion is enhanced in the presence of ice.

3. c omutational Features

a. Cumulation Model

In the Circulation Model, vertical variations of ocean current, temperature, and salinity are approximated by a set of basis functions with equations governing the coefficients determined using the Galerkin method of weighted residuals. Prior to introducing the basis functions, the vertical coordinate z is transformed linearly into a sigma-coordinate ranging in value from -1 at the ocean bottom to +1 at the sea surface.

Transformation of momentum and salt balances, and conservation of mass and heat into the sigma-coordinate system provides a set of governing equations. For horizontal velocity components, two equations are derived from a horizontal momentum balance. For heat and salt balances, one equation each is derived from a horizontal flux balance. There is one equation relating sea surface elevation and the depth-averaged values of horizontal velocity, which has the appearance of mass conservation. There is also one equation defining a new dependent variable, analogous to the vertical velocity component, as a function of the sea surface height and horizontal velocity, integrated from the bottom to each level.

The two horizontal velocity components, temperature, and salinity are expanded in a series of Legendre functions that vary in depth with the sigma-coordinate

$$u(x,y,\sigma,t) = u_1(x,y,t)P_2(\sigma) + \ldots$$

where σ suggests the sigma coordinate. The first Legendre function P_1 is a constant so that the fiit coefficient represents the vertically averaged value.

The Galerkin method of weighted residuals is introduced to derive equations governing each of the coefficients. Each coefficient may vary with horizontal position (x,y) and time (t). Each of the four basic transformed governing equations (u, v, temperature, and salinity) is multiplied in turn by each of the Legendre functions and integrated over the vertical domain ($-1 < \sigma < 1$). Errors in the equation governing the coefficients are orthogonal to the Legendre basis.

After the sigma transformation and Legendre approximation, the Circulation Model consists of a system of coupled nonlinear partial differential equations approximating the conservation laws and describing changes in the coefficient of the Legendre polynomials. Integration of these equations requires that we discretize the horizontal domain and time. A split mode difference scheme is introduced, with the free-surface elevation treated separately from the three-dimensional flow variables.

A staggered spatial grid is introduced in the x-y plane. A rectangular mesh is formed with Ax and Ay as horizontal grid increments. Sea surface elevation, temperature, salinity, and vertical velocity are specified in the center of each cell. The u velocity component is specified on the cell face normal to the x direction, and the v velocity component is specified on the cell face normal to the y direction. This is the standard Arakawa C-grid.

Text and plots in the documentation suggest, and the coding confirms, that a geographic grid is available. In addition, nesting of finer grids has been performed, and triangular cells have been used in specific applications. The model description does not include these features.

Spatial grid resolution is roughly 15-25 km for simulation grids over several regional domains: the Gulf of Alaska, and the Bering, Chukchi, and Beaufort Seas. Fine scale grids of about 1 km were also used in embedded simulations.

Temporal variations in the height or elevation of the free surface depend only on the vertical average of the horizontal current components, which are represented by the coefficients of the first Legendre polynomial. An explicit finite difference approximation is introduced for this mode, and it must satisfy the Courant-Fredrichs-Levy (CFL) condition, which limits the time step to the time required for a shallow water wave to propagate across a cell, given by:

$$At < \Delta x / \mathrm{sqrt}(gh).$$

The text suggests that external mode equations (higher order Legendre modes) are solved by an implicit finite difference method, with time derivatives and vertical diffusive terms approximated by centered time differences. However, the computer program included in the documentation states that a fully explicit momentum balance equation is used.

b. Oil Spill Trajectory Model

No mention is made of the time steps used in the hydrodynamic calculations. The following values were listed as time steps for the Trajectory Model, although it is possible that smaller time steps were required to avoid instabilities in simulations of the barotropic mode. The FNOC wind field was input on a 2.5 degrees lat/long grid every six hours. The spatial grid used with the hydrodynamic model was geographically rectangular, with increments of 0.2 degree latitude and 0.313 degree longitude. Tidal currents (vertically averaged and therefore two dimensional) had time steps of one hour. Simulations of density-driven baroclinic flow were performed using three-dimensional simulations for each season. Wind-driven barotropic flow (vertically averaged and therefore two dimensional) had time steps of six hours. These simulations used either the free-drift or the full ice model. Hourly and six-hourly values could then be obtained by interpolation.

The documentation states that computer programs for evaporation, entrainment (dispersion), spreading, and mousse formation (emulsification) are the SAIC routines.

c. OIL WEATHERING MODEL

1. Model Description

The Weathering Model, developed by Science Applications International Corporation (SAIC), utilizes a pseudocomponent characterization of crude oil to derive the time-dependent mass balance and composition of oil remaining in a slick (asingle spinet). The model considers weathering by evaporation, dispersion (entrainment), mousse formation (emulsification), and spreading. The code was written in FORTRAN and includes all necessary I/O routines, error routines, and integration routines, and is capable of running on a microcomputer. The model was documented in a project final report by Payne et al. (1984a). The model is interactive and requests environmental data such as wind speed and scenario definitions by prompting the user with questions and suggested input. Specific crude oils and their physical parameters are contained in an internal library. The user may choose physical parameters of the oil either from this data base or input them separately.

Output from the model consists of mass remaining in the slick, mass dispersed, mass evaporated, fraction of mass remaining in the slick, area of the slick, thickness of the slick, viscosity, specific gravity, total volume of the slick, and dispersion and evaporation rates. These quantities are provided for each time step.

Oil weathering in the presence of sea ice presents a variation on the problem of oil weathering. The Weathering Model has been modified to accommodate four scenarios: oil in pools on surface of ice, oil spreading under the ice, oil trapped in a broken ice field, and open ocean (no sea ice). Oil weathering in the presence of sea ice has been documented in a report by Payne et al. (1984b). The user's manual for this model is given in Kirstein and Redding (1987).

2. Physical and Chemical Attributes

An oil spill can weather in open water by four processes: evaporation, dispersion, mousse formation, and spreading. For an open ocean spill which takes place at time zero, these processes should be nearly complete at the end of 100 hours.

The evaporation portion is probably the best defined part of the computer model. The evaporation of oils has a solid theoretical base, both in terms of the dependence of evaporation on wind speed and temperature, and on the boiling points of the various oil fractions. The authors present this material well, and it is the strongest part of the model.

The major over-simplifying assumption is that the oil is always well mixed, or that the evaporative loss is independent of slick thickness. When the slick is thick and there is sunlight, this is not true, but, given the approximations and deficiencies in the descriptions of the other processes, this is hardly an important defect. Also the scale of the spill is not taken into account in the program; large and small spills are treated the same.

When the program runs, it presents the user with a series of menus or screens. The user then steps through the questions asked on each screen to run the program. In the first step of running the model, the operator needs to load the distillation characteristics of the spilled oil. For contingency planning, this information is either available as a library function within the program, or can be loaded by the operator. The first screen allows the operator to specify the kind of crude oil which is spilled.

The next screen specifies the weathering process. The operator gives the size of the spill in barrels, what is apparently the air temperature (for some reason the water temperature is left unspecified), and the wind speed. The operator is then asked to choose whether he wishes the process to occur with spreading, dispersion, and mousse formation. Then the model runs. The output from this process is presented in the form of tables, which show the amount of oil in each distillation cut, as well as the change in the amount of spill remaining.

The dispersion into the water column model is described by two empirical equations. The first equation yields a function 'F', which is defined as "the fraction of sea surface subject to dispersions per second." F is not coupled to the second equation, which gives the fraction of oil for each cut which is dispersed into the water column as droplets. The amount dispersed into the water column is a function of wind speed, component viscosity, surface tension, and slick thickness. Since dispersion really depends on wave breaking and the total length or circumference of the oil slick exposed to the wave field, this dispersion model is suspect.

The mousse formation model is also drawn from Mackay et al. (1980), and again the reader is presented with little or no discussion as to how the model works. Mousse formation is described by an empirical equation, probably based on a few laboratory experiments, which appears to give the formation rate of mousse. Again, the original report would need to be checked to verify how this model works, but unlike the evaporation model, it appears to have an empirical rather than a theoretical basis.

This model uses an empirical spreading model developed by Mackay, which is not based on the classical oil spreading theory model. The reason for use of the empirical model is that the authors feel it applies better to rough seas than the theoretical spreading models. This model apparently has as its input the viscosity derived from the evaporation model. Also examination of the spreading code shows that the slick starts its spreading at a thickness of 2 cm. Judging by the news reports of the Exxon Valdez spill, it appears that wind herding and wave herding can maintain a slick at a greater thickness, so that this thickness stipulation may be a problem. The authors of the code realize that the spreading model needs improvement, and claim to have designed the code so that a newer version can be inserted.

Sea ice enters the Weathering Model in two ways: the oil can weather on top of the ice, or in a broken ice field. If it is in a broken ice field, then the rate of mousse formation is increased, the rate of dispersion into the water column is increased, and the spreading rate is apparently reduced. If the oil is allowed to weather in pools on top of the ice, the user specifies the pool depth, temperature, wind speed, and so forth. The only difference between this model and the open ocean model is that there is no spreading, dissolution, or mousse formation. The oil pool model then, is simply a model for the evaporation of a contained patch of oil.

More importantly, this part is the entire model for the direct interaction of oil and sea ice. There is no mechanism for getting the oil to the top of the ice. Nowhere in any of the material is there reference to brine channels, oil entrapment under the ice by freezing into under-ice pools, nor any seasonal dependence to the release of oil frozen into the ice.

The broken ice field is characterized by a single number, the ice concentration, which is the area fraction covered by ice, such as 0.7. The model makes no provision for the size or roughness of the broken ice. The broken ice cover affects the oil in three ways. First, the mousse formation rate is accelerated by changing a constant from its open water value of 1 to a broken ice default of 10 (page 26). There is no documentation cited for this, however. Second, the dispersion rate into the water column is accelerated by changing the value of a constant from its open water default of 1 to a broken ice default of 10 (page 30). The authors say this change is based on "limited data", again with no documentation cited. And third, the spreading rate across the surface is reduced. Their spreading model is a non-mechanistic model based on Mackay et al. (1980). The computer code states that "The functional dependence of spreading with fraction of ice cover is not known. For now, a linear dependence is assumed'. The authors assume that the spreading rate is reduced linearly with ice concentration, so that the spreading rate in a 50% ice concentration is one-half the spreading rate in open water. The authors also recommend (page 24) that the present model be replaced by a "more realistic and mechanistic one."

3. Computational Features

The Weathering Model describes behavior at one location as a function of time. There are no spatial variations, horizontal or vertical, through the water column. A fourth order Runge-Kutta time integration is performed. The time integration for each configuration (oil in surface pools, oil in broken ice, oil on open water) is performed within a single integration subroutine, so intermediate solutions are not available.

The time step for temporal integration is set to allow a five percent change in the most rapidly varying pseudo-component, but may not exceed 0.5 hours nor be less than 0.05 hours. Components that weather too fast are assumed to be gone within a time step and removed from the simulation.

D. OIL/SPM MODEL

1. Model Description

The Oil/SPM Model, also developed by SAIC, was designed to provide predictions of oil droplet and SPM interactions in the range of parameters encountered in the environment. The models, documented in Payne et al. (1987), are one-dimensional and provide a vertical oil concentration profile as well as the mass of oil associated with free oil drops in the water column, mass of oil drops attached to SPM, and the mass of oil drops attached to the bottom, all as a function of time. The model is written in BASIC, is interactive, and provides typical values when requesting user-required inputs. The model was developed on an IBM-compatible microcomputer.

The studies reported by Payne et al. (1987) indicate that complete modeling of these interactions is extremely complex in a full three-dimensional model. A model with that detail would encompass dispersion of oil droplets, the kinetics of interaction of a distributed size range of oil droplets with a distributed size range of SPM, the agglomeration rate of oiled SPM, selective partitioning behavior due to varying chemical composition, and resuspension and transport of bottom sediments, Selective partitioning occurs among the discrete phases of dispersed oil droplets, dissolved oil droplets, free SPM, oiled-SPM agglomerates, and oiled-SPM sediments.

As a result, a much-simplified, one-dimensional computer model was prepared to predict the rate of agglomeration of free oil droplets with the SPM. The agglomeration rate is closely analogous to a chemical reaction rate in that it is proportional to the concentrations of oil droplets and SPM and considers collision cross-sections, with only a fraction of collisions actually resulting in an agglomeration. The agglomeration rate depends upon the turbulent energy dissipation rate, the water viscosity, the SPM concentration, and a lumped rate parameter derived from laboratory experiments. The turbulent energy dissipation rate will vary with depth, sea state, and weather conditions, especially wind speed. The lumped rate parameter depends upon characteristics of the oil and SPM, most of which have not been determined in sufficient detail at this time for the full model. In addition, the output from the Oil/SPM Model depends upon the rate of dispersion (entrainment) of discrete oil droplets from the oil slick (the oil source term), which needs to be supplied by other models.

2. Physical and Chemical Attributes

a. OILSPMXS Code

This code describes the dispersion of oil droplets into the water column. From other work by the authors, the dispersion of oil and sediment into the water column depends on ocean currents and ocean waves; namely the breaking of oil-covered waves disperses oil into the water column, and the non-linear interaction of waves and currents generates a suspended sediment. Instead of using this information, however, the initial screen prompt asks for either operator values or default values for the turbulent diffusivity, rise velocity, initial oil flux, and water depth. The code then gives the amount of oil suspended in the water column.

b. SPMONLY Code

This code gives the amount of sediment suspended in the water column. The criticisms are the same as above. The physical process depends on the non-linear interaction of an ocean current with surface waves, and the fact that the ocean floor is covered with a fine grain sediment. The first screen in this model allows the operator to either specify or accept as default constants the turbulent diffusivity, the terminal velocity, and the sediment flux rate from the bottom. The program then solves the diffusion equation for a sediment profile at various time intervals.

c. OILSPM3 Code

This code describes the interaction of the oil droplets with the suspended sediment profile. The model follows a diffusion equation similar to OILSPMXS and SPMONLY. Again this is a 1-D model, where the various parameters described in the two previous codes are specified on the screen. The code uses a steady-state SPM profile to start the calculation; the oil in the water column starts at zero. This code gives, as a function of time, the amount of oil lost to the bottom, the amount suspended in the water column, and the amount bound to suspended sediment in the interior. Again, environmental inputs are ignored, and the program uses default fluxes of sediments and oil droplet entrainment.

3. Computational Features

The models are dependent on time and vertical position. There is no horizontal variation. Concentrations of oil droplets, SPM, and oil-SPM agglomerate each satisfy a linear partial differential equation where the partial time derivative plus advection balances diffusion and a source term. The three equations are coupled through the source terms. The user inputs the particle velocities at which components are advected.

Separate equations for concentration of oil droplets and for concentration of SPM are presented. Each of these is solved analytically using a Laplace transform. The inverse transforms are expanded analytically, with the roots of the transcendental equations determined numerically. The oil droplet concentration profile is coded in program OILSPMXS. The SPM concentration profile is coded in program SPMONLY.

In the program 01LSPM3, the coupled equations are solved numerically using a Crank-Nicholson scheme. This implicit numerical integration scheme is unconditionally stable. Time steps are therefore restricted only to capture physical changes in the solution.

Time steps are input as a fraction of a dimensionless time, with 1/20 recommended. Dimensionless time is water depth (cm) squared divided by turbulent diffusivity (recommended 100 cm*cm/s) divided by pi squared. This time step assumes that advection is slower than diffusion. Smaller time steps can be used if the user desires to print solutions more frequently.

The documentation suggests that SPM be distributed throughout the water column initially. The initial conditions could therefore be determined from steady-state conditions obtained from program SPMONLY, a capability also included in OILSPM3. Oil is then spilled into water that has sediment.

The computer programs are coded in BASIC; the other three oil spill computer models are FORTRAN 77 programs. Converting the BASIC codes to FORTRAN is an option. Also, there are compilers available for BASIC and FORTRAN which allows FORTRAN codes to call subroutines written in BASIC.

SECTION III
COMPARISON OF MODELS

The oil spill models were loaded onto, compiled with, and linked on a MicroVAX and an IBM PC/AT to characterize and compare the models. Informational matrices were prepared to summarize the important features of each model. The matrix for operating on the MicroVAX, Table 1, (1) lists the operating system, compiler, and external libraries required when running these models on a MicroVAX, (2) details the language used and the file sizes for the source code, the compiled code, and the executable code, and (3) provides the total memory required to run each model. Table 2 lists similar information for operating on the IBM PC/AT. The two parts shown for the Circulation/Trajectory Model are listed separately since they are compiled separately and run sequentially, passing the data in a static data file. The Oil/SPM Model was compiled on the IBM PC/AT using QuickBASIC. It is the smallest of the models; it was not compiled on the MicroVAX.

The data in Tables 1 and 2 require some explanation. In these tables, the size of source cede is the total size of the FORTRAN or BASIC source code statements in ASCII. The MicroVAX files were created by modem transfer from an IBM PC/AT. The compiled size refers to the object files created by the respective FORTRAN or BASIC compilers. On the MicroVAX, they include the cross-reference information for the link map and source-level debugging. The size of the executable files are very different; they include space for the arrays on the IBM PC/AT but not on the MicroVAX. The memory required on the MicroVAX was the maximum memory used during execution; on the IBM PC/AT, the size of the executable file was used since there is no way to monitor it during execution on a non-multi-tasking system and it included all the necessary data storage.

This data indicates that all of these codes can easily be stored on readily-available hard drives for microcomputers (e.g., 20 MByte disk drives). With the exception of the Circulation Model, they all are small enough to execute on microcomputers with 1 MByte of RAM. The Circulation Model will probably require 4 MBytes of RAM, which is now readily available on Macintosh and MSDOS microcomputers.

The matrix shown in Table 3 was prepared to facilitate comparison of the models and aid in the evaluation of compatibility between the models. It combines the physical modeling, the numerical modeling, and the computer requirements into one table. In effect, the BDM team has distilled the data in the source codes, the user's manuals, the reports, and the data sets to provide the essence of the four computer models in this table,

In particular, the matrix summarizes the important elements of each model: input, output, time step values, grid resolution, applied force, boundary conditions, physio-

Table 1. VAX Comparison Matrix

	Coastal Zone Oil Spill	Circulation and Oil Spill Trajectory Model		Oil Weathering	Oil/Suspended Particulate Matter
		Circulation	Trajectory		
Language	FORTRAN	FORTRAN	FORTRAN	FORTRAN	BASIC
Source Size	380kB	78kB	151kB	107kB	35kB
Compiled Size	206kB	57kB	85kB	73kB	*
Executable Size	140kB	39kB	43kB	56kB	*
Memory Required	179kB	1713.5kB	147.5kB	58kB	*

Host Hardware: MicroVAX - 630QB
Operating System: VAX/Micro VMS v-4.7
Compiler Name: VAX FORTRAN v4.5

External Libraries: DEC STARLET.OLB
DEC FORRTL.EXE
DEC UVMTHRTL.EXE
DEC LIBRTL.EXE

* not compiled on VAX

Table 2. IBM Comparison Matrix

	Coastal Zone Oil Spill	Circulation and Oil Spill Trajectory Model		Oil Weathering	Oil/Suspended Particulate Matter
		Circulation	Trajectory		
Source Size	366kB	74kB	143kB	108kB	35kB
Compiled Size	303kB	122kB	98kB	108kB	43kB
Executable Size	403kB	1877kB	244kB	146kB	62kB
Memory Required	403kB	1877kB	244kB	146kB	119kB

Host Hardware: IBM PC-AT
Operating System: DOS 3.3
Compiler Name: Lahey FORTRAN F77L and
Microsoft QuickBASIC V4.00 with Overlay Linker V3.61

External Libraries: none

Table 3. Model Comparison Matrix

	Coastal Zone Oil Spill	Circulation and Oil Spill Trajectory Model		Oil Weathering	Oil/Suspended Particulate Matter
		Circulation	Trajectory		
Input	coastal reach & wind data, type of oil	wind, tide, & icc data	point of spill, type of oil	oil characteristics, weathering scenario	oil and SPM data
output	location & distribution of oil	velocity profiles	oil spill trajectory, mass balance	amt. of oil in each cut, amt. remaining	concentration gradients, material balance data
Time Step Values	3-6 hrs.	6 hrs.	1 hr.	3-30 min.	1 min.
Grid Resolution	1-10 km	wind 2.5 deg. lat/long; others 0.2 deg. lat., 0.313 deg. long.	10-40 km	spillet	1m
Applied Force	winds, currents, waves	winds	winds, currents, tides	none	none
Boundary Conditions	type of coast and dimensions	applied stress function of wind stress at surface, no salt flux through top or bottom	oil spill can be in open warm, broken ice, or pack ice	oil can weather in open water, in pack ice, or on top of ice	no oil lost horizontally by dispersion or spreading
Physio-Chemical Assumptions	no ice present, oil represented as circular spinets	incompressible flow, vertical accelerations small	ice follows viscous model, ignores losses by evaporation and dispersion	one location, oil always well-mixed, no disperson from wave action	independent of wind, waves, 1-D model only, no ice present
Numerical Method of Solution	explicit time integration	basic conservation eqns. solved in explicit FD form by Galerkin method	3-D mass transport eqn. solved by particle-in-cell technique	4th order Runge-Kutte time integration	1-D PDE solved by Laplace transforms, Crank-Nicholson integration each time step
Runtime Memory	403kB	1877kB	244kB	146kB	119kB
I/O Storage	500 kB	30 MB	2 MB	10 kB	1 kB
Model Author	● pplied Science Associates, Inc.	Applied Science Associates, Inc.	Applied Science Associates, Inc.	Science Applications Int'l. Corp.	Science Applications Int'l. Corp.
Date Completed	1988	1988	1988	1987	1987

chemical assumptions, numerical methods employed, runtime memory, I/O storage, model author, and date completed. The information regarding the Circulation/Trajectory Model is again divided into two columns.

BDM has interpreted the data in Table 3 as follows. The inputs for all models are similar: climatological data, bathymetric data, and oil characterization data. Data arrays, such as winds, can easily be interpolated between the grids of each model. To assemble sufficient data to run all of these models together will, however, be a significant effort. Sea ice is included only in the Trajectory Model and Weathering Model, not in the others. Therefore, further modelling and code development effort will be necessary to model oil in sea ice near shore and oil/SPM interactions under sea ice. The output data formats are highly varied. To allow the models to work together, their output routines will have to be modified to provide the necessary input data for other models. Graphical displays of output data will also be very useful in visualizing the results of the combined models. The time step sizes are compatible except for the Oil/SPM Model, which has a much shorter time step. The Weathering Model will start with short (3 minute) time steps with fresh oil but will quickly lengthen its step size to its maximum. To integrate the Oil/SPM Model, it may have to run hundreds of time steps for each time step for the other models. The Oil/SPM Model grid resolution is much smaller than the others but refers to the vertical direction. If it were to be converted to a two-dimensional model, its horizontal grid will be similar to the others. The applied forces are similar: winds, currents, tides, and waves. The redundant and missing physio-chemical assumptions are discussed in more detail later in this report. The numerical methods of solutions shown are highly varied. It would be a significant effort to convert them all to a common time-integration method. It would be less effort to leave these time-integration routines intact and run each model independently for a global time step, such as 6 hours. The Circulation Model is by far the largest, with the largest I/O and runtime memory requirements; it will require the largest available microcomputers to operate.

SECTION IV
MODEL INTEGRATION

The objectives were to analyze the four models and recommend necessary modifications to allow their sequential or integrated use in a combined oil fate model.

BDM has evaluated various combinations of the four oil spill model. Comparisons of code organization and potential changes to the individual models (to improve the functionality and usefulness of the combined model) were evaluated in terms of the ability of the combined model to perform its primary function of predicting the fates of oil spills.

BDM has considered combining models by matching the time steps, grid sizes, and data sets, by recommending ways of eliminating redundancies between the models being coupled, and by identifying missing features. The process of combining the models also considered the various subsets of the four models which are required to simulate the various scenarios.

A. OIL SPILL SCENARIOS

The BDM approach to the development of a combined oil spill model has considered:

(1) A wide range of Alaskan OCS oil spill scenarios
(2) The applicability of the models to each scenario
(3) Methods for coupling the models
(4) The structure of the synthesized model.

The combinations of three choices (nearshore/offshore, ice/no ice, and surface/subsurface oil spills) lead to eight possible oil spill scenarios which provide a full range of situations against which combined models can be tested for applicability, as illustrated in Figure 2. Ideally, various combinations of the four models should be able to accommodate any of the scenarios. Figure 3 compares the four models to the scenarios. The top portion of Figure 3 shows the capabilities of each model mapped against the scenarios. The bottom figure indicates which models can be used in each scenario. There are many open squares -- the whole issue of nearshore sea ice is not addressed by any of the models. All other situations are at least addressed, if not always satisfactorily (see Section H). For nearshore, COZOIL contains features to model oil weathering and Oil/SPM interaction, albeit in a less sophisticated manner than the Weathering and Oil/SPM Models. The Weathering and Oil/SPM Models could be adapted to the nearshore environment if needed. It is appropriate that subsurface weathering be open squares on

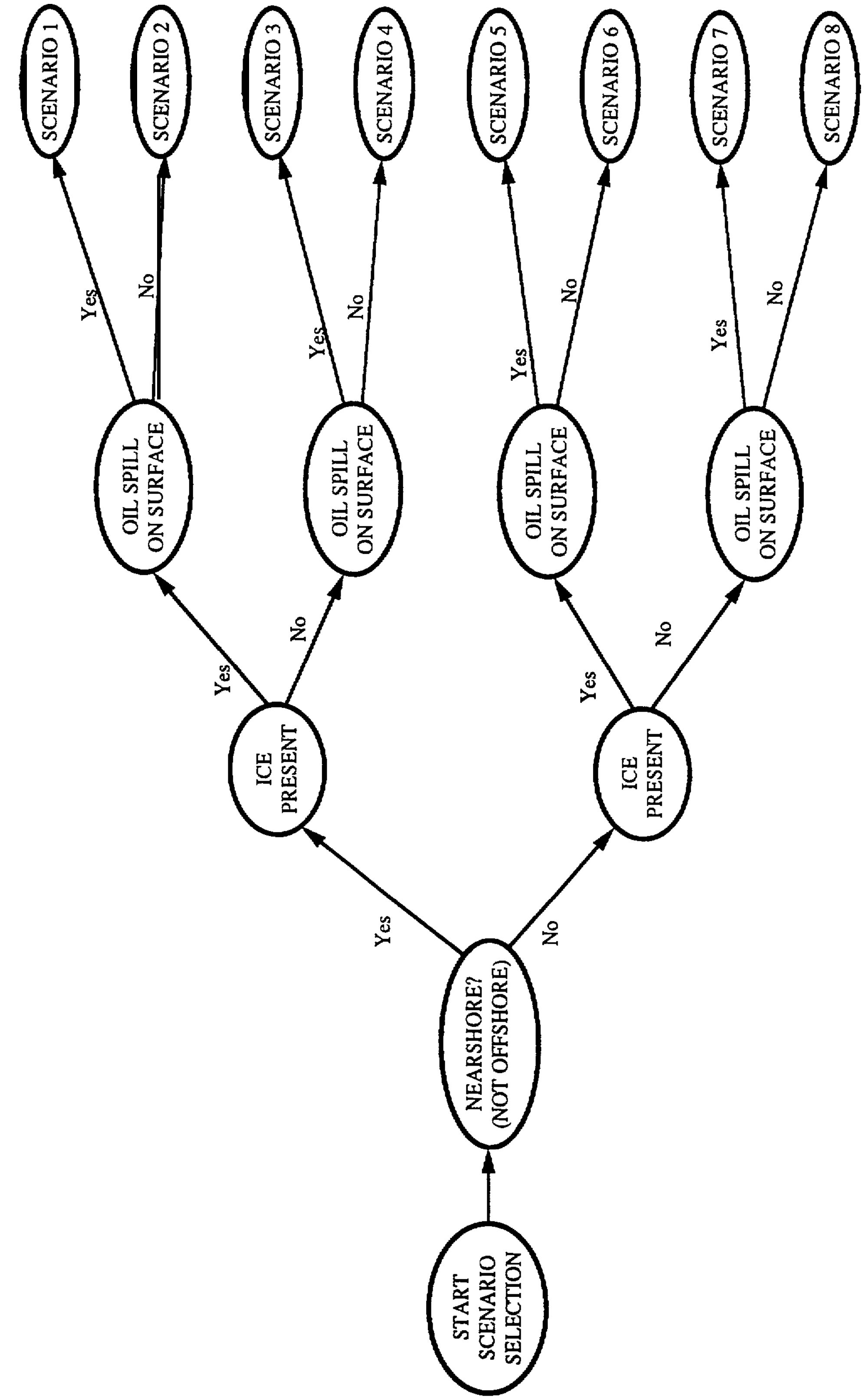

Figure 2. Basic Oil Spill Scenarios

MODEL	NEARSHORE	OFFSHORE	ICE	NO ICE	SURFACE	SUBSURFACE
COZOIL	●			●	●	●
CIRCULATION/ TRAJECTORY		●	●	●	●	●
WEATHERING		●	●	●	●	
OIL/SPM		●		●	●	●

(a) Capabilities of Each Model

SCENAR1O				COZOIL	CIRCULATION/ TRAJECTORY	WEATHERING	OIL/SPM
1	NEARSHORE	ICE	SURFACE				
2			SUBSURFACE				
3		NO ICE	SURFACE	●			
4			SUBSURFACE	●			
5	OFFSHORE	ICE	SURFACE		●	●	
6			SUBSURFACE		●		
7		NO ICE	SURFACE		●	●	●
8			SUBSURFACE		●		●

(b) Applicability to Eight Oil Spill Scenarios

Figure 3. Applicability of the Four Models to the Scenarios

Figure 3, since it is not an important fate mechanism to model. The Oil/SPM Model is most suitable for waters outside the surf zone, but on the continental shelf because the Oil/SPM Model does not incorporate the surf zone or beach environments, and because Oil/SPM interaction is not an important fate mechanism in the deep ocean where SPM concentrations are low. Oil/SPM interactions with sea ice is however an important feature which is not included in these models. Examples are springtime spills near estuaries when heavy sea ice is present, spills near shore when fast ice is present, and spills in harbors and bays when pancake ice is present. In each case the spilled oil will simultaneously interact with the ice and the SPM.

B. CONSIDERATIONS FOR COMBINING THE MODELS

Whatever form the combined oil spill model takes, the complete model will have several components. Consider Figure 4, which shows the need for input/output and database components of the model. It also shows a need for a way to define a new spill. The new spill will account for where the oil went in the last time step of the model as well as for additional oil spilled and for oil cleaned up. An expanded version of Figure 4 is shown in Figure 5, where input includes scenario rules and a library of oil spill models. The output has interactive post-processing and spill analysis, and the database has climatological and oil properties data. Nevertheless, the elements are the same, including the need to define a new spill.

1. General Considerations

The strengths of the four oil spill models have been summarized in Table 4. The COZOIL and Circulation/Trajectory Models are similar in that they both use large, horizontal grids; in contrast, the Weathering Model is applied at a point, and the Oil/SPM Model equations are solved over a single vertical array representing the water column. Knowing this, it is conceivable that the COZOIL and Circulation/Trajectory Models could be run jointly by passing oil spill and hydrodynamic data across a common boundary. The hydrodynamics in the Circulation/Trajectory Model should be used to drive the nearshore hydrodynamics of the COZOIL Model in any case. The Weathering and Oil/SPM Models could conceivably be applied as needed at the locations of spinets.

The Circulation/Trajectory Model is a collection of models which in some sense demonstrates within its own system one of the major aims of this project. In the way it is used, it essentially amounts to running independent models for tidal currents, barotropic currents, baroclinic currents, ice and/or surface currents, then combining (in a

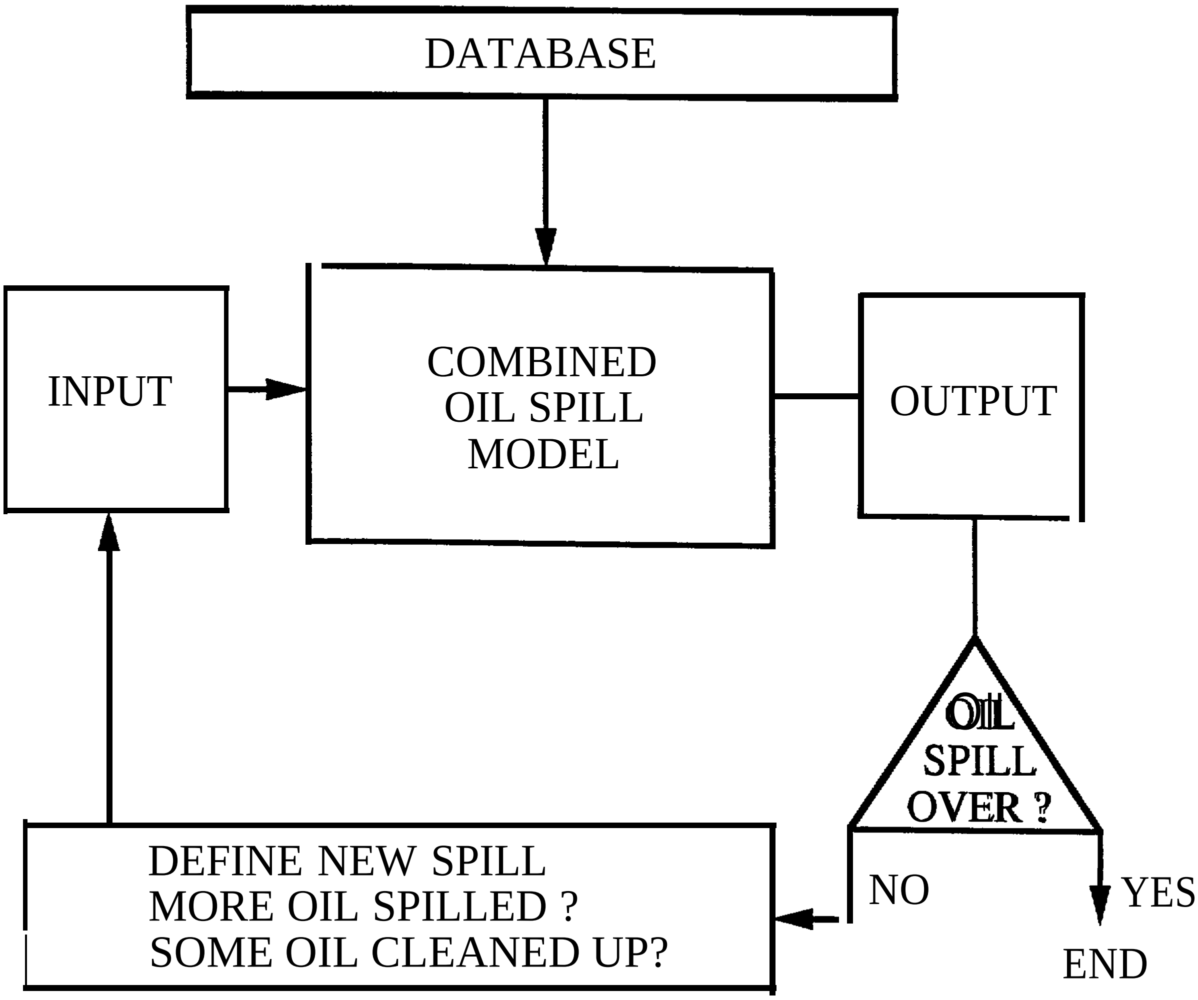

Figure 4. Top Level Flow Chart

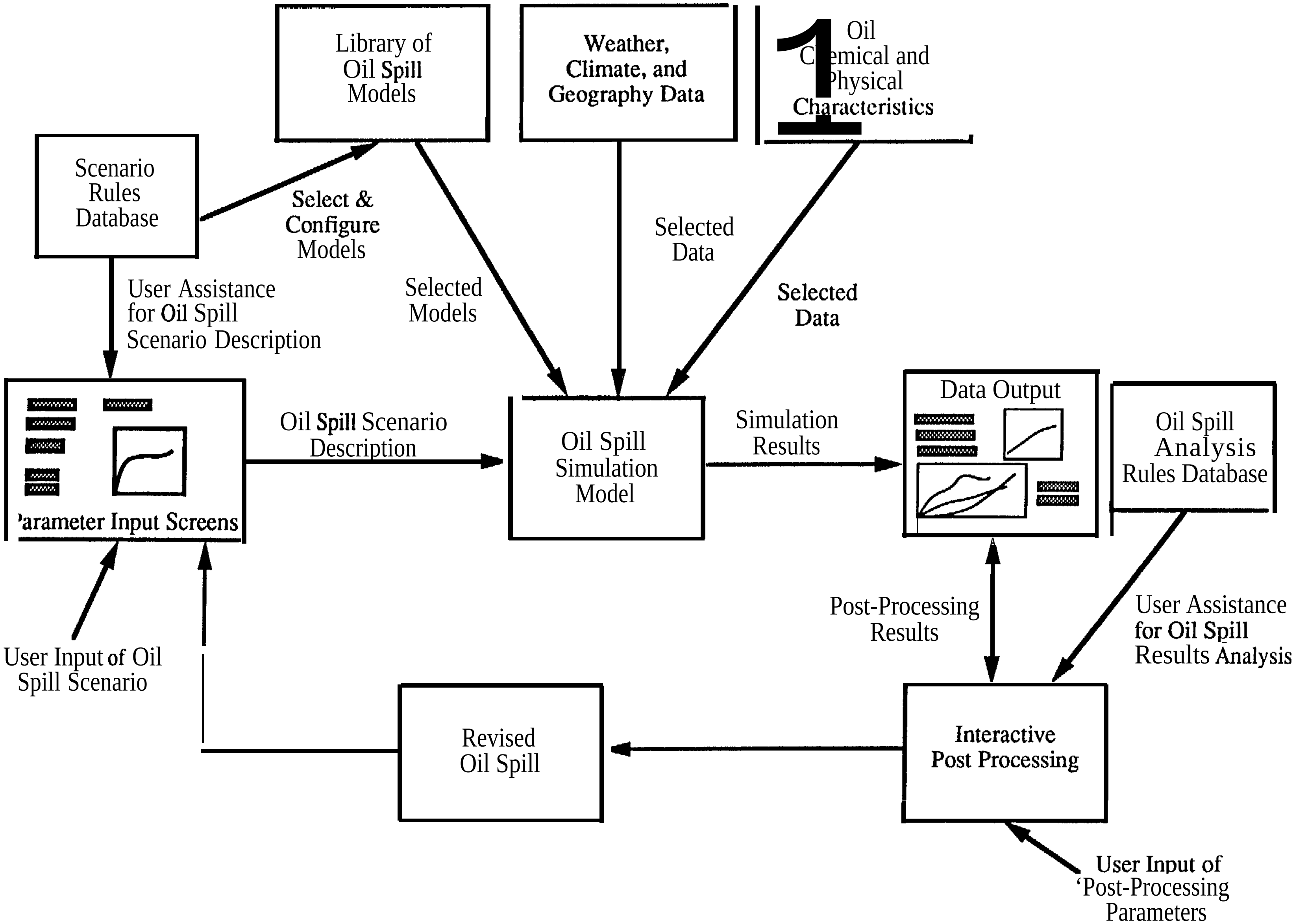

Figure 5. Combined Oil Spill Fate Model

Table 4. Summary of Model Features

- Coastal Zone Oil Spill Model
  - Predicts time-varying distribution of oil introduced into ice-free coastal domain separated into three partitions: nearshore, surf zone, and coast
  - Tracks spinets (multiple, discrete batches of oil) on and below surface
  - Deterministic model of shoreline: 30 x 300 km area, 10x 10 km grid size, and 3-6 hour time steps for up to 90 days
  - Input parameters define study location and physical properties, environmental data, and oil spill properties and dimensions
  - Output parameters define spatial distribution of oil droplets and oiled particles

- Circulation and Oil Spill Trajectory Model
  - Calculates hydrodynamics, wind, ice, and oil spill trajectories and fates with two computer codes: Circulation and Trajectory
  - Circulation Model
    - 3-D spectral hydrodynamics model solves conservation equations for water mass, density, and momentum
    - Generates surface velocity vectors for tidal and residual currents
    - Incorporates FNOC data sets into concurrent wind fields
    - Does not include surf zone or coast features
  - Oil Spill Trajectory Model
    - Calculates trajectory of spilled oil and predicts its fate with sea ice effects
    - Superposes wind-induced, tidal, and residual current drift to get trajectories for multiple spinets
    - Performs oil weathering on spinets (evaporation, dispersion, emulsification, and spreading)

- Oil Weathering Model
  - Provides pseudocomponent characterization of crude oil to derive time-dependent mass balance and composition of oil in slick
  - Weathering by evaporation, dispersion, mousse formation, and spreading, but no surf zone or coast effects
  - Accommodates three ice scenarios: oil in pools on surface, spreading under ice, and trapped in broken ice field
  - Input parameters define environment and physics of crude oil
  - Output parameters define oil fates (mass in slick, dispersed, and evaporated), slick dimensions and properties, and dispersion 'and evaporation; rates

- Oil/SPM Model
  - Predicts oil droplet and SPM interactions using 1-D vertical oil concentration profile to calculate rate of agglomeration of free oil droplets with SPM
  - Does not include sea ice, surf zone, or coast effects
  - Input parameters define rate of dispersion of discrete oil droplets from oil slick and environmental data
  - Output parameters define vertical oil concentration profile and mass of free oil drops in water column, mass of oil drops attached to SPM, and mass of oil drops attached to bottom

linear fashion) the resulting output to advect an oil spinet, which undergoes transformation according to another "oil fate" model similar to the COZOIL weathering model.

Ice dynamics, which are not present in the COZOIL Model, are treated either with a free drift model of Overland et al., 1984; or by a full ice model adapted from Kowalik. The Overland work describes a neutral boundary layer model that uses "second-order" closure to solve for the surface velocity in terms of stress, including bottom effects if the water is shallow. It is not clear how this is incorporated into the Circulation/Trajectory free-drift model, although it is doubtful that the model solves the equations over a 1001 point vertical grid as Overland did. In the full ice model, equations for ice compactness and ice thickness are carried for two categories of ice thickness, following Hibler's approach. A viscous constitutive relation between ice stress and strain is used instead of the viscous/plastic or elastic/plastic theologies, which would probably allow more realistic shear in near shore regions.

It would be a major undertaking to use the Circulation/Trajectory Model in any way different from the demonstration scenarios presented in the manual. Presumably the wind and hydrographic data would be available for running the hydrographic models, although the North Slope demonstration run misses the westward intensification of the Beaufort Gyre offshore of the shelf break--which is certainly present in Mountain's dynamic topography, and should show up in the baroclinic model (Mountain, 1974). Thus to use it in the Beaufort or Chukchi might require a good deal more preparation of the driving data sets. The User's Guide was not very helpful in laying out the sequential steps required for actually setting up and running the model.

In most respects, the Circulation/Trajectory Model already has an interface to a separate oil-fate model. To simulate a set of spill scenarios including nearshore/beach effects, one option is to modify the oil-fate section of the Circulation/Trajectory Model rather than build an interface which would, for example, pass a file of spinet characteristics from the Circulation/Trajectory Model to COZOIL. In other words, someone with enough skill to setup and use the Circulation/Trajectory Model would probably find it easier to just incorporate the desired features of COZOIL into the Circulation/Trajectory code.

In contrast to the COZOIL report, the Circulation/Trajectory Model documentation includes a helpful set of parameter studies. In the central Bering, for example, we find that various assumptions regarding the wind-driven barotropic current (including no barotropic current at all) have little impact on the results. It is doubtful whether the barotropic current emphasis is worth while, since it is probably the baroclinic response to particular storm events that matters. In terms of the user interface and the interface with other models, someone setting out to do a meaningful study of oil spill impact in a particular region would face a formidable task in setting up this model. In addition to the unavoidable task of setting up grids, assembling meteorological and oceanographic data, and developing algorithms for output interpretation, one would find themselves questioning and perhaps adapting many of the underlying model algorithms as well.

2. Overlapping Parameters. Time Steps. and Grid Scales

BDM has addressed which models have overlapping parameters and, where input and output parameters do overlap, whether the time step, grid scale, and forcing of the models logically allows them to be used together. The input parameters on the grids (such as winds and temperatures) require an interpolation routine to use the same data source.

The COZOIL Model was developed with coupling to the Circulation/Trajectory Model in mind (note that ASA was involved in the development of both models). The COZOIL Model can accept hydrodynamic data from a two or three dimensional circulation model. Furthermore, if the Circulation/Trajectory Model is used, then oil conditions can serve as initial conditions for COZOIL when oil is transported nearshore.

The COZOIL Model is essentially a standalone system. The user sets up the grid, specifies coastal characteristics, prescribes the wind time series and a simplistic tidal current model, and either looks at the statistics of several spinets, or synthesizes an actual spill event out of a series of spinets. The boundary conditions and perhaps interior grid oceanographic conditions could be coupled with the corresponding output of, e.g., the Circulation/Trajectory Model. This would only apply in an ice-free scenario.

In the Weathering Model, a fourth order Runge-Kutta time integration is performed. The time integration for each configuration (oil in surface pools, oil in broken ice, oil on open water) is performed within the time integration subroutine, but intermediate solutions are not available. The time step for temporal integration is set to allow a five percent change in the most rapidly varying pseudo-component, but may not exceed 0.5 hours nor be less than 0.05 hours. Components that weather too fast are assumed to be gone within a time step and removed from the simulation.

The Weathering Model is probably the most comprehensive yet developed. It has been tested against laboratory and field spill data. It can probably be used in conjunction with a hydrodynamics ‘point’ model, but the Weather Model will have to be extended to describe the behavior of a field of values. This will require more than just applying it to a set of cells in a horizontal grid because the spreading process must describe the spread of oil from one cell to its neighbor.

Although the weathering code is rather linear in its structure, it appears to be a modified version of the open ocean code, and as such suffers in its structure. Too much work is performed within the time interaction subroutine, and many of the calculations are made in duplicate parts of the code. It would be far better to develop a new set of subroutines to do these calculations. Furthermore, the time integration must be extracted from the time integration subroutine, BRKG4, if the code is to be integrated into a more complete model.

3. Redundant Model Features

The bullets in Figure 6 indicate which models have which redundant features. The COZOIL Model is involved in all redundant features since it is a comprehensive model.

It appears that the weathering behavior is rather similar in the Circulation/Trajectory Model (ASA), COZOIL (ASA), and the Weathering Model (SAIC). Features of the SAIC Weathering Model have already been incorporated into the Circulation/Trajectory and COZOIL Models. It appears that the Circulation/Trajectory Model includes all features of the SAIC Weathering Model but, in addition, includes transport by ice and relative to ice. It therefore includes and supersedes the SAIC Weathering Model.

The COZOIL Model contains a simplified model for Oil/SPM interaction, similar to those features in the Oil/SPM Model. The Oil/SPM Model is not very interesting in the deep ocean; it is applicable on the continental shelf and nearshore. Thus, these models are redundant in the nearshore. The 1-D Oil/SPM Model is more detailed but would need to be implemented in a 2-D or 3-D version to be used nearshore.

There are numerous redundant features between the Circulation/Trajectory Model and the COZOIL Model, except that the former is mainly an open ocean model and the latter a nearshore model as they now stand. Having these two models interface about 30 km offshore avoids a redundancy.

4. Missing Model Features

BDM has determined that all four models could reasonably and economically be adapted for sequential or integrated use in the combined oil fate model with minor modifications. Missing features and suggested modifications are identified in Table 5 and described in detail in the following.

The glaring omission in COZOIL for much of Alaskan waters is sea ice. It seems that many of the processes so painstakingly detailed in both the environmental and "fates" sections of the model would be entirely inappropriate if sea ice were present, or even if the beach were frozen. Certainly these conditions are found along much of the

Model Feature	Coastal Zone Oil Spill	Circulation and Oil Spill Trajectory	Oil Weathering	Oil/Suspended Particulate Matter
Weathering				
Spreading	•	•	•	
Evaporation	•	•	•	
Dispersion	•	•	•	
Mousse formation	•	•	•	
SPM Interaction	•			•
Spillet Transport	•	•		
Hydrodynamics	•	•		

Figure 6. Redundant Model Features

Table 5. Missing Model Features

- COZOIL
  - No Sea Ice and Frozen Beaches for Nearshore
  - No Nearshore Transport Mechanisms
    - Wind Drift with Coast Effects
    - Storm Surge Setup and Setdown
    - Steady-State Currents to Start Model

- Circulation/Trajectory
  - Lacks Sophisticated Offshore Wind Drift with
    - Accurate Surface Currents
    - Wind Spreading Mechanisms
  - Lacks Detailed Offshore Subsurface Pollutant Transport

- Weathering
  - No Spatial Variations
  - Lacks Validated Model of Dispersion, Spreading, and Mousse Formation with Sea Ice

- Oil/SPM
  - No Horizontal Advection and Diffusion of Oil with Suspended Particulate Matter
  - No Oil/SPM Interactions Under Sea Ice
  - No Surface Flux of Oil into Water Column Based on Sea State
  - No Sediment Flux at Bottom Based on Sediment, Wind, Wave, and Current Conditions
  - No Oil Flux into Sediment Based on Sediment Conditions
  - No Oil Droplet Size Dispersed into Water Column
  - No Biological Uptake of Oil

Alaskan coast line for much of the year (10 months a year on the Beaufort Sea coast and 6 months a year on the Bering Sea coast).

In the area of upper ocean currents and near surface transport, the COZOIL Model seems fairly naive. An example is the wind-drift current model, which is basically a simple momentum balance in which average current is obtained by dividing the slab momentum by the water depth. Some of its simplicity is sacrificed by making it time dependent. Also, the model is "spun up" with the full inertial terms for each spinet. This is incorrect because the current does not start when the oil spills. It would be more realistic to use the simpler steady-state response. Even in the context of microcomputer computing power, the processes could be treated much more realistically.

We question the balance of the COZOIL Model in its overall approach. As stated above, the treatment of the transport mechanisms, even in the absence of ice, is pretty crude. COZOIL has a "3%" rule for wind drift despite the proximity of the coast, no provision for "storm surge" setup or setdown, and a very simplistic wind driven current regime. Is this commensurate with an exhaustive description of a particular section of beach, and the small scale details of deposition and weathering there? In other words, is it really important to know whether some small amount of oil leaches out of emulsified mousse along a particular section of beach, if the uncertainty in a spill's beachhead is several tens of kilometers? It would be well worth the effort to do some carefully planned "parameter studies" for gauging the relative importance of the various processes listed above.

The COZOIL Model is essentially concerned with oil/beach interaction, with the offshore transport part tacked on rather haphazardly. It may be necessary to track a slick close to the surf zone with a more sophisticated hydrodynamics model (something along the lines of the Circulation/Trajectory Model but with closer attention paid to coastal processes). When an oil beachhead is established, calculate the oil/beach deposition and weathering with COZOIL or a similar model. This could reduce the domain size (thus increasing grid resolution) and simplify calculations considerably. Perhaps a completely separate module could then be used for the scenario with sea ice and/or frozen beach.

In the Circulation/Trajectory Model, by far the most important factor is the wind drift, so this should be of top priority--unfortunately, this seems to be the least sophisticated aspect of the entire model. Recent test results reported by Reed, et al. (1990) show that the wind plays a major role in the spill on the surface by pushing a heavy patch of oil faster, leaving a streamer of thick oil behind, and spreading an oil sheen out to the sides. The subsurface pollutant transport part of the Circulation/Trajectory Model is also weak.

In the presence of ice, the wind-driven velocity of the oil is the sum of ice velocity and oil velocity relative to the ice. When the relative speed is below a threshold, the oil is trapped and moves with the ice. In free-drift, wind-driven surface currents are neglected, and the ice velocity is assumed as 3.3% of the wind velocity deflected 35 degrees to the right. The text suggests that in full ice coverage, when ice stress is important (typically north of St. Lawrence Is.), the fully coupled ice-hydrodynamics model is used to describe the ice motion. Although the fully coupled ice-hydrodynamic model can be used, the report leaves some question as to whether or not it has actually been used. It would be better to use the fully coupled ice-hydrodynamic model whenever ice was present.

The Weathering Model describes behavior at one location as a function of time. There are no spatial variations, horizontally or vertically, through the water column. In addition, sea ice enters the Weathering Model in a very casual way. In the mousse and dispersion model, a constant changes from 1 to 10; in the spreading model, the rate varies linearly with the open water fraction. The evaporation code is suitable for use in a more sophisticated oil/ice model, but the dispersion, mousse formation, and particularly the spreading model features should be carefully examined for use with sea ice before incorporation.

For sea ice models, more research and model development is needed on topics such as the under-ice dispersion of oil into the water column. We know qualitatively how oil disperses into the water column under open ocean conditions. Namely, the cause of droplet formation from oil slicks is due to wave breaking at the edges of the slicks, following which the oil droplets are thrown into the water column. What about oil under the ice? Are there similar mechanisms for dispersing oil under a sea ice cover? For example, in early OCSEAP laboratory experiments (Martin, 1977), it was observed qualitatively in laboratory studies that droplet formation occurred during pressure ridge formation. Can droplets form also from turbulent shear generated under an ice cover? To model the dispersion of an under-ice oil spill, questions such as these need to be investigated.

The Oil/SPM Model appears to couple sensibly with the other models. The problem is that it is concerned only with the rate of change in the vertical profile of suspended oil and solid particulate. Horizontal advection and diffusion are not considered. Perhaps the simplest way to couple the SPM effects would be to rewrite the subsurface transport model in the Circulation/Trajectory Model. This would not be a trivial task, but at present no simple realistic coupling appears possible. Problems in coupling the Oil/SPM code to other physics is comparable to coupling the SAIC Weathering Model to the Circulation/Trajectory Model, except that ASA has already done the latter.

There is no sea ice in the Oil/SPM Model, and, given that we do not even know how oil dispersion occurs under sea ice, it will be difficult to generate a realistic model of this process. From the qualitative OCSEAP experiments (Martin, 1977), we suspect that dispersion will take place through ridge formation or oil entrainment in a turbulent shear flow. There are also plenty of ice core observations showing a strong sediment signal at different depths, so that sediment is sometimes suspended under sea ice. The problem is important, but modelling it will be very difficult.

The one-dimensional Oil/SPM Model is useful because it allows an estimate of how long it will take for spilled oil to reach the bottom in an environmentally sensitive region. The problem with the model is that the surface fluxes of oil and sedimentat the top and bottom of the water column depend only on default constants and are decoupled from any environmental model. This means for the naive user that oil would be entrained at the same rate on a day with zero winds and no surface waves as during a severe storm! Additionally, for application to the real world, this model should be coupled to a data base of nearshore sediment conditions. This serves two purposes. The user would have some idea first, whether the bottom material is capable of going into suspension, and second, whether it is a favorable material for taking up oil.

It is possible to use the oil weathering model's dispersion term as input to the Oil/SPM Model. The problem is that the ability of sediment to take up oil strongly depends on the oil droplet sizes being on the order of 1-10 microns. The Weathering Model does not consider droplet size but gives only an estimate of the amount of oil dispersed into the water column. To quote from Payne, et al., (September 15, 1987) the "existing open-ocean oil-weathering code contains an algorithm for dispersion of oil into the water column'' (page 2-5), but that "there are no acceptable models which predictoil-droplet size from a dispersing slick." This difficulty with oil droplet size must be resolved before the Oil/SPM and Weathering Models can be coupled together. Also, the Oil/SPM Model still requires ocean wave and current data to describe the sediment flux from the bottom.

In summary, there is no point incorporating either of these models into a general oil spill model unless two improvements are made. First, the oil dispersion and sediment uptake terms must be tied into a wind, wave and current data base; second, the model must be tied to a sediment inventory data base.

The Oil/SPM Model is primarily applicable to shallow water, where winds and waves generate suspended sediment. The depths cited throughout the report include 2-10 m, so that this is a near coastal phenomena. The oil interacts with the SPM through two mechanisms:

(1) oil droplets collide with SPM, and
(2) dissolved species are absorbed by SPM.

The Oil/SPM Model considers only the first effect. As an example of the importance of this process, under high SPM concentrations, 10-15% of a spill in the Baltic was removed from the water column by sedimentation. Note also that there are different kinds of SPM's. For example, clay and glacial derived tills attract much more oil than minerals. The model also ignores biological effects, so that the uptake of oil droplets by phytoplankton and the incorporation of oil into fecal pellets, which then fall to the bottom, are neglected. There is speculation in the recent Exxon Valdez reports that this source of oil for the bottom sediments is greater than oil incorporation into SPM.

The critical parts of the model areas follows. Any predictive model must be able to predict the amount of SPM in the water column, which will depend on the wind, wave, and nearshore environment, then predict if the spilled oil will be broken into small droplets by waves, and finally predict if the droplets will be collected by the SPM. Therefore, the predictive equations for the oil and SPM depend strongly on the wind, wave, and ocean turbulence equations, as well as on the local sediment properties.

The Oil/SPM Model contains a suspended sediment, bottom boundary layer submodel, which takes into account the non-linear dynamics of surface wave and current interactions in bottom boundary layers. It is the long waves and low frequency currents which resuspend sediments; whereas it is the short choppy seas that generate oil droplets from slicks. For sea ice, the long waves and currents will continue to be important in ice-covered seas, and thus oil /SPM interactions will probably occur under ice.

c. VIABLE STRUCTURES OF THE COMBINED OIL FATE MODEL

Some considerations for combining the models were discussed in Section IV, Heading B, above. In the earlier discussion it was pointed out that the complete oil spill simulation model required components that were input/output software, database components, and a component which defined a new oil spill after some time step of having run the model. This new scenario section would account for the fate of the oil previously spilled as well as any new oil spilled or any oil cleaned up during the time period. In this section the discussion will concentrate only on the portion of the complete oil spill simulation model which represents the combination of the four oil spill models being reviewed in this report. After consideration of the physics, chemistry, numerics, and code structure of the four codes, it appears that there are three logical ways of combining the codes. Each of the three possible methods of combining the codes have some advantages and some limitations which will be discussed in detail below. The three possible approaches are

(1) Sequential approach for combining the existing codes.

(2) Development of a code based on the Circulation/Trajectory Model.

(3) Develop anew code from the basic equations of each code.

Nearshore, the COZOIL Model is nearly complete, but the Weathering Model may improve the quality of the weathering effects and include sea ice. Offshore, the COZOIL Model is not appropriate. It thus appears that two unique subsets of the models are required: Weathering with COZOIL, and Circulation/Trajectory with Weathering and Oil/SPM. It will occur, however, that an oil spill will extend from one scenario to another as, for example, an offshore spill that drifts next to a land mass.

It would, however, be a fairly major undertaking to interface the COZOIL Model properly with the Circulation/Trajectory Model. It might be less effort to incorporate the desired features of COZOIL into the Circulation/Trajectory Model rather than build an interface between the two models.

No matter which method of combining the models is selected (including *status quo*), the issue of shelf life should be raised. To have a shelf life of five years, individual models need to be updated or replaced with codes reflecting new field data and test results. A viable structure for the combined oil fate model should readily allow the incorporation of these updates without impacting the overall function of the combined model. The list of missing model features in Table 5 is representative of potential technical developments (by test or modelling) which might render the existing codes obsolete if they were not incorporated.

1. Sequential Approach for Combining the Existing Codes

One candidate for combining the four models is to leave each model separate and operate them sequentially, and, after each time step (which might represent an hour or a day), redefine the oil spill in terms of the output from each model. The actual time steps used within each model might be quite different; however, they would be run until they had each provided output over the chosen time step. This approach will be discussed in this section.

At one time OCSEAP thought it desirable to have one comprehensive model to describe ice trajectories, oil trajectories, oil weathering, and fate. Another approach, however, is to isolate each model where possible and to perform the calculations sequentially. The sequential approach simplifies each calculation and allows the oil spill behavior and fate to be recalculated by different methods without recalculating the ice and ocean motion fields. There are situations in which this speed and flexibility is desirable.

Such an approach, however, may require more user interaction with the model than is desired.

A flow chart of the sequential approach is shown in Figure 7. As the flow in the figure shows, environmental and oil spill data must be entered to the models. First the code must determine whether the location of the spill is nearshore or offshore. Only if the spill is nearshore is the COZOIL Model used. In most ways, this model is complete since it has weathering, circulation, and fate combined in it. However, for offshore spills, the Weathering, Circulation/Trajectory, and Oil/SPM Models could be operated independently. At present there is a weathering module within the Circulation/Trajectory Model which one would suppress in favor of using the Weathering Model. The Oil/SPM Model is a one-dimensional model looking at vertical variations; it could be applied to vertical variations of oil transported using the Circulation/Trajectory Model from the previous time step. If the oil spill involved both nearshore and offshore regions, then all four models would be used and the new oil spill volume, location, and oil type would be combined for both nearshore and offshore to describe the new spill. The major advantages of this sequential operation are that each model can operate on its appropriate time and space scales and that the results are brought together only after the operation of each model. The primary disadvantage of the sequential approach is that by separating the physics into the component models, the optimal solution for the physics may not be obtained.

2. Develop a Code Based on the Circulation/Trajectory Model

Another approach is to fully integrate two or more of the models using common data sets, time steps, grid sizes, and sharing data between time steps for full coupling of the models. For example, (1) use the Weathering, Circulation/Trajectory, and Oil/SPM Models and incorporate features from the COZOIL Model for the nearshore area, or (2) add open ocean circulation to the COZOIL Model and improve the Oil/SPM and Weathering features with those codes. The models are used on a time step (to be determined) to define a new oil spill and the fate of the oil over this time step. The process continues until the quantity of oil remaining is insignificant.

If the four models are to be integrated with one model as the central link pin, then the Circulation/Trajectory Model is the clear candidate. Essentially, the Weathering Model has been previously incorporated into the circulation model. The COZOIL Model has most of the features of the other three models built in, with the additional feature of interaction with the beach. However, the COZOIL Model treats the oceanography in a considerably simpler manner than the Circulation/Trajectory Model. Therefore, if one is seeking a single code developed from the four, it would seem advisable to extend the oceanography in the Circulation/Trajectory Model to the nearshore and incorporate the oil

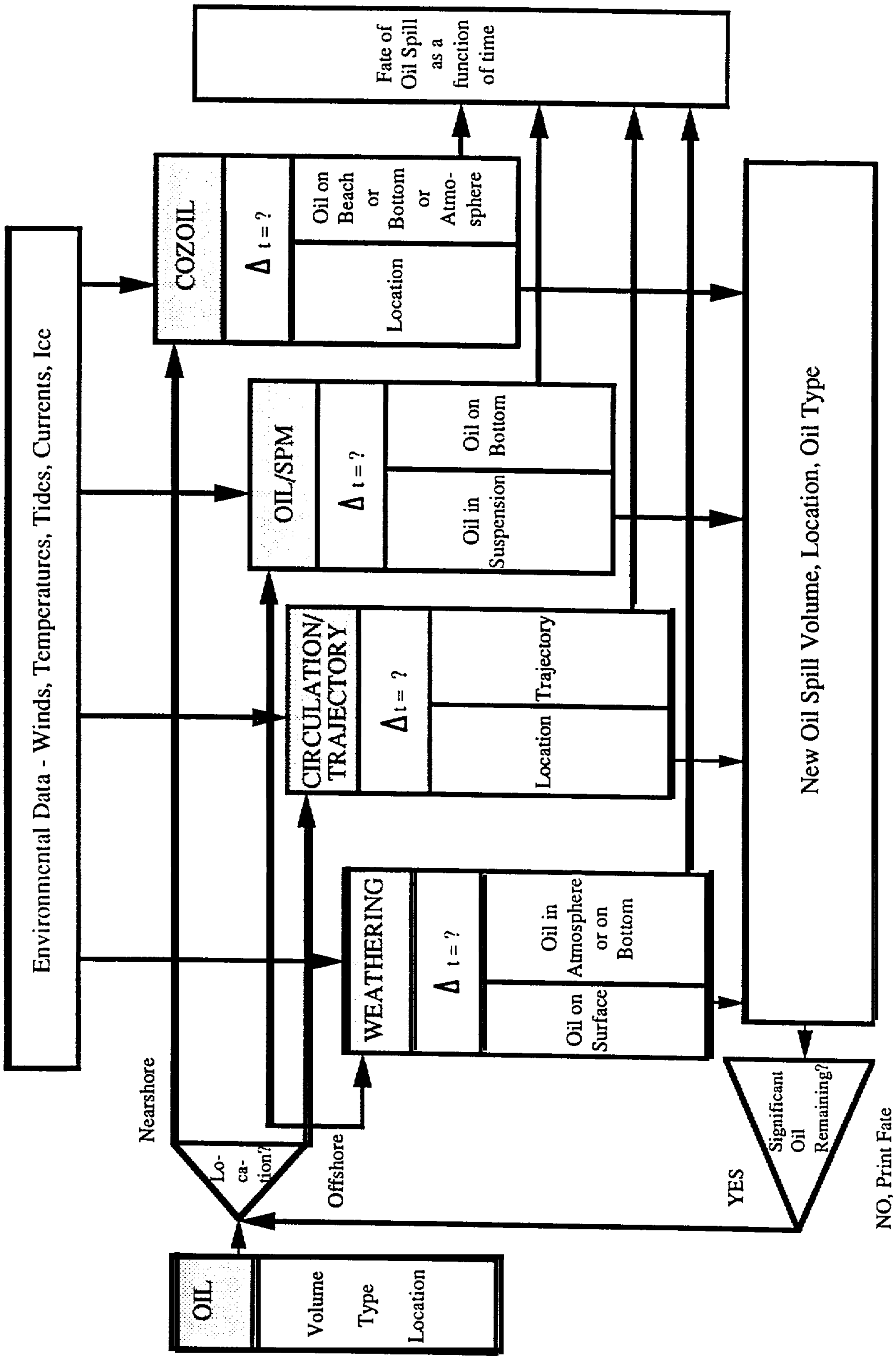

Figure 7. Sequential Approach

interaction with the beach from the COZOIL Model. Following this line then, the Circulation/Trajectory Model can provide the structure to integrate the Weathering and COZOIL Models. The Oil/SPM Model appears to couple sensibly with the Circulation/Trajectory Model. The difficulty is that the Oil/SPM Model is concerned only with the rate of change in the vertical profile of suspended oil and solid particulate. Horizontal advection and diffusion are not considered. Probably the simplest way to couple the Oil/SPM effects would be, however, to rewrite the subsurface transport module in the Circulation/Trajectory Model. This would not be a trivial task, but, at present, no simple realistic coupling appears possible. The problems of coupling the Oil/SPM code to the other physics is comparable to coupling the Weathering Model to the Circulation/Trajectory code, which has already been done.

This approach of using the Circulation/Trajectory Model as the cornerstone to the model integration retains most of the previous code development and provides for a unified model. However, it should be pointed out that the documentation for using the Circulation/Trajectory Model is lacking in many ways and, therefore, code documentation will be a significant effort. Also, amassing data for input to the Circulation/Trajectory code as it presently stands is a lengthy task requiring a knowledgeable operator.

3. Develop a New Code from the Model Physics

A third option for the development of a unified model from the four existing models would be to start with the physics and chemistry as described in the basic equations that underlie the models and develop a new unified code. Such an approach has many advantages. One advantage is code efficiency, since each physical process would only be considered once. A second is numerical optimization, in that all required numerical schemes could be considered simultaneously. Also, the unified code could be tailored to a specific given computer hardware and/or tailored to available, commercial software for handling the input/output as well as pre- and post-processing, etc. With proper architecture, the new code could have the features of being updated easily later. This approach has one major disadvantage in that it does not utilize the considerable effort which has already been expended in model development. It will therefore be the most costly of the three approaches discussed here. If, however, a single model is desired, it will lead to the optimum model when properly exercised, debugged, and documented.

SECTION V
COMBINED OIL FATE MODEL DEVELOPMENT

In general, the combined oil fate model will consist of input/output software, some combination of the existing four oil spill models, new oil spill model features to be developed, and the required database. The effort to develop these code segments has been divided into the four tasks described in Section A below. These tasks were then combined into various combinations to assess the development effort required to create the desired combined model.

A. <u>COMPONENTS OF DEVELOPMENT EFFORT</u>

The development of the combined code will involve the following four tasks:
Task 1- Development of Input/Output Software
Task 2- Combined Oil Spill Model Development
Task 3- Addition of Missing Features
Task 4- Acquisition of Databases

The required levels of effort for Tasks 1 and 2 depend upon priorities yet to be established. Consequently, several options are described for Tasks 1 and 2 in the following. Table 6 provides relative estimates for the levels of effort for each of these task options. programmatic decisions regarding the exact scope of each task are required before more precise estimates can be made.

Task 1a - Development of Input/Output Software with Simple Architecture
Use a minimum, simple architecture which can be operated by a knowledgeable person experienced in oil spill modeling.

Task lb - Development of Menu-Driven Input/Output Software
Develop menu-driven input/output software which will guide the generation of input data, perform data transfer between I/O routines and the oil spill models, and produce the desired output plots, all with a few key strokes.

Table 6. Development Effort by Task, by Skill Type, in Man-Months

DEVELOPMENT TASK		TASK TITLES	OCEANOGRAPHER, ATMOSPHERIC SCIENTIST, CHEMIST	NUMERICAL ANALYIST	SYSTEMS ANALYIST, SENIOR PROGRAMMER	PROGRAMMER	TOTAL
1	a	Development of Input/Output Software with Simple Architecture			2	4	6
	b	Development of Menu-Driven Input/Output Software	—		4	8	12
2	a	Combined Existing Oil Spill Models			4	8	12
	b	Combined Model Based on Circulation/Trajectory Model	4	3	3	8	18
	c	New Integrated Oil Spill Model	4	8	4	8	24
3		Addition of Missing Features	16	2	2	4	24
4*		Acquisition of Databases					

* A Database is Needed, but h Does Not Effect the Model Development

Task 2a - Combine Existing Oil Spill Models
Combine the four existing oil spill models as they stand with an executive program that will allow each program to run by itself or in a linked mode, passing a minimum of data between models.

Task 2b - Combined Model Based on Circulation/Trajectory Model
Build a model around the Circulation/Trajectory Model by combining the vertical SPM model with the Circulation/Trajectory Model's transport through the water column, adding the Weathering Model components not all ready in the Circulation/Trajectory Model, and adding the surf zone and beach interaction features from the COZOIL Model.

Task 2c - New Integrated Oil Spill Model
Develop a new integrated oil spill model by starting with the physio-chemical equations from each existing model, coding a coupled, simultaneous solution technique, and optimizing the resulting code.

Task 3- Addition of Missing Features
Improve the existing four oil spill models by adding the missing and inadequate features discussed in Section IV, Heading B, Subheading 4.

Task 4- Acquisition of Databases.
Build the climatological, bathymetric, and oil characterization databases needed for the running the combined model.

B. ASSESSMENT OF DEVELOPMENT EFFORT

The development effort will depend strongly upon the selected levels of effort for each task. Table 7 delineates various sets of the task options, discusses the advantages and disadvantages of various sets, and provides the total level of effort based on the estimates in Table 6. No estimates for the levels of effort for building a database have been made. The estimates will be required but are separate from the model. Many task option sets were rejected outright since they would produce an unbalanced level of detail in various aspects of the code. Set 1 would combine the four models with no improvements and would not

Table 7. Description of Possible Combined Models

SET	TASKS FROM TABLE 6	COMMENTS	PERSON-MONTHS * OF DEVELOPMENT
1	1a, 2a	Adequate, Low Cost	18
2	la, 2a, 3	Not User Friendly, Better Than Set 1	42
3	la, 2b	Good Spill Model, Not User Friendly	24
4	la, 2b, 3	Too Much on Spill Model, Not Enough on Input/Output	48
5	la, 2c	Too Much on Spill Model, Not Enough on Input./Output	30
6	la, 2c, 3	Too Much on Spill Model, Not Enough on Input/Output	54
7	lb, 2a	User Friendly but Too Much on Input/Output, Not Enough on Models	24
8	lb, 2a, 3	User Friendly but Too Much on Input/Output, Not Enough on Models	48
9	lb, 2b	User Friendly, Balanced Model, Moderate Cost	30
10	lb, 2b, 3	Improvement of Model 9	54
11	lb, 2c	Good Single Model	36
12	lb, 2c, 3	Best of Everything	60

* Does Not Include Database Acquisition

be very user-friendly. However, it would require the least effort. Other than Set 1, the next sets that seem reasonable are Sets 9-12. Set 9 is balanced between operating the system and oil spill model. Set 10 improves the model by including the missing features of Section IV, Heading B, Subheading 4. Sets 11 and 12 are like Sets 9 and 10 but with a simple model for the spill. In summary, Sets 1, 9, and 12 provide a broad range of reasonable choices for the further development of these oil spill models. A final selection among these three cannot be made without additional information, such as the eventual applications of the combined model and the development funds available.

SECTION VI
CONCLUSIONS

BDM has examined the four oil spill models provided by the government for this study. Eight basic oil spill scenarios were considered for the Alaskan OCS region. Redundant model features and missing model features have been identified. Various methods for combining the computer codes were compared. Three sets of the following tasks were selected:

Task 1- Development of Input/Output Software
Task 2- Combined Oil Spill Model Development
Task 3- Addition of Missing Features
Task 4- Acquisition of Databases

A low cost task set is to develop the I/O software with simple architecture, combine the existing oil spill models in the simplest manner, and prepare a database, without addressing the missing features. An intermediate task set is, to develop menu-driven 1/0 software, combine the four oil spill models around the Circulation/Trajectory Model, and prepare a database, again without addressing the missing features. The top of the line task set is to develop menu-driven 1/0 software, develop a new integrated oil spill model, add code to address the missing features, and to prepare a database. It is recognized, however, that the final selection will depend strongly upon the desired applications of the combined code and the funds available.

The combined oil fate model should have a shelf life of five years if individual models are updated to reflect new field data and test results. Incorporating the most significant missing model features (e.g. adding sea ice to theCOZOIL Model) will greatly strengthen the combined model. Also, more user-friendly input and output procedures would increase utilization and productivity of the models.

SECTION VII
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