REVISION AND EXPERIMENTAL VERIFICATION OF THE
HAZARD ASSESSMENT COMPUTER SYSTEM MODELS FOR
SPREADING, MOVEMENT, DISSOLUTION, AND DISSIPATION OF
INSOLUBLE CHEMICALS SPILLED ONTO WATER — —

F. T. DODGE
J. T. PARK
J. C. BUCKINGHAM
R. J. MAGOTT

FINAL REPORT
JUNE 1983

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Washington, D.C. 20593
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Revision and Experimental Verification of the Hazard Assessment Computer System Models for Spreading, Movement, Dissolution, and Dissipation of Insoluble Chemicals Spilled Onto Water

F.T. Dodge, J.T. Park, J.C. Buckingham and R.L. Magott

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Computerized models are developed to predict the spreading, movement, evaporation, and dissolution of floating slicks formed by accidental spills of insoluble chemicals. Separate models are developed for continuous and instantaneous spills. The waterway can be a river, channel, lake, or coastal water. The models emphasize the dynamics of the thick slick (i.e., the gravity-viscous spreading phase) since the thick slick contains nearly all the spilled chemical and represents the most prolonged hazard.

Predictions of the spreading models are compared to results of instantaneous and continuous spill tests conducted in a large laboratory basin and a laboratory channel. The evaporation and dissolution predictions are compared to wind tunnel and wind-wave tunnel tests. Agreement of the models and the tests is generally good.

Chemical Spills Evaporation Document is available to the public
Waterways Dissolution through the National Technical
Floating Slicks Dissipation Information Service,
Slick Movement Spreading Springfield, Virginia 22161

Unclassified Unclassified

Final Report is in two volumes. Volume 2, "Test Data Volume" is bound separately.
### METRIC CONVERSION FACTORS

#### Approximate Conversions to Metric Measures

<table>
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<th>Symbol</th>
<th>When You Have</th>
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|       | Area          |             |                  |
|       | square meters | 0.09        | square feet      |
|       |                  | 1.2         | square yards     |
|       |                  | 0.11        | hectares         |

|       | Mass (weight)  |             |                  |
|       | grams          | 0.06         | kilograms        |
|       |                  | 2.2          | pounds           |
|       |                  | 1.1          | tons (1000 lbs)  |

|       | Volume         |             |                  |
|       | liters         | 0.24        | quarts           |
|       |                  | 0.97        | pints            |
|       |                  | 3.8          | gallons          |

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### Approximate Conversions from Metric Measures

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|       | Area          |             |                  |
|       | square meters | 10.76       | square feet      |
|       | square feet   | 0.09        | square meters    |
|       | hectares      | 0.0001      | square meters    |

|       | Mass (weight)  |             |                  |
|       | grams          | 0.035       | kilograms        |
|       |                  | 2.2          | pounds           |
|       |                  | 1.1          | tons (1000 lbs)  |

|       | Volume         |             |                  |
|       | liters         | 1.09        | quarts           |
|       |                  | 3.78        | pints            |
|       |                  | 15.6         | gallons          |

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<td>5°C (hot)</td>
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*Note: 1 °C = 1.8 °F; 1 atm = 1.01 x 10^5 N/m²; 1 g = 0.035 oz.*
ACKNOWLEDGEMENTS

The authors wish to acknowledge the guidance and encouragement of the U. S. Coast Guard Technical Monitors, Lts. Guy Colonna and Kyle Blackman. Special thanks are also due to:

- Professor Donald Mackay of the University of Toronto for his advice and physical insight;
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<td>Results of Dissolution Tests in SwRI Wind Tunnel</td>
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<td>Description of Demonstration Cases</td>
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<td>Interactive Input for Demonstration Case No. 1</td>
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<td>VI.2b</td>
<td>Sample Computed Output for Demonstration Case No. 1</td>
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<td>Interactive Input for Demonstration Case No. 2</td>
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<td>Sample Computed Output for Demonstration Case No. 2</td>
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<td>Interactive Input for Demonstration Case No. 3</td>
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<td>VI.4b</td>
<td>Sample Computed Output for Demonstration Case No. 3</td>
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<td>VI.5a</td>
<td>Interactive Input for Demonstration Case No. 4</td>
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<td>Sample Computed Output for Demonstration Case No. 4</td>
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<td>Interactive Input for Demonstration Case No. 5</td>
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<td>VI.6b</td>
<td>Sample Computed Output for Demonstration Case No. 5</td>
<td>183</td>
</tr>
</tbody>
</table>
# LIST OF PRINCIPAL SYMBOLS

## Common Symbols
- \( t \): time
- \( \rho \): water density
- \( \rho_0 \): chemical density
- \( \nu_w \): water kinematic viscosity

## Spreading Models
- \( A, \overline{A} \): area of thick and thin slick
- \( A_1, \overline{A}_1 \): initial areas of thick and thin slick
- \( C_{1m}, C_{2m} \): constants in channel spreading models; \( m = 0 \) for instantaneous spill; \( m = 1 \) for continuous spill; \( m = 2 \) for continuous spill in a current.
- \( g \): acceleration of gravity
- \( h, \overline{h} \): thickness of thick and thin slick
- \( h_1, \overline{h}_1 \): initial thickness of thick and thin slick
- \( K_{1m}, K_{2m} \): constants in open water spreading models; \( m = 0 \) for instantaneous spill; \( m = 1 \) for continuous spill; \( m = 2 \) for continuous spill in a current.
- \( m \): discharge rate of continuous spill
- \( \dot{m}_{loss} \): rate of mass lost from thick slick
- \( R \): radius of thick slick
- \( T \): tidal period
- \( U_c \): current
- \( U_0, U_1 \): steady and oscillating amplitude of tidal current
- \( U_T \): surface transport velocity; \( U_c + 0.035 \nu_w \)
- \( V_0 \): volume of instantaneous spill
- \( V_w \): wind speed
- \( w \): river or channel width
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>width of triangular slick</td>
</tr>
<tr>
<td>x</td>
<td>location of downstream (leading) edge of triangular slick</td>
</tr>
<tr>
<td>(a)</td>
<td>tidal phase</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>(1 - \rho/\rho_0)</td>
</tr>
<tr>
<td>(\theta)</td>
<td>wind direction angle</td>
</tr>
<tr>
<td>(\mu_w)</td>
<td>viscosity of water</td>
</tr>
<tr>
<td>(\sigma_{aw}, \sigma_{ow}, \sigma_{oa})</td>
<td>interfacial tensions: air-water; chemical-water; chemical-air.</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>net spreading coefficient</td>
</tr>
</tbody>
</table>

**Evaporation and Dissolution Models**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_*)</td>
<td>friction concentration, (-J_0/\rho u_*)</td>
</tr>
<tr>
<td>(c_+)</td>
<td>((C - C_s)/c_*)</td>
</tr>
<tr>
<td>(C)</td>
<td>mean local concentration</td>
</tr>
<tr>
<td>(C_s)</td>
<td>surface concentration (saturation value)</td>
</tr>
<tr>
<td>(C_f)</td>
<td>friction coefficient, (2 \tau_0/\rho_a V_w^2)</td>
</tr>
<tr>
<td>(C_\infty)</td>
<td>freestream concentration ((= 0))</td>
</tr>
<tr>
<td>(d)</td>
<td>river or channel depth</td>
</tr>
<tr>
<td>(D)</td>
<td>molecular diffusivity; subscript (a) = air; subscript (w) = water.</td>
</tr>
<tr>
<td>(Da)</td>
<td>Dalton number, (J_0/\rho_a V_w (C_s - C_\infty))</td>
</tr>
<tr>
<td>(Da_*)</td>
<td>inner-scale Dalton number, (J_0/\nu u_* (C_s - C_\infty))</td>
</tr>
<tr>
<td>(h_m)</td>
<td>mean wave height</td>
</tr>
<tr>
<td>(h_{m+})</td>
<td>(h_m u_*/w_0)</td>
</tr>
<tr>
<td>(h_s)</td>
<td>bottom roughness</td>
</tr>
<tr>
<td>(J_0)</td>
<td>mass flux from slick surface</td>
</tr>
</tbody>
</table>
### LIST OF PRINCIPAL SYMBOLS (CONTD)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Reynolds number based on slick length</td>
</tr>
<tr>
<td>Re&lt;sub&gt;x&lt;/sub&gt;</td>
<td>Reynolds number based on downstream position x</td>
</tr>
<tr>
<td>Sc</td>
<td>Schmidt number, ( \nu_a/D_a ) or ( \nu_w/D_w )</td>
</tr>
<tr>
<td>Sc&lt;sub&gt;t&lt;/sub&gt;</td>
<td>Turbulent Schmidt number, equals 0.85 [28]</td>
</tr>
<tr>
<td>( u_* )</td>
<td>Friction velocity, ( \sqrt{\tau_0/\rho} )</td>
</tr>
<tr>
<td>( u_+ )</td>
<td>( (U-U_s)/u_* )</td>
</tr>
<tr>
<td>( U )</td>
<td>Mean local velocity</td>
</tr>
<tr>
<td>( U_s )</td>
<td>Wind-induced surface velocity</td>
</tr>
<tr>
<td>( z )</td>
<td>Height above surface</td>
</tr>
<tr>
<td>( z_0 )</td>
<td>Roughness parameter</td>
</tr>
<tr>
<td>( z_+ )</td>
<td>( z u_<em>/\nu_w ) or ( z u_</em>/\nu_a )</td>
</tr>
<tr>
<td>( z_{0+} )</td>
<td>( z_0 u_<em>/\nu_w ) or ( z_0 u_</em>/\nu_a )</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Boundary layer thickness</td>
</tr>
<tr>
<td>( \delta_+ )</td>
<td>Inner-scale boundary layer thickness, ( \delta u_<em>/\nu_a ) or ( \delta u_</em>/\nu_w )</td>
</tr>
<tr>
<td>( \delta_{c+} )</td>
<td>Inner-scale concentration boundary layer thickness</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Von Karman's constant</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Kinematic viscosity; subscript a = air; subscript w = water.</td>
</tr>
<tr>
<td>( \rho_a )</td>
<td>Air density</td>
</tr>
<tr>
<td>( \tau_0 )</td>
<td>Surface shear stress</td>
</tr>
</tbody>
</table>
I. EXECUTIVE SUMMARY

This final report covers all four tasks of a project to revise and verify experimentally the spreading, movement, dissolution, and dissipation models for lighter-than-water insoluble chemicals of the Hazard Assessment Computer System. The report documents (1) the analysis, development, and verification of the final form of the models, (2) experimental procedures and representative test data, and (3) listings and flow charts for the computerized models.

I.1 Background

Analytical and computer models have been developed previously for the U. S. Coast Guard for use in predicting the spreading, evaporation, and dissolution of a lighter-than-water insoluble chemical spilled into a waterway. A later independent study found that the models contain a number of serious deficiencies:

1. Only instantaneous spills are treated in detail, and the continuous spill model neglects many important effects.
2. Effects of currents and winds on the spreading processes are neglected.
3. Spreading of the slick is not coupled to the loss of mass by evaporation and dissolution.
4. The evaporation and dissolution models are based upon questionable mass-transfer assumptions.
5. Movement of the slick by winds, currents, and waves is not included.
6. None of the empirical constants in the models have been verified experimentally.

For these reasons, the Coast Guard has sponsored the present program to correct the indicated deficiencies and to validate the revised models experimentally.
I.2 Program Tasks

I.2.1 Literature Review and Reformulation/Revision of Models

The literature review on spreading, evaporation, and dissolution of floating chemicals performed for this task concluded that major revisions to the models were needed to treat continuous spills and spills in a current. More realistic evaporation and dissolution models were also indicated. Since the methods used in the existing models did not generally represent the best available state-of-the-art techniques and, further, the models could give unreliable predictions for many types of spills and chemicals of interest, only the existing model for an instantaneous spill in calm water could be retained, and it had to be modified to account for mass loss by evaporation and dissolution. New or modified models were indicated for all other cases of interest.

In summary, the following new or modified models were developed:

1. Instantaneous spill in a current;
2. Continuous spill in calm water;
3. Continuous spill in a current;
4. Rate of mass transfer by evaporation;
5. Rate of mass transfer by dissolution; and

In addition, all the spill models now include the effects of a loss of mass. The models are also in a form suitable to treat spills in channels, rivers, lakes, and coastal waters. The waterway current can be constant, or it can be made to vary in time or spatial position, or both. The wind can be specified as constant or as a function of time. In short, the revised models can be used for nearly every practical combination of chemical properties, waterway type, chemical spill discharge rate and duration, and spill volume.

The models have been programmed for computerized solution, and program listings and flow charts are given in this report.
1.2.2 Experimental Design

In order to provide data to verify the models, an extensive test program was designed. The program was organized into two separate types of tests: (1) the spreading of large-scale spills in water with and without a current, and (2) the determination of evaporation and dissolution mass-transfer rates for non-spreading, floating spills. A sensitivity analysis of the models was conducted to aid in the test design. This analysis revealed those parameters that have the most influence on the spreading, evaporation, and dissolution predictions and therefore should require control and accurate measurement. The test plan was approved by the Coast Guard.

1.2.3 Data Collection and Analysis

Tests of the spreading dynamics of spills were conducted in two facilities:

1. A specially-constructed outdoor basin, approximately 18 meters square by 0.3 meter deep, in which large quantities of chemical could be spilled instantaneously or continuously in water without a current, and

2. A modified indoor channel, about 14 meters long and 2.5 meters wide, in which the spreading of continuous spills in various currents could be conducted.

Over one hundred spreading tests were conducted in these facilities. The primary data measured were the size and shape of the slick as a function of time.

Tests to determine mass transfer rates due to evaporation and dissolution of floating chemicals were conducted in two different facilities:

1. A specially-constructed environmental wind tunnel, in which winds up to 5 meters/second could be blown over chemicals floating in a pan about 0.4 meter wide by 1.2 meters long, and

2. A wind-wave tunnel at Flow Research, Inc. (Kent, Washington), in which floating chemicals could be subjected to the simultaneous influence of wind and waves.
About fifty evaporation and dissolution tests were conducted. Detailed concentration measurements as a function of wind speed and wave characteristics constituted the primary data measured in these tests.

1.2.4 Revision and Demonstration of the Models

In this task, the models of spreading, evaporation, and dissolution of instantaneous and continuous spills were compared to the data from a few typical tests, and the "best" values of each empirical constant appearing in the models were selected. The results of the remaining tests were then used as independent data for model verification. Generally good comparisons were obtained between the test data and the models.

It is concluded that the revised models are satisfactory for use in the Hazard Assessment Computer System. Some further experimental and analytical work is recommended to increase the applicability of the models:

- Dissolution of slick into the water caused by wave action;
- Slick formation for a continuous spill when the net transport velocity is very small;
- Anomalous behavior of some chemicals for some spill conditions;
- Long-term movement and breakup of the slick in open water.
II. INTRODUCTION

As part of the Hazard Assessment Computer System of the Chemical Hazards Response Information System, models have been developed previously to predict the spreading, evaporation, and dissolution of lighter-than-water insoluble chemicals spilled in waterways from accidental punctures of ship tanks ([1], Models 3, 8, and 10; [2], Models II and IV). Since the models are used both for contingency planning and for the evaluation of accidents in progress, they were formulated in a general enough way to treat spreading, evaporation, and dissolution processes without requiring a complete description of water velocity profiles, bottom roughnesses, waterway cross-sections, puncture shapes, and other data that are unlikely to be available in practice. As a result, the models are more idealized than a corresponding model developed specifically for a given spill and waterway would need to be. Critical reviews [3,4] have shown that, even so, the models are overly limited in scope and contain errors in their basic physical representations. Therefore, the Coast Guard has sponsored the present program to correct the indicated deficiencies and to validate the revised models experimentally.

The previous reviews [3,4] and the review conducted as part of the present work have concluded that the current HACS models are deficient in the following ways.

Spreading Processes

1. Only instantaneous spills are treated in detail.
2. The continuous spill model neglects many important effects and predicts absurd results for a chemical whose density is nearly the same as water.
3. The effects of currents and winds in altering the dynamics of the spreading and the shape of the slick are neglected.
4. The model describing the spreading of low-viscosity chemicals is based upon unrealistic assumptions.
5. Spreading of the slick is not coupled to the loss of mass by evaporation and dissolution.
6. The empirical constants in the models have not been verified experimentally.

**Evaporation Processes**

1. The evaporation mass transfer coefficients used in the models apply strictly only to smooth flat plates.
2. The latent heat of evaporation is assumed to be supplied by the underlying water and the chemical itself, neglecting the much larger heat transfer from solar radiation and from the air to the slick. Evaporative cooling of the chemical and the water is substantially overpredicted in most cases as a result.

**Dissolution Processes**

1. The dissolution mass transfer coefficient, which is derived from empirical data on the absorption of gas into water, is not relevant for the dissolution of insoluble chemicals. (It is recognized, however, that the prediction of dissolution of an "insoluble" chemical in a waterway with wind, current, and waves is a formidable task and that a simplified model is necessary.)

**Slick Movement**

1. Movement of the chemical slick by winds, currents, and waves is not included in the models.

Because of these deficiencies, the use of the available models is limited to instantaneous spills in channels or in unbounded, open expanses of water, without currents, winds, or waves. Even for the small range of cases where the models can be used, the predictions are not always reliable because of the use of empirical constants that have not been experimentally verified.
The present program was designed to reformulate the models in the light of the above criticisms and to validate the models experimentally. The program efforts were arranged into four tasks.

Task 1 - Literature Review and Reformulation/Revision of Models

For this task, the spreading-evaporation-dissolution-movement models for lighter-than-water insoluble chemicals were reformulated to remove the limitations and to correct the deficiencies listed above.

Task 2 - Experimental Design

For this task, a set of experiments was designed to validate the reformulated models. Emphasis was placed on the spreading dynamics of instantaneous and continuous spills and on the evaporation and dissolution processes of floating chemical slicks.

Task 3 - Data Collection and Analysis

For this task, the experimental program designed in Task 2 was executed. The spreading of both instantaneous and continuous spills was investigated in calm water and in a flowing channel, using large-scale facilities at Southwest Research Institute. Mass transfer coefficients for evaporation and dissolution of floating, insoluble chemicals were determined from wind tunnel tests at Southwest Research Institute and from wind-wave tunnel tests at Flow Research, Inc. at Kent, Washington.

Task 4 - Revision and Demonstration of Mathematical Models

For this task, the reformulated models were compared to the experimental results and revised as indicated by the comparisons. Each model was also computerized and documented.

This report is generally organized in agreement with the four tasks; the major exception is that the model revisions indicated by the test results are incorporated in the descriptions of the models at the time they are first given. All the data from the tests are presented in the companion Test Data Volume of this Final Report.
III. REFORMULATION OF MODELS

III.1 Background and Common Assumptions

The models developed in this report are based upon a number of assumptions that have been made primarily to eliminate the need for detailed descriptions of the waterway and the spill, rather than to simplify the basic physical phenomena. To avoid repetition, the assumptions common to all the models are listed together here.

Waterway Assumptions

W.1 If the waterway is a river or channel, the width is constant. The surface current can be a function of time but, at any time, it is the same at all points along the surface. If the waterway is a lake or coastal water, the current can vary over the surface in a discrete fashion as well as with time.

W.2 Blockage and interference effects due to the presence of the cargo ship in the waterway are neglected.

Spill Assumptions

SP.1 A continuous spill is characterized by a constant mass flow rate, a specified spilling duration, and the relevant physico-chemical properties.

SP.2 An instantaneous spill is characterized by the total mass of chemical released and the relevant physico-chemical properties.

Spreading Assumptions

S.1 Details of the spill source, such as the puncture size, the discharge velocity, and the location of the puncture with respect to the waterline, are neglected.
S.2 The variation of physico-chemical properties, such as the spreading coefficient, as the chemical dissolves into the water is neglected.

Evaporation and Dissolution Assumptions

E.1 Mass transfer on both sides of the air-water-chemical interface is described by a convective process based upon boundary layer theory.

E.2 Sufficient heating of the slick from the surrounding environment (solar radiation and heat transfer from the air and the water) is assumed such that the temperature change of the slick from evaporative cooling can be neglected.

The consequences of these assumptions are not severely limiting. The waterway assumptions imply only that localized effects cannot be predicted. The spill assumptions are all physically reasonable. The spreading assumptions imply that the dynamics of the spreading cannot be predicted in detail at points very close to the source, but this is acceptable since floating spills typically spread over large areas and the potential lack of an accurate spreading-rate prediction near the source is therefore not of crucial importance. Assumption E.2, concerning the smallness of evaporative cooling, has been made to eliminate the need for a complicated heat transfer model. (For very volatile or cryogenic chemicals, which are not of interest here, the assumption may be invalid.) Dissolution, as computed on the basis of boundary layer theory (assumption E.1), may account for only a small part of the mass transfer into the water when droplets of the chemical are dispersed directly into the water by the action of the waves. In addition, other kinds of diffusion processes may be important for those chemicals that have an affinity for water at the molecular level, even though they are insoluble. Thus, of all the models developed here, the dissolution model is the most idealized. However, there are no models available at this time that can describe more realistically the actual dissolution processes that occur for a floating slick of insoluble chemical in the presence of winds, waves, and currents.
The analytical models used to predict the spreading, evaporation, dissolution, and movement of continuous and instantaneous spills are presented in Sections III.2 through III.5. Table III.1 summarizes the presentations and can serve as a guide for reference.

III.2 Spreading Models

III.2.1 General Discussion

The venting rate model of the Hazard Assessment Computer System has been revised and validated [5,6], and it may be used to estimate both the total amount of cargo released into the waterway and the duration of the discharge. (Discharges of moderate duration, say about 10 minutes, can be analyzed as a continuous release, but in the computerized version of the models, recommendations, based on physical considerations, are made in the output as to whether such a spill should be analyzed more appropriately as instantaneous.) Knowing the amount of chemical discharged and the discharge duration, spreading models are needed to predict the size and shape of the floating slick and how the size and shape change with time. Models are developed below that can be applied to rivers, channels, lakes, and coastal waters to make the required predictions. In general, only calm water with or without a current will be treated; waves may alter somewhat the rate of spreading predicted for calm water, but these effects are beyond the present state-of-the-art. The spreading models also provide a convenient center about which to make mass balances of the spilled material.

In the past, two different methods have been used to formulate spreading models [7,8]. In one, the forces tending to promote and to retard the spreading are determined from physical laws, and the spreading models are deduced from the balance of the forces. In the other, the spreading is merely hypothesized to be similar to turbulent diffusion, and the spreading law is formulated using the principles of Fickian diffusion. The first method is chosen here for several reasons:

1. The dynamical basis of the diffusion models is obscure [8]. Spreading by turbulent diffusion is physically justifiable
### TABLE III.1  GUIDE TO ANALYTICAL MODEL DEVELOPMENT

<table>
<thead>
<tr>
<th>WATERWAY</th>
<th>CURRENT AND WIND</th>
<th>SPILL TYPE</th>
<th>DESCRIPTION</th>
<th>REPORT PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>Zero or Non-zero</td>
<td>Instantaneous</td>
<td>One-dimensional spreading model</td>
<td>19-21</td>
</tr>
<tr>
<td>or River</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zero</td>
<td>Continuous</td>
<td>One-dimensional spreading model</td>
<td>21-23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Water</td>
<td>Zero or Non-zero</td>
<td>Instantaneous</td>
<td>Radial spreading model</td>
<td>13-19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zero</td>
<td>Continuous</td>
<td>Radial spreading model</td>
<td>21-23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel</td>
<td>Non-zero</td>
<td>Continuous</td>
<td>One-dimensional spreading with effects of current</td>
<td>24</td>
</tr>
<tr>
<td>or River</td>
<td></td>
<td></td>
<td>included</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Water</td>
<td>Non-zero</td>
<td>Continuous</td>
<td>Elongated triangular spreading model</td>
<td>23-24</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Channel</td>
<td>Non-zero</td>
<td>Instantaneous</td>
<td>Evaporation rate model</td>
<td>29-32</td>
</tr>
<tr>
<td>or River</td>
<td>wind</td>
<td>or Continuous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Open Water</td>
<td>Non-zero</td>
<td>Instantaneous</td>
<td>Evaporation rate model</td>
<td>29-32</td>
</tr>
<tr>
<td></td>
<td>wind</td>
<td>or Continuous</td>
<td></td>
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<tr>
<td>Channel</td>
<td>Non-zero</td>
<td>Instantaneous</td>
<td>Dissolution rate model</td>
<td>36-39</td>
</tr>
<tr>
<td>or River</td>
<td>wind</td>
<td>or Continuous</td>
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<tr>
<td>Open Water</td>
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<td>Instantaneous</td>
<td>Dissolution rate model</td>
<td>36-39</td>
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<td></td>
<td>wind</td>
<td>or Continuous</td>
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<tr>
<td>Channel</td>
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<td>Instantaneous</td>
<td>Slick movement model</td>
<td>40-41</td>
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<td>or River</td>
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<td>or Continuous</td>
<td></td>
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<tr>
<td>Open Water</td>
<td>Non-zero</td>
<td>Instantaneous</td>
<td>Slick movement model</td>
<td>41-43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>or Continuous</td>
<td></td>
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</tr>
</tbody>
</table>
only for "passive" substances that dissolve in water and become indistinguishable from it (except for "marked particles").

2. Methods for predicting diffusion coefficients for the surface spreading of insoluble, floating chemicals are not available. Most work in the past has been after-the-fact curve fitting to the observed spreading rates of large-scale spills in open water [7,9,10].

A third approach combines both types of models [11,12], but this does not avoid the problem of finding diffusion coefficients. The models developed in this report are based upon the first approach mentioned above. Such models are capable of being interpreted physically and lead to expressions containing a minimum of empirical constants; in addition, the empirical constants can be determined readily by laboratory-scale experiments.

III.2.2 General Description

The revisions that have been made to the previous spreading models [1,2] consist of:

- adding realistic models of continuous spills;
- including the effects of current and wind on the shape and the spreading of continuous and instantaneous spills; and
- including the effects of a loss of mass from the spill (evaporation and dissolution).

In addition, the models have been put in a form that permits a ready solution when a loss of mass occurs. The empirical constants in the models have been determined by experimentation, in some cases for the first time, and in all cases by the use of larger spills than had previously been used.

III.2.3 Instantaneous Spills

The development of predictive methods for instantaneous spills is exemplified by Ray's work [13], which has since been expanded and modified.
by others [14,15]. Earlier Blokker [16] had considered some parts of the same problem. The final forms of the models used in the present report are similar to the modifications suggested by Mackay [17].

Figure III.1 shows several stages in the idealized spreading of a floating, insoluble chemical in an open body of calm water without a current. The spill is assumed to occur instantaneously. During the time period when the slick is relatively thick, gravity (i.e., buoyancy) causes the chemical to spread laterally. As can be seen from Figure III.1a, there is unbalanced force, $F_g$, directed radially outward around the non-submerged part of the periphery of the slick; the magnitude of the force is roughly:

$$F_g = 2\pi R \left[ \frac{1}{2} \rho_0 gh^2 \right]$$

(III.1)

Here, $g$ is the acceleration of gravity and the other quantities are defined in the figure. Because of the unbalanced force, the spilled chemical rapidly attains a radial velocity that can be estimated roughly as $R/t$, where $t$ is the elapsed time since the spill occurred. The average acceleration of the spilled liquid is thus $R/2t^2$. Fay [13] hypothesized that, in this early phase, the gravitational spreading force is balanced almost entirely by the inertial force associated with the acceleration of the slick. Thus:

$$2\pi R \frac{1}{2} \rho_0 gh^2 \left(1 - \frac{\rho_0}{\rho}\right) \approx \rho_0 \left(\frac{\pi R^2 h}{2t^2}\right)$$

(III.2)

Solving for $R$ as a function of time gives:

$$R = K_{10} (V_0 \rho) \frac{1}{6} t^\frac{3}{2}$$

(III.3)

Here, $K_{10}$ is a constant of proportionality, $V_0 = \pi R^2 h$ is the volume of the spill, and $\Lambda = 1 - \rho_0/\rho$.

At some later time, the acceleration of the spill will have decreased significantly because the viscous drag of the water on the slick will have become predominant; see Figure III.1b. The viscous drag can be estimated as follows. The thickness $\delta$ of an unsteady, viscous boundary layer is
Figure III.1 Phases in the Idealized Spreading of a Floating, Insoluble Chemical
roughly \((\mu_w t/\rho_w)^{1/2}\), and the viscous shear at the water-chemical interface is about \(\mu_w V/\delta\). The velocity \(V\) will again be approximated as \(R/t\). During this period, the balance of gravitational and viscous drag forces is thus:

\[
2\pi R^{1/2} \rho_0 g h^2 \left(1 - \rho_0/\rho\right) \ll \pi R^2 \left[ \mu_w (R/t)/(\mu_w t/\rho)^{1/2} \right] \tag{11.4}
\]

Solving for \(R\) as a function of time gives:

\[
R = K_20 \sqrt{V_0 g \Delta \mu_w} \left(\frac{\rho}{\mu_w}\right)^{1/4} t^{1/4} \tag{11.5}
\]

where \(\mu_w = \mu_w/\rho\) is the kinematic viscosity of the water. A factor of \((\rho_0/\rho)^{1/4}\) in Equation (11.5) has been neglected on the basis that it is close to unity. In fact, in all the spreading models, \(\rho_0\) and \(\rho\) will be assumed to be interchangeable except when their ratio is subtracted from one (i.e., except in \(\Delta\)). Equation (11.5) is strictly valid only when the thickness of the slick is less than the thickness \(\delta\) of the boundary layer. When this is the case, the slick appears to move as a "slug". The flow in the slick is undoubtedly of the slug type when the viscosity \(\mu_0\) of the spilled material is much greater than \(\mu_w\), but Buckmaster [18] has shown that a slug flow is the type of flow that occurs even when \(\mu_0 < \mu_w\), so long as \(\mu_0/\mu_w > 0.1\) or so. Since \(\mu_0/\mu_w > 0.1\) includes all chemicals of interest to the Coast Guard, a separate "low viscosity" spreading model such as given in [1] is not developed here.

At some point, the slick becomes so thin that gravity forces are negligible. Then, the relatively small interfacial tension at the periphery will be the dominant spreading force. From Figure III.1c, the net spreading force is now roughly \(2\pi R (\sigma_0 - \sigma_{ow}) = 2\pi R g\), where \(\sigma\) is the "spreading coefficient". Here, \(\sigma\) is assumed to be positive, although negative values are also possible; the case when \(\sigma < 0\) will be discussed later. The balance of forces is:

\[
2\pi R \sigma \ll \pi R^2 \left[ \mu_w (R/t)/(\mu_w t/\rho)^{1/2} \right] \tag{11.6}
\]

Solving for \(R\) as a function of time gives:
Note that in this phase of the spreading, the rate of spreading is independent of the spilled volume. But since the time at which Equation (III.7) becomes applicable depends on the spilled volume, the magnitude of $R$ is actually an implicit function of $V_0$. It is also worth noting that Equations (III.1) - (III.7) apply even when the volume $V_0$ itself changes with time, as it would for a continuous spill or when evaporation and dissolution occur.

The approximate elapsed time when one phase of spreading ends and another begins is assumed to be the time when the preceding and the succeeding phases predict the same slick radius [13,14,15]. Thus, the end of the gravity-inertial phase, and the beginning of the gravity-viscous phase, can be found by equating (III.3) and (III.5) to give:

$$t_1 = \left(\frac{K_{20}}{K_{10}}\right)^{\gamma} [V_0/\rho \omega g A]^\kappa$$

(III.8)

Likewise, the beginning of the surface tension-viscous phase occurs at

$$t_2 = \left(\frac{K_{20}}{K_{30}}\right)^{\gamma} [V_0/\rho \omega g \nu A]^{\kappa}$$

(III.9)

In the surface tension-viscous spreading regime, the slick is extremely thin, on the order of $10^{-5}$ to $10^{-4}$ meters, according to the experiments to be described later. The evaporation and dissolution from such thin slicks is negligible; that is, a thin slick would rapidly disappear if the evaporation and dissolution were not negligible. Most of the hazards are presented by the earlier phases of spreading (the so-called "thick slick"). Thus, in the instantaneous models developed here, the "thin" or surface tension-gravity slick will be neglected. Further, the end of the first phase (the gravity-inertial phase) of the spreading occurs soon after the spill occurs, in comparison to the total time duration over which the thick slick spreads. In addition, the spreading during the first phase is somewhat dependent on the size of the puncture in the ship tank, whether the puncture is submerged or not, and other details of the source of the spill that cannot be included in the model. For those reasons, the gravity-inertial phase of the spreading is only included in the model as an initial
condition on the gravity-viscous phase. Since the gravity-viscous phase constitutes the great bulk of the thick slick spreading time, neglecting the details of the gravity-inertial phase is not a serious limitation to the model.

When mass is lost from the spill by evaporation and dissolution, the preceding formulation of the model is inconvenient, since \( V_0 \) is then a function of time. For that reason, the model of gravity-viscous spreading is rewritten as suggested by Mackay [17]. From Equation (III.5), the surface area of the slick is:

\[
A = \frac{1}{2} K_{20} \left( \frac{V_0 \cdot g \Lambda / \sqrt{\gamma_w}}{V_0} \right)^{\frac{1}{2}} t^{\frac{1}{2}}
\]  

(III.10)

The rate of change of the area with respect to time is thus:

\[
\frac{dA}{dt} = \frac{1}{2} K_{20} \left( \frac{V_0 \cdot g \Lambda / \sqrt{\gamma_w}}{V_0} \right)^{\frac{1}{2}} t^{-\frac{1}{2}}
\]

\[
+ \frac{1}{2} K_{20} \left( \frac{gAV_0 / \sqrt{\gamma_w}}{V_0} \right)^{\frac{1}{2}} t^{1/2} (dV_0/dt)
\]

(III.11)

Eliminating the time variable between Equations (III.10) and (III.11) and using the definition that \( \dot{m}_{\text{loss}} = -\rho_0 dV_0/dt \) gives:

\[
\frac{dA}{dt} = \frac{1}{2} \left( \pi K_{20} \right)^{1/2} \left[ g \Lambda / \sqrt{\gamma_w} \right]^{-1/2} h^{-1/2} A^{-1/2}
\]

\[
- \frac{1}{2} \left( \dot{m}_{\text{loss}} / \rho h \right)
\]

(III.12)

This equation must be augmented by the initial condition that \( A = A_i \), where \( A_i \) is the area of the thick slick at the end of the gravity-inertial phase:

\[
A_i = \frac{1}{2} K_{20} \left( \frac{K_{20}/K_{10}}{V_0 \cdot g \Lambda / \sqrt{\gamma_w}} \right)^{1/2}
\]  

(III.13a)

The time at which \( A_i \) occurs is given by Equation (III.5):

\[
t_i = \left( \frac{K_{10}/K_{10}}{V_0 \cdot g \Lambda / \sqrt{\gamma_w}} \right)^{1/2}
\]

(III.13b)
Equation (III.13a) is obtained by combining Equations (III.8) with either (III.3) or (III.5). A relation predicting the value of $h(t)$ is also needed; since $\rho_0 A h$ is equal to the total mass in the spill, it is evident that:

$$\frac{dh}{dt} = \frac{\Delta m_{\text{loss}} + \rho_0 h (dA/dt)}{\rho_0 A} \quad (III.14)$$

with the initial condition that $h_i = V_0/A$ at time $t_i$. Note that the loss of mass is neglected during the short period when the slick is spreading in the gravity-inertial phase.

Models for a spill in a channel of width $w$, where the spreading occurs one-dimensionally rather than radially, can be developed analogously. Table III.2 summarizes these one-dimensional and radial instantaneous-spill models. The numerical values for the empirical constants, $C_{10}$, $C_{20}$, $K_{10}$, and $K_{20}$ shown in the table will be discussed in Section V.1.

In the computerized models, the radial-spreading model is also used to compute the initial phases of spreading of a spill in a channel. The one-dimensional spreading model is used to continue the computations after the slick has spread completely across the width of the channel (that is, after the effects of the channel boundaries become evident). The radial and one-dimensional models can also be applied to spills occurring when there is a current or a wind. The current and wind merely translate the entire slick as a body without affecting the spreading. Motion of the slick is discussed later in Section III.5.

When the surface tension spreading coefficient $\sigma$ is negative, the models developed above for the surface tension-viscous phase of spreading are no longer applicable. In fact, a surface tension spreading phase does not exist when $\sigma < 0$, and the spreading ceases when the gravity force is balanced by the interfacial tension. At that time, the slick breaks up into many smaller slicks, or "lenses" [19]. The main effect on the spreading of the thick slick, which is the part of the slick of primary interest here, is that the spreading may cease at a somewhat larger thickness than when $\sigma > 0$. The ultimate thickness can be estimated [19] as
<table>
<thead>
<tr>
<th>Spill Location</th>
<th>Spreading Model</th>
<th>Initial Conditions</th>
</tr>
</thead>
</table>
| Channel       | \[
\frac{dA}{dt} = \frac{3}{2} (C_{20})^{\frac{2}{3}} \left[ \frac{w^2 (g\Delta)^2}{v_w} \right]^{\frac{1}{3}} h^{\frac{4}{3}} A^{-\frac{2}{3}} - \frac{1}{2} \left( \frac{\dot{m}_{loss}}{\rho c h} \right) \]
\[
\frac{dh}{dt} = \left[ \frac{\dot{m}_{loss}}{\rho h} \left( \frac{dA}{dt} \right) \right] / \rho_0 A
\] | \[
t_i = \left( \frac{C_{20}}{C_{10}} \right)^{\frac{2}{3}} \left[ \frac{(V_0/w)^{\frac{2}{3}}}{(g\Delta)^2 v_w^2} \right]^{\frac{1}{3}}
\]
\[
A_i = 2 C_{20} \left( \frac{C_{20}}{C_{10}} \right)^{\frac{2}{3}} \left[ \frac{V_0}{V_{o/s}} \frac{w}{(g\Delta)} \right]^{\frac{1}{3}}
\] | \[
h_i = V_0/A_i
\] |
| Open Water    | \[
\frac{dA}{dt} = \frac{1}{2} (\pi K_{20})^2 \left[ \frac{(g\Delta)^2}{v_w} \right] h^{\frac{4}{3}} A^{-\frac{2}{3}} - \frac{2}{3} \left( \frac{\dot{m}_{loss}}{\rho_0 h} \right)
\]
\[
\frac{dh}{dt} = \left[ \frac{\dot{m}_{loss}}{\rho_0 h} \left( \frac{dA}{dt} \right) \right] / \rho_0 A
\] | \[
t_i = \frac{(K_{20})^2}{K_{10}} \left[ \frac{V_0}{g \Delta v_w} \right]^{\frac{1}{3}}
\]
\[
A_i = \pi K_{20} \left( \frac{K_{20}}{K_{10}} \right)^{\frac{2}{3}} \left[ \frac{V_0^2 g\Delta}{v_w^2} \right]^{\frac{1}{3}}
\] | \[
h_i = V_0/A_i
\] |
For example, if $a = -1 \times 10^{-3}$ newtons/meter, $\rho_o = 900$ kg/m$^3$, and $\Delta = 0.1$, the predicted $h_{minimum}$ is about $1.5 \times 10^{-3}$ meters. It is recommended that, when $a < 0$, Equation (III.15) should be used to compute a minimum value of slick thickness; this value can then be used as an input to the computerized model to account for the diminished spreading of the thick slick.

### III.2.4 Continuous Spills

The models described in Section III.2.3 for instantaneous spills are readily modified to cover continuous spills when there are no currents or winds. The spilled volume $V_0$ is merely replaced by the volume discharged up to time $t$, i.e., by $\dot{m}/\rho_o$. (Recall that the derivation of the models did not require that $V_0$ be constant.) For example, Equation (III.5) becomes

$$R = K_{21} \left[ \left( \frac{\dot{m}}{\rho_0} \right)^2 \frac{g \Delta}{\sqrt{\pi W}} \right]^{1/w} t^{2/s}$$

(III.16)

(The constant of proportionality $K_{21}$ is allowed for generality to be different from $K_{20}$, the constant in Equation (III.5)). When the models are expressed in terms of areas, the resemblance to the instantaneous models is even more clear. Table III.3 summarizes these models. Once again, the model for an open-water spill is used in the computerized version to predict the spreading of a spill in a channel until the time when the spill completely fills the width of the channel. (The numerical values of $C_{11}, C_{21}, K_{11},$ and $K_{21}$ are discussed in Section V.1)

One major difference between a continuous and an instantaneous spill is that for a continuous spill the surface tension-viscous phase occurs simultaneously with the gravity-viscous phase rather than following it in time. Thus, the part of the slick that is spreading in the gravity-viscous phase (i.e., the thick slick) must supply the mass needed by that part of the slick spreading in the surface tension-viscous phase (i.e., the thin slick). Although the apparent loss of mass from the thick slick is small, the models do account for it. The method used is that suggested by Mackay [17]. The thin
<table>
<thead>
<tr>
<th>Spill Location</th>
<th>Channel</th>
<th>Open Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreading Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t = \frac{3}{2} \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>h = \bar{C} \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>\frac{\partial h}{\partial t} = 2.76 \frac{(\bar{C}^2)^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>\frac{\partial h}{\partial t} = 0</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>\frac{\partial A}{\partial t} = \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>\frac{\partial A}{\partial t} = 6.02 \frac{(\bar{C}^2)^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>\frac{\partial h}{\partial t} = 0</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>A = 2.01 \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>h = \bar{C} \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
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<tr>
<td>A = \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
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<tr>
<td>h = \bar{C} \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
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</tr>
<tr>
<td>A = \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
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<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>h = \bar{C} \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
<tr>
<td>A = \frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
<td>\frac{\bar{C}^2}{\bar{C}} \frac{w^2}{2} h^\frac{3}{2}</td>
</tr>
</tbody>
</table>
slick is assumed to have a constant thickness $h$. Further, the initial area of the thin slick is assumed to be some multiple (Mackay suggests eight) of the initial area of the thick slick. The rate of change of the thin slick area, $\bar{A}$, is also shown in Table 111.3. Since the experiments to be described later did not attempt to establish the empirical constants of the surface tension-viscous phase, the constants suggested in the literature [7, 8, 13, 14] are used in the models. It is emphasized that the spreading of the thin slick is used only to compute a relatively small, apparent loss of mass from the thick slick so, these approximations used in developing thin slick models are not a limiting factor in the accuracy of the models.

When there is a current or wind that transports the slick, the shape of a continuous spill is distorted and the previous models are not applicable. The upstream edge of the slick remains fixed to the source but the rest of the spill is transported downstream. Thus, the slick is no longer symmetric (one-dimensional or circular) about the source. Waldman, et al. [7] has, however, developed a model of a continuous spill in a current that is adapted here for a loss of mass. For a spill in open water, as an example, the downstream edge is assumed to be swept away from the source at a speed equal to the current $U_T$. $(U_T$ will also be made to include the effects of wind, as discussed later.) The upstream edge remains attached to the source. The sides of the slick are assumed to spread laterally in accordance with one-dimensional gravity-viscous spreading. The resulting slick has a triangular shape, with the vertex at the source and the base at the downstream edge. To develop the model, it is imagined that a stream of instantaneous spills, each of volume $\bar{m} \delta t/2\rho_0$ is transported downstream with a speed $U_T$, and the slick from each such spill spreads along a channel of width $U_T \delta t$ perpendicular to the direction of the current. (The factor of one-half accounts for the fact that only half the spill spreads in each direction.) The width $W(x)$ of the resulting slick at any downstream location $x$ can therefore be derived from transforming the one-dimensional instantaneous-spill spreading model as follows:

$$W(x) = 2 K_2 \left( \frac{g A \left( \bar{m} \delta t/2\rho_0 \right)^2}{(U_T \delta t)^2 V_w} \right)^{1/4} U_T x^{1/4} \left( x = U_T t \right).$$

(III.17)
The initial conditions for the gravity-viscous phase can be derived similarly. Waldman's type of model will not accurately represent the shape of the slick or the area when the transport velocity \( U_T \) is small compared to the gravitationally-induced spreading velocity. When \( U_T \) is small, the slick will not take the shape of a triangle with the vertex at the source, but instead will be an ellipse that surrounds the source and extends somewhat farther downstream of the source than upstream. This kind of spreading may arise when there is a wind but no current, since only a small part of the total wind contributes to \( U_T \). The computerized models do not include such cases explicitly. It is suggested that they be treated by first setting \( U_T \) to zero identically to compute the size of the slick as a function of time, and then repeating the calculations with the true value of \( U_T \) to compute both the downstream position of the slick and an estimate of the mass evaporated from the slick.

For a continuous spill in a channel, the model assumes that the spreading is in the downstream direction. The upstream edge of the slick remains attached to the source and the downstream edge is swept away by a combination of spreading and transport. Thus, \( U_T w \) must be added to the \( \frac{dA}{dt} \) expression derived previously for a continuous spill in a channel without a current.

Table III.4 summarizes the models of continuous spills in a current. In the computerized versions of the continuous spill models, an appropriate instantaneous spill model is used to continue the spreading predictions after the discharge has stopped. For example, for a spill in open water, the instantaneous spill model for open water is used with an initial area, thickness, and mass equal to the final values of the slick from the continuous spill. There may be a mismatch in the shape of the slick at the time the switch is made, since the instantaneous spill assumes a circular shape while a continuous spill in a current predicts a triangular shape, but a more complicated transition model is not believed to be warranted. After some time has elapsed, the predicted shape of the instantaneous spill is, in any event, more in accordance with expectations. (The numerical values of \( C_{12}, C_{22}, K_{12}, \) and \( K_{22} \) are discussed in Section V.1.)
<table>
<thead>
<tr>
<th>Spill Location</th>
<th>Spreading Model</th>
<th>Initial Conditions</th>
</tr>
</thead>
</table>
| Channel       | \[
\begin{align*}
\frac{dA}{dt} &= \frac{3}{2^{3/2}} (C_{22})^{\gamma_3} \left[ \frac{w^2 (\rho_0 A)^2}{\nu_w} \right] \frac{h^{\gamma_3}}{\gamma_3} A^{-\gamma_3} \\
+ \frac{1}{2} \left[ \dot{m} - \dot{m}_{loss} - \rho_0 \ddot{h} \left( \frac{dA}{dt} \right) \right] / \rho_0 h + U_T w \\
\frac{dh}{dt} &= \left[ \dot{m} - \dot{m}_{loss} - \rho_0 \ddot{h} \left( \frac{dA}{dt} \right) - \rho_0 \ddot{h} \left( \frac{dA}{dt} \right) \right] / \rho_0 A \\
z_{\text{upstream}} &= 0 \\
z_{\text{downstream}} &= \Lambda/w \\
\frac{d\Lambda}{dt} &= 2.76 \left[ \left( \frac{\nu^2}{\rho} \right)^2 / \nu_w \right] \Lambda^{\gamma_3} / \Lambda^{\gamma_3} + U_T w \\
\frac{d\ddot{h}}{dt} &= 0
\end{align*}
\] | \[
\begin{align*}
t_1 &= (C_{22})^{\gamma_3} \left( \frac{\dot{m}/\rho_0 w}{\nu_w} \right)^{\gamma_3} \\
A_1 &= \left( \frac{C_{22}}{C_{12}} \right)^{\gamma_3} \left[ \left( \frac{\dot{m}/\rho_0 w}{\nu_w} \right)^{\gamma_3} w^{\gamma_3} \right]^{\gamma_3} \\
h_1 &= \dot{m} t_1 / \rho_0 A_1 \\
\bar{A}_1 &= 8 A_1 \\
\bar{n}_1 &\approx 10^{-4} - 10^{-5} \text{ meters}
\end{align*}
\] |
| Open Water    | \[
\begin{align*}
\frac{dA}{dt} &= \frac{11}{8} (K_{22})^{\gamma_1} \left[ \left( \frac{\nu^2}{\rho} \right)^2 U_T / \nu_w \right] \Lambda^{\gamma_1} \Lambda^{\gamma_1} \\
\dot{\dot{h}} &= \dot{\dot{m}} - \dot{\dot{m}}_{loss} - \rho_0 \ddot{h} \left( \frac{dA}{dt} \right) \\
\frac{dh}{dt} &= \left[ \dot{\dot{m}} - \dot{\dot{m}}_{loss} - \rho_0 \ddot{h} \left( \frac{dA}{dt} \right) \right] / \rho_0 A \\
z_{\text{upstream}} &= 0 \\
z_{\text{downstream}} &= U_T t \\
\frac{d\ddot{A}}{dt} &= 2.06 \left[ \left( \frac{\alpha U_T^2 / \rho}{\nu_w} \right)^2 \right] \Lambda^{\gamma_3} \Lambda^{\gamma_3} \\
\frac{d\ddot{h}}{dt} &= 0
\end{align*}
\] | \[
\begin{align*}
t'_1 &= (K_{22})^{\gamma_3} \left[ \left( \frac{\dot{m}/2 \rho_0}{\nu_w} \right)^{\gamma_3} \right]^{\gamma_3} \\
A'_1 &= K_{22} \left( K_{12} / K_{12} \right)^{\gamma_3} \left[ \left( \frac{\dot{m}/2 \rho_0}{\nu_w} \right)^{\gamma_3} \right]^{\gamma_3} \\
h'_1 &= \dot{m} t'_1 / \rho_0 A'_1 \\
\bar{A}'_1 &= 8 A'_1 \\
\bar{n}'_1 &\approx 10^{-4} - 10^{-5} \text{ meters}
\end{align*}
\] |
III.2.5 Maximum Size of Slick

All the models must take into account the possibility that the slicks attain a maximum possible size. For oil, it has been observed that spreading eventually stops for a variety of reasons [7,8]. Experiments with pure chemicals, as described later, show that although the thin slick may never cease to spread (when $\sigma > 0$), the thick slick apparently stops spreading when the average thickness is of the order of $10^{-4}$ meters. When the thickness is less than $10^{-4}$ meters, the thick slick becomes indistinguishable from the thin slick. Since the interest in the Hazard Assessment Computer System is primarily in the thick slick, the spreading is assumed to stop when the thickness of the thick slick is less than $10^{-4}$ meters. (In the computerized version, the user has the option of changing the minimum allowable thickness for the thick slick.)

III.3 Evaporation Models

III.3.1 Discussion

In general, the mass and heat transfer processes associated with chemical spills in the environment will be turbulent. For chemical spills which float on water, the convective mass transfer associated with evaporation will be by a turbulent boundary layer. The primary source of information applicable to the present problem for spills on water is the literature on air-sea interactions. The air-sea interaction research involves all of the relevant mechanisms associated with chemical spills on open water. An excellent review of the subject has been written by Coantic [20], and a recent collection of papers on the subject is contained in Favre and Hasselmann [21].

According to Resch and Selva [22], the fluxes for momentum and mass transfer are given by

$$ Io = \rho_a V_w^2 (C_f/2) \quad (III.18) $$

$$ Jo = \rho_a V_w (C_s - C_w) \Delta a \quad (III.19) $$
where \( \tau_0 \) is the shear stress, \( \rho_a \) the air density, \( V_w \) the freestream wind velocity, \( C_f \) the friction coefficient, \( J_0 \) the mass flux, \( C_s \) the mass fraction of chemical vapor at the surface which is assumed to be at saturation, \( C_{\infty} \) its freestream value which is assumed to be zero, and \( Da \) the Dalton number. From these equations the surface shear stress and mass flux can be predicted if \( C_f \) and \( Da \) are known from theory. The other quantities can be measured either directly or indirectly. From Schlichting [23] and classical turbulent boundary-layer theory, the friction coefficient for a smooth flat plate is

\[
C_f/2 = 0.037 \, Re_L^{-1/5} \tag{III.20}
\]

where \( Re_L = V_w L/\nu_a \) is the Reynolds number based upon the length, \( L \), of the plate. By Reynolds analogy from Eckert and Drake [24], the Dalton number is

\[
Da = 0.037 \, Re_L^{-1/5} \, Sc^{-2/3} \tag{III.21}
\]

where \( Sc = \nu_a/D \) is the Schmidt number and \( D \) the molecular diffusivity of the chemical in air. This Dalton number relation was used in [1] for the calculation of mass transfer in the present HACS program.

The present flat plate boundary layer model in HACS is not applicable to flows over water for the following reasons:

(a) According to Wu [25], the ocean is aerodynamically smooth only for wind speeds of less than 3 m/s.
(b) A water surface is not rigid.
(c) Reynolds analogy is not valid for rough surfaces. Roughness will increase momentum transfer, but heat and mass transfer may diminish with roughness.
(d) A length scale \( L \) is difficult to define in an atmospheric boundary layer.

The previous theoretical development for turbulent boundary layers is based upon outer-scale variables where the outer scales are \( V_w, L \), and the
boundary layer thickness $\delta_a$. The boundary layer thickness is related to the longitudinal length scale by

$$\frac{\delta_a}{x} = 0.37 \frac{\text{Re}_x}{x}^{1/5}$$ (III.22)

The revised model for HACS is based on inner-scale variables. Near the water surface the velocity and concentration profiles are universal and independent of the outer scales. The fluxes away from the surface where molecular effects are small are given by

$$\frac{\tau}{\rho_a} = -<uw>$$ (III.23)

$$\frac{J}{\rho_a} = <cw>$$ (III.24)

where the cross-correlation $<uw>$ is also known as the Reynolds Stress. In the layer outside the viscous sublayer the fluxes are constant and the profiles are logarithmic. As a consequence of the constant flux hypothesis, the profiles are

$$u_+ = \frac{U - U_s}{u_*} = A \ln \left( \frac{z_+}{z_0+} \right)$$ (III.25)

$$c_+ = \frac{C - C_s}{c_*} = A \text{Sc}_t \ln \left( \frac{z_+}{z_{0c+}} \right)$$ (III.26)

where $A = k^2$ is the reciprocal Von Karman constant, $z_0$ the integration constant or roughness parameter, $\text{Sc}_t$ the turbulent Schmidt number, $z_+ = zu_*/v$, $u_*$ and $c_*$ are the friction velocity and concentration, and $U_s$ and $C_s$ are the surface values of velocity and concentration. The profiles in Equations (III.25) and (III.26) are dependent only on the surface roughness and not on any external length scale.

III.3.2 General Description

The evaporation model for the HACS revision is based on inner-scale variables in contrast to outer-scale variables of the previous HACS model. The new model has the following features and advantages:
(a) No external length scale such as a spill dimension is required for the calculation of Dalton number, $Da$.

(b) Roughness effects, i.e., wave height, are included. The flow is defined to be rough at wind speeds above 5 m/s.

(c) Only standard meteorological and oceanographic data (that is, air temperature, barometric pressure, wind velocity, sea surface temperature, and wave height) are required as input data.

(d) Wind velocity data are based upon a standard height of 10 meters.

Additionally, all the necessary physical property data for air, water, and some representative chemicals have been included in the computerized model to make the mass transfer calculations. Chemical diffusivities are required for the Schmidt number in the mass transfer calculations, but this information is not included in the present CHCRIS Hazardous Chemical Data files. A detailed description of the mathematical models for the chemical properties is contained in Appendix A with tables of the properties at standard conditions.

III.3.3 Evaporation Rate

A reciprocal Dalton number is calculated for mass transfer from a theory by Kader and Yaglom [26,27] and Yaglom and Kader [28] which is given by

$$Da_* = A \frac{Sc_t}{u_*} \ln \delta_+ + \beta (Sc, h_m) + \beta_1$$  \hspace{1cm} (III.27)

where $\delta_+$ is the boundary layer thickness in inner-scale variables, $\beta$ is a universal function based upon Schmidt number and the mean protrusion (wave) height $h_m$, and $\beta_1$ is a constant dependent on flow geometry. For a boundary layer $\beta_1$ is 2.35. The Dalton number $Da_*$ is non-dimensionalized with $u_*$ rather than $V_w$. The inner and outer scale Dalton numbers are related by

$$Da = Da_* \left(\frac{u_*}{V_w}\right)$$  \hspace{1cm} (III.28)

Thus, the mass transfer calculation is accomplished in Equation (III.19) by replacement of $V_w Da$ by $u_* Da_*$. The $\beta$ function for a smooth surface
from Kader and Yaglom [27] is

\[
\beta = 12.5 \, \text{Sc}^{2/3} + A \, \text{Sc}_t \ln \text{Sc} - 5.3 \tag{III.29a}
\]

and for a rough surface from Yaglom and Kader [28] is

\[
\beta = 0.55 \sqrt{\text{h}_{m+}} \left( \text{Sc}^{2/3} - 0.2 \right) - A \, \text{Sc}_t \ln \text{h}_{m+} + 11.2 \, \text{Sc}_t \tag{III.29b}
\]

Also, from [28] the turbulent Schmidt number, \( \text{Sc}_t \), is 0.85.

A sample calculation of Dalton number for the evaporation of water from a smooth surface is presented in Figure III.2 where the Schmidt number for water vapor is 0.593. The theory of Kader and Yaglom [27] is compared to that of Street [29] which is a related theory. A review of these and other mass transfer theories is presented in [30]. Also, for comparison, the results of wind tunnel experiments [22,31] are also included in Figure III.2. The results in [22] are probably from smooth flow since their wind speed was 3.5 m/s; however, some results in [31] are for rough flow. Since no wave height measurements were reported for either set of experiments, no comparison is possible with rough flow theory. The following conclusions can be drawn from Figure III.2:

(a) The scatter in data for evaporation experiments is large.
(b) The agreement between theory and experiment is poor.
(c) The theories of either Yaglom and Kader [28] or Street [29] are adequate for the present application.

The only information required in addition to the meteorological and oceanographic data for the calculation of mass transfer is the friction velocity. The friction velocity is computed from the wind-stress coefficient as follows:

\[
u_w = V_w \left( C_f/2 \right)^{1/2} \tag{III.30}
\]

where \( V_w \) is the wind velocity measured at 10 meters above the water and \( C_f/2 \) is the wind-stress coefficient. Numerous models of wind-stress
Figure III.2. Comparison of Theoretical and Experimental Dalton Numbers for Smooth Flow Over Water (Sc = 0.593). Open Symbols are for Wind Waves and Closed Symbols are for wind and mechanical waves.
coefficient are available in the oceanographic literature. Some representative relations are summarized in Table III.5.\(^1\) The equations selected for this program are from Wu [25]

\[
C_f/2 = (0.8 + 0.065 V_w) \times 10^{-3} \tag{III.31a}
\]

for \(1 < V_w < 20 \text{ m/s}\) and

\[
C_f/2 = (1.25/V_w^{1/6}) \times 10^{-3} \tag{III.31b}
\]

for \(V_w \leq 1 \text{ m/s}\). In the computer program, the \(1 \text{ m/s}\) boundary between the two values of wind-stress coefficient is set at 3.064 m/s. At this wind velocity the two wind-stress coefficients have the same value. In addition, Wu [25] states that the flow is aerodynamically smooth for \(V_w < 3 \text{ m/s}\). The selection of Wu's model was arbitrary. However, the Wu model is simple, and it is similar to those of other investigators.

In the event that wave height information is not available, the wave height can be modeled with the following relation from Van Dorn [34]

\[
h_m = 0.01384 V_w \tag{III.32}
\]

where \(V_w\) is in meters/second and the mean wave height, \(h_m\), is in meters. This equation is valid only for a fully developed sea; thus, it is an upper bound for wind generated waves. With Equations (III.31a) and (III.32) the wave height can be calculated from the wind speed as an inner-variable scale. The result is plotted in Figure III.3.

\(^1\) A plot of some of these relations is presented in [32,33]
<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>$10^3(C_f/2)$</th>
<th>Velocity Range (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amoroch &amp; DeVries</td>
<td>1981</td>
<td>$1.21 \left(1 + \exp \left[(2.5 - V_w)/1.56\right]\right)^{-1} + 1.04$</td>
<td>0-40</td>
</tr>
<tr>
<td>Garratt</td>
<td>1977</td>
<td>$0.75 + 0.067 V_w$</td>
<td>4-21</td>
</tr>
<tr>
<td>Large &amp; Pond</td>
<td>1981</td>
<td>$1.2$</td>
<td>4-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.49 + 0.065 V_w$</td>
<td>11-25</td>
</tr>
<tr>
<td>Smith</td>
<td>1980</td>
<td>$0.61 + 0.063 V_w$</td>
<td>6-22</td>
</tr>
<tr>
<td>Smith &amp; Banke</td>
<td>1975</td>
<td>$0.63 + 0.066 V_w$</td>
<td>3-21</td>
</tr>
<tr>
<td>Wu</td>
<td>1980</td>
<td>$0.08 + 0.065 V_w$</td>
<td>1-20</td>
</tr>
<tr>
<td>Wu</td>
<td>1969</td>
<td>$1.25/V_w^{1/3}$</td>
<td>0-1</td>
</tr>
</tbody>
</table>

NOTE: $V_w$ is the wind velocity at 10 meters.
Figure III.3. Mean Wave Height in Law-of-the-Wall Coordinate for a Fully Developed Sea as a Function of Wind Speed

\[ h_{m+} = \frac{h_m u_*}{\nu_a} = 0.01384 V_w \frac{u_*}{\nu_a} \]
III.4 Dissolution Models

III.4.1 Discussion

The dissolution model in the present HACS model is one which is valid only in rivers and streams. The dissolution model included in HACS [2] was developed by Fortescue and Pearson [35] for the dissolution of gases in flowing water. A more recent model has been included in the revision.

For dissolution in open bodies of water such as lakes and coastal waters, the mass transfer model described in the previous section has been applied to dissolution. The mass transfer process on the two sides of the gas-liquid interface has been assumed to be the same. A boundary layer is formed in the liquid by the transfer of momentum to the water by the wind. Since the shear stress across the interface is assumed to be continuous, the friction velocities in air and water are related as follows:

\[ u_{*w} = u_{*a} \left( \frac{\rho_a}{\rho} \right)^{1/2} \]  

(III.33)

With this assumption, dissolution of the chemical spill into the water can be computed with the same equations as its evaporation into the air.

III.4.2 General Description

The dominant effect in dissolution is the Schmidt number for the chemicals in water, which is on the order of a thousand. According to Shaw and Hanratty [36], the Dalton number for sufficiently large Reynolds number and Schmidt number will reduce to

\[ Da_* = K \text{Sc}^{-n} \]  

(III.34)

where \( 2/3 \leq n \leq 3/4 \) and \( K \) is a constant determined from experiment. As the previous section states, information for Schmidt number is not included in CHRIS. The description in Section III.3.2 for evaporation is also valid for dissolution. The length dimension for \( \delta_* \) in Equation (III.27) must be large compared to \( \delta_c \) and was assumed to be one meter.
III.4.3 Mass Transfer From Slick Into Water

The mass transfer calculations for dissolution in lakes, coastal waters, and the open ocean are accomplished with the same equations as for evaporation. From the wind velocity, the friction velocity in air is computed from Equations (III.30) and (III.31a,b) and the friction velocity in water from Equation (III.33). The Dalton number $Da_*$ is calculated from Equations (III.27) and (III.29a,b) where the physical properties such as Schmidt number, density, and viscosity are for water. Then, the mass transfer in physical units is computed from Equations (III.28) and (III.19) where the density is now the water density, $C_s$ now the water solubility of the chemical in mass fraction of water, and the freestream concentration, $C_\infty$, is zero.

The Dalton number for dissolution in a river or stream is calculated from a formula recommended by Ueda, et al. [37] as follows:

$$Da_* = 0.0626 \, Sc^{\frac{2}{3}}$$

(III.35)

In this formulation, the Dalton number $Da_*$ is based upon the friction velocity for the bottom. No correlation for the friction coefficient for rivers exists which is similar to that for wind stress in Table III.5. In the absence of such a correlation, the following was applied from Schlichting [23] for a completely rough regime.

$$\left(\frac{C_f}{2}\right)^{\frac{1}{2}} = \frac{U_c}{u_*} = 5.66 \log \left(\frac{2d}{h_s}\right) + 4.92$$

(III.36)

where $h_s$ is Nikuradse's sand roughness, $d$ is the depth of the river, and $U_c$ is the mean current. Also, Fischer, et al. [38] claim a reasonable assumption is $u_* = 0.1 \, U_c$.

Shear stress velocity can easily be computed from Equation (III.36) for a river; however, an estimate must be made for the bottom roughness. Experimental results for various channels compiled from Fischer, et al. [38,39] are summarized in Table III.6 and plotted in Figure III.4. The data in Figure III.4 are compared with the smooth channel theory of
<table>
<thead>
<tr>
<th>Year</th>
<th>Channel</th>
<th>Mean Depth d (cm)</th>
<th>Mean Velocity $u_{c}$ (cm/s)</th>
<th>Shear Velocity $10^{-6} \cdot \frac{C}{2}$</th>
<th>$10^3 \cdot \frac{C}{2}$</th>
<th>$10^{-6} \cdot \frac{C}{R}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Missouri River near, Nebraska</td>
<td>210</td>
<td>175</td>
<td>7.4</td>
<td>10.82</td>
<td>1.78R</td>
</tr>
<tr>
<td>1973a</td>
<td>Lab. model of Issel River</td>
<td>90</td>
<td>13</td>
<td>0.78</td>
<td>3.6</td>
<td>0.47</td>
</tr>
<tr>
<td>1973b</td>
<td>Issel River</td>
<td>400</td>
<td>96</td>
<td>7.5</td>
<td>6.106</td>
<td>15.30</td>
</tr>
<tr>
<td>1970</td>
<td>McKenzie River</td>
<td>670</td>
<td>137</td>
<td>15.2</td>
<td>7.325</td>
<td>47.25</td>
</tr>
<tr>
<td>1976</td>
<td>Fort Simpson</td>
<td>400</td>
<td>540</td>
<td>8.0</td>
<td>0.220</td>
<td>66.06</td>
</tr>
<tr>
<td>1964</td>
<td>Cooper Nuclear Station, Nebraska</td>
<td>400</td>
<td>305</td>
<td>8.8</td>
<td>4.249</td>
<td>16.40</td>
</tr>
<tr>
<td>1964</td>
<td>Columbia River</td>
<td>68.3</td>
<td>63</td>
<td>6.3</td>
<td>10.50</td>
<td>1.744</td>
</tr>
<tr>
<td>1967</td>
<td>Irrigation Canal</td>
<td>669.7</td>
<td>66</td>
<td>6.1</td>
<td>8.542</td>
<td>1.754</td>
</tr>
</tbody>
</table>

Note: Compiled from Fischer, et al. [34] and Fischer [39]
Blasius Equation: $C_f/2 = 0.0396 \, \text{Re}^{-0.25}$

Figure III.4. Friction Coefficient for Open Channel Flows. Numbers Correspond to Experimental Data in Table, and Solid Line is Blasius Equation.
Blasius for turbulent flow. All data, with the exception of Yotsukura and Sayre [40] are consistent with a rough wall hypothesis. The average value of the shear stress coefficient, \( C_f/2 \), for the experimental data is \( 5.4 \times 10^{-3} \) which corresponds to a relative roughness of \( 2d/h_s = 34.4 \) from Equation (111.36). Thus, roughness height can be estimated from

\[
h_s = 0.0581 \, d
\]  

(III.37)

where the mean depth, \( d \) of the river must be given.

III.5 Movement Models

III.5.1 Discussion

Wind, waves, and currents affect both the shape of a continuous spill, as was discussed in Section III.2.4, and the drift or overall movement of either an instantaneous or a continuous spill. Nearly all the transport predictions in the literature conform to the basic premises of the "Navy" model [41] which states that the vector displacement \( \Delta \mathbf{R} \) of an element of the slick is

\[
\Delta \mathbf{R} = \mathbf{U}_c \Delta t + K_w \, \mathbf{V}_w \Delta t + \mathbf{U}_w \Delta t
\]  

(III.38)

Here \( \Delta t \) is the computational time period; \( \mathbf{U}_c \) is any current that is not produced by the wind; \( \mathbf{V}_w \) is the wind 10 meters above the water and \( K_w \) is a factor that relates the wind to the current produced by it; and \( \mathbf{U}_w \) is a drift-current produced by any waves not directly due to the wind. The value of the wind factor \( K_w \) is subject to some dispute, but values of 0.03 to 0.04 are commonly accepted [7]. In the computerized models here, a value of \( K_w = 0.035 \) is used. The effect of waves in producing a net transport current \( \mathbf{U}_w \) is usually small and is neglected [7, 8, 42]. For the computerized models developed here, the currents and wind values are supplied as input data, as described below. Sets of typical data for selected bodies of water of unusual importance can also be developed in advance, which is the method used in the Norwegian "OILSIM" model [11].
111.5.2 Rivers and Channels

For rivers and channels, either a constant current or a tidally-varying current can be used in the computerized models. Tidal currents are assumed to be of the form

$$U_c = U_0 + U_1 \sin \left( \frac{2\pi}{T} (t + \alpha) \right)$$  \hspace{1cm} (III.39)

where $U_0$ and $U_1$ are the constant and the time-varying components of the current, $T$ is the tidal period, and $\alpha$ is a parameter chosen such that the appropriate phase of the tide will coincide with time $t = 0$ of the spill initiation. The wind is assumed either to be constant or a specified function of time. A time-varying wind is simulated by giving the wind speed at up to ten different instants of time.

**Instantaneous Spills.** - The slick formed from an instantaneous spill is transported in accordance with the motion of its centroid. That motion is computed directly from Equation (III.38); however, only the component of the wind aligned with the channel is used in the wind term, $0.035 V_w \Delta t$.

**Continuous Spills.** - Equation (III.38) is used to evaluate the transport velocity $U_T$ needed in the spreading model. Since a time-varying $U_T$ is not permitted in the continuous-spill spreading models as formulated here, a time-average $\overline{U_T}$ is computed whenever $\overline{U_c}$ or $\overline{V_w}$ is a function of time; the average is taken over the shorter of the spill duration or the tidal cycle to give

$$U_T = U_c + 0.035 V_w \cos \theta$$  \hspace{1cm} (III.40)

where $\theta$ is the angle the wind makes with the current direction.

The slick formed by a continuous spill must remain attached to the source. If the current is tidal, and the reverse flow is significant, the slick is allowed to move with the reversed flow after the spreading has been accounted for. The condition used to determine the significance of the
movement is whether the average value of $U_T$ is greater or less than three-tenths of the maximum value of $U_T$. When $\bar{U}_T > 0.3 (U_T)_{\text{maximum}}$, the back-and-forth motion of the slick is small compared to the overall downstream motion of the leading edge, and the reversed motion of the slick is neglected. When $\bar{U}_T < 0.3 (U_T)_{\text{maximum}}$, on the other hand, a definite reverse motion of the slick is noticeable, and the slick may move upstream of the source temporarily. In the computerized version, the motion of the leading and trailing edges of the slick for this latter case are approximated as:

$$\Delta Z_{le} = \Delta A/2w + U_T \Delta t$$ (III.41a)

$$\Delta Z_{te} = -\Delta A/2w + U_T \Delta t$$ (III.41b)

Here $\Delta A$ is the change in area caused by the spreading (computed from the average $\bar{U}_T$) over the time interval $\Delta t$. If Equation (III.41b) predicts that $Z_{te} > 0$ (where $Z_{te} = \sum \Delta Z_{te}$ summed up to the time of interest), the computerized model sets $Z_{te} = 0$ since the trailing edge of the slick cannot move downstream of the source. (That is, a tidal current may transport part of the slick back past the source but it cannot separate the slick from the source.)

After a continuous discharge has ceased, the subsequent motion of the slick is treated similarly to that from an instantaneous spill.

III.5.3 Open Water

In the computerized models, two kinds of "open water" can be specified: lakes and coasts. A lake can be further idealized as essentially circular or rectangular, or the boundary coordinates of the lake can be specified at up to ten locations to allow a more realistic description. Likewise, a coast can be specified as straight or by giving up to ten pairs of coordinates to describe a more realistic shape. The wind can be specified either as constant or as a function of time in a way similar to that described for rivers and channels. The current can be given as a constant for the entire...
body of water, or as a function of time (by giving values at up to ten instants of time), or as a function of position (as described below), or as a function of both time and position.

To describe a current as a function of position in the computerized models, a grid is superimposed on the water-body description, as shown in Figure III.5. The $x$ and $y$ components of the currents must be specified for each of the nine rectangular "boxes" (for lakes) or "slices" (for coasts). (The numbering system used in the computerized models is shown in the figure.) If the current is also a function of time, the $x$ and $y$ components must be given for each of the boxes or slices at up to ten instants of time.

**Instantaneous Spills.** - The movement of the slick formed from an instantaneous spill is computed as a function of time from Equation (III.38) until the edge of the thick slick arrives at a boundary of the open water.

**Continuous Spills.** - For a continuous spill, the time-average value of $U_T$ for the box or slice containing the spill source is used in the spreading models to compute the spreading rate. The positions of the leading and trailing edges of the slick are computed, however, from the currents appropriate to their positions whenever the current is a function of position. The method used is similar to that described previously for tidal currents in a river or channel. This can lead to some discrepancies between the area of the slick, the width of the slick, and the positions of the leading and trailing edges, but the computation described is the best that is possible unless a much more complicated spreading model is used.

The dynamics of the spreading are computed as a function of time until the leading edge of the thick slick arrives at a boundary. After a continuous discharge has ceased, the subsequent motion of the slick is treated similarly to that from an instantaneous spill.
a. CURRENT GRID FOR A LAKE

b. CURRENT GRID FOR A COAST

Figure III.5 Specification of Currents for Open Water
III.6 **Effects of Spill Parameters on Model Predictions**

### III.6.1 Discussion

The spreading, evaporation, dissolution, and movement models contain a large number of parameters. In order to demonstrate the use of the models and the importance of various parameters, the effects of four of the more important parameters are investigated: volume of chemical released or discharge rate; chemical density; current; and wind speed. These parameters are varied about a "standard" set of parameters for a spill in a large water body. The standard chemical is chosen to have the same properties as octane, with the exception of density. Octane is nearly insoluble (its maximum solubility is 0.02 kg/m³), so the effects of the parameter variations on dissolution are small in comparison to their effects on evaporation; this behavior is, however, typical of most of the chemicals of interest to the USCG.

### III.6.2 Instantaneous Spills

An instantaneous spill is assumed to occur in a large body of water having a depth of 100 meters and a current of 0.51 m/sec. The wind speed is 3 m/sec oriented at 19.7° with respect to the current. The chemical has a standard density of 800 kg/m³, a vapor pressure of 13.92 millibars, and a spreading coefficient of $3.42 \times 10^{-3}$ Newton/meter. The standard volume of chemical spilled is 60 m³.

Figure III.6 shows the variation with time of the area and the thickness of the slick as a function of the spilled volume. In all cases, the area increases rapidly at first when the spill is relatively thick, followed by a longer period when the spreading rate is much slower. (The gravity-inertial phase lasts about two minutes, at which time the standard area is about $1 \times 10^4$ m². Most of the spreading therefore occurs in the gravity-viscous phase, in accordance with the assumptions used in developing the models.) The rate of spreading throughout clearly depends on the spilled volume. In the absence of evaporation, the areas at any time should be in
INSTANTANEOUS SPILL

\( \rho_0 = 800 \text{ kg/m}^3 \)

\( p_v = 13.92 \text{ millibar} \)

Wind Speed = 3m/sec @ 19.7°

Current = 0.51 m/sec

\( V_0 = 10 \text{ m}^3 \)

Figure III.6  Effect of Spilled Volume on Size and Thickness of Instantaneous Spills
the ratio of the spill volumes to the two-thirds power, as shown by Equation (III.10). In fact, the curves show that this ratio holds approximately during the time when the spill area increases even when evaporation occurs. The slick areas eventually decrease as a result of evaporation; more will be said about this effect below. The slick thicknesses decrease uniformly, although even after two hours the thicknesses are still well above the cut-off value of $1 \times 10^{-4}$ meter.

Figure III.7 shows the effects of varying the chemical density when the spilled volume and the other parameters are held constant. Again, the variation is roughly in agreement with Equation (III.10) during the time when the areas are increasing. But, as shown by the curves for $\rho_0 = 800$ kg/m$^3$ and $\rho_0 = 900$ kg/m$^3$, and even more significantly for the unrealistic case of $\rho_0 = 100$ kg/m$^3$, Equation (III.10) is not capable of predicting the correct trend when evaporation becomes dominant. The less-dense chemicals spread more rapidly initially and thus experience a higher rate of evaporation; thus, the higher evaporative losses for them cause the rate of spreading to slow earlier.

The effects of wind speed are shown in Figure III.8. Since higher wind speeds increase the rate of evaporation, the trend of these curves is similar to that shown in Figure III.7 for density variations. The curves for the extreme wind speed of 30 m/sec show the trend most clearly. (The range of wind speeds for which the models are expected to be applicable will be discussed later.)

The effects of varying the current over a factor of one-hundred (i.e., from 0.051 m/sec to 5.1 m/sec) give a trend similar to the wind speed variation, but the magnitudes of the area and thickness changes are much less and therefore are not shown here. It is concluded that the current has only an indirect effect on evaporation. Of course, the movement of the slick is directly related to the current.

Figures III.6, III.7, and III.8 all showed that the rate of spreading eventually became negative as a result of evaporative losses. Such behavior is probably physically incorrect, because as long as the slick is thicker than the cutoff value ($1 \times 10^{-4}$ meters), it should continue to spread in the gravity-viscous phase although at a rate slowed by evaporation. This
Instantaneous spill

$V_0 = 60 \text{m}^3$

$p_0 = 13.92 \text{ millibars}$

Wind Speed $= 3 \text{ m/sec @ 19.7°}$

Current $= 0.51 \text{ m/sec}$

Figure 111.2 Effect of chemical density on size and thickness of instantaneous spills.
Figure III.8  Effect of Wind Speed on Size and Thickness of Instantaneous Spills

INSTANTANEOUS SPILL

- \( V_0 = 60 \text{ m}^3 \)
- \( \rho_0 = 800 \text{ kg/m}^3 \)
- \( \rho_v = 13.92 \text{ millibar} \)
- Current = 0.51 m/sec

SPILL AREA

SPILL THICKNESS

ELAPSED TIME, MINUTES
lack of physical reality in the late-time predictions is caused by the use of a "lumped" mass model rather than a differential model. For example, the dA/dt expression given in Table III.3 is based upon a constant thickness h for the entire slick. In reality, h is greater near the center and approaches the minimum value (1 x 10^-4 meters) near the edges. Incorporating the variation of h in the model would tend to increase the positive terms in the expression for dA/dt and decrease the negative effect of the loss term 2 m_{loss}/3 \rho_0 h. More importantly, the loss term itself was derived from the assumption that evaporation and dissolution effectively act as a lumped "sink" just as the spilled mass acts as a lumped "source" at the center of the spill. In reality, the losses are distributed over the entire surface of the slick, i.e., as a distributed sink. Although the difference in the models is negligible as long as dA/dt > 0, the distributed model would never predict that dA/dt < 0. Instead, the rate of decrease of h would be accelerated late in the spreading. A differential, or distributed model would be, of course, much more complicated mathematically. Since the lumped model gives realistic results over most of the spill duration (except for extreme cases such as \rho_0 = 100 kg/m^3), the effort involved in developing a differential model is not believed to be warranted.

III.6.3 Continuous Spills

The standard continuous spill has a discharge rate of 0.0333 m^3/sec over a total duration of thirty minutes. The total volume of the spill is thus 60 m^3, the same as for the standard instantaneous spill. The other parameters of the spill are the same as those of the instantaneous spills.

Figure III.9 shows the effects of changing the discharge rate. (The three rates give total spill volumes equal to 100, 60, and 10 m^3, the same as for the instantaneous spills.) The quantities displayed in the plots are the downstream width of the triangularly-shaped slick and the slick thickness. (The spill area can be computed by multiplying half the width by the spill length, which is equal to the product of the net transport velocity \U_T and the elapsed time; as discussed in Section III.5, \U_T is \((U_c + 0.035 \U_w \cos \theta)' + (0.035 \U_w \sin \theta) \)^{1/2}. At the end of
CONTINUOUS SPILL

$\dot{m}_0 = 800 \text{ kg/m}^3$

$\rho_v = 13.92 \text{ millibars}$

Wind Speed = 3 m/sec @ 19.7"

Current = 0.51 m/sec

Figure III.9  Effect of Discharge Rate on Width and Thickness of Continuous Spill.
thirty minutes, the areas of the continuous spills are about twice those
of the corresponding instantaneous spills, and the thicknesses about one-
half. The variation with respect to discharge rate from curve-to-curve
is roughly in agreement with Equation (III.16).

The variation of the spill width and thickness with chemical density
is shown in Figure III.10. Two values of density around 800 kg/m³ are shown,
as well as the extreme case of \( \rho_0 = 100 \) kg/m³. It can be seen that for
\( \rho_0 = 100 \) kg/m³ the width and area increase so rapidly initially that evap-
orative losses cause the width to decrease (but not the total area) after
about ten minutes. The negative rate of change of the width is physically
unrealistic, for the same reasons as discussed previously in Section III.6.2.

Figure III.11 shows the effects of current. Since the length of the
slick increases when the current increases, the current has a significant
effect on the width and the area of the slick formed by a continuous spill,
in contrast to its negligible effect on an instantaneous spill. The de-
crease in the width is considerably less, however, than the increase in the
length, so the net effect is that the slick area is increased when the
current is increased.

Figure III.12 displays the effects of wind speed on the spill width
and thickness. Most of the changes in the width and thickness are due to
the changes in the evaporative losses, although there is also an effect of
the wind speed on \( U_T \) and thus an indirect effect similar to that shown
previously for a variation in current.

III.7 Wind and Current Limitations on Models

According to Wu [25], a water surface will form breaking waves and
spray for wind speeds above about 15 m/sec. Since the slick will also begin
to disintegrate, this value represents the limit on wind speeds for which the
models are expected to give reliable predictions.

The models should be applicable for all normal values of current ex-
perienced in practice.
CONTINUOUS SPILL
\( \dot{m}/\rho_0 = 0.0333 \text{ m}^3/\text{sec} \)

\( \rho_v = 13.92 \text{ millibar} \)

Wind Speed = 3 m/sec @ 19.7°

Current = 0.51 m/sec

FIGURE III.10  Effect of Chemical Density on Width and Thickness of Continuous Spills.
CONTINUOUS SPILL
\( \frac{\dot{m}}{\rho_0} = 0.0333 \text{ m}^3/\text{sec} \)
\( \nu_0 = 800 \text{ kg/m}^3 \)
\( P_v = 13.92 \text{ millibar} \)
Current = 0.51 m/sec

FIGURE III.11 Effect of Wind Speed on Width and Thickness of Continuous Spills

53
Figure III.12  Effect of Current on Width and Thickness of Continuous Spills
IV. EXPERIMENTAL DESIGN AND DATA COLLECTION

IV.1 Experimental Design

The purpose of the experimental design was to develop a test plan for experiments that would provide validation data for the revised models of both instantaneous and continuous spills. The process involved several elements:

- test program objectives
- model sensitivity analysis, and
- test plan.

The work carried out in each of these elements is described in the following sections.

IV.1.1 Test Program Objectives

Objectives for the test program were formulated in two main categories:

- spreading, and
- evaporation and dissolution.

This breakdown of the test program was the result of the perceived impracticality of simultaneously obtaining spreading rate data and detailed mass-transfer data from large-scale spill tests. Consequently, spill tests were designed to obtain data for validating the spreading models, and separate non-spreading tests were designed to obtain data for validating the evaporation and dissolution models. A small number of spill tests were also designed to determine any effects of evaporation on spreading. No tests were conducted specifically to validate the slick motion model; that model, i.e., Equation (III.38), has been adequately verified by other tests in the past [7,8,9].

Spreading Tests. The objective of these tests was to conduct a set of spills, on as large a scale as was practical, from which spreading rates...
and slick sizes could be determined. The tests were designed to systematically vary the influence of:

- quantity spilled (instantaneous spills)
- discharge rate (continuous spills)
- chemical specific gravity
- chemical spreading coefficient
- magnitude of current (continuous spills).

The size and shape of the slick were to be determined as functions of time primarily by the use of flow visualization. To achieve these objectives, a large outdoor basin was constructed to study instantaneous and continuous spills in water without a current, and a large flow channel was modified to study continuous spills in a current. Some tests using the outdoor basin were designed to study combined evaporation and spreading. For these tests, chemicals having a range of vapor pressures were tested.

**Evaporation and Dissolution Tests.** The evaporation and dissolution tests were designed to vary, in a controlled environment, the influences of:

- chemical thermophysical properties,
- wind speed, and
- wave height.

In order to make the detailed measurements needed to validate the mass-transfer models, it was necessary to insure that the floating chemical slick remained stationary.

Thus, to achieve the test objectives, an environmental wind tunnel was constructed in which an open pan of chemical could be exposed to various wind speeds. Tests in which the chemical could be subjected to both wind and waves were designed for a large wind-wave tunnel at Flow Research, Inc., in Kent, Washington. Mass-transfer rates were to be determined primarily through concentration sampling of the air and the water.
IV.1.2 Sensitivity Analysis

An analysis was performed on the revised spreading, evaporation, and dissolution models in order to determine the sensitivity of the predicted spreading rates and mass losses to changes in the values of the model parameters. Such an analysis is useful in determining which parameters have the greatest influence on the predicted results and therefore need to be controlled and measured during experiments. It also reveals the parameters that have little influence on the predictions and can therefore be omitted from the test specifications.

For each spreading model, the change in the slick diameter at a specified time after the spill had occurred (generally, fifteen minutes), and the time required to evaporate the entire slick, was computed for a +10% change in the value of each parameter about a selected baseline condition. The sensitivity coefficient for each parameter was then computed, using the slick area as an example, by the equation:

$$SC_X = \frac{\Delta A/A_0}{\Delta X/X_0}$$

Here $\Delta A$ is the computed change in area from $A_0$ for a $\Delta X$ change in the parameter $X_0$. When $SC_X$ is positive, $A$ increases as $X$ increases; the opposite holds when $SC_X$ is negative. The magnitude of $SC_X$ indicates the sensitivity of $A$ to $X$; if $|SC_X| = 1.0$, the percentage change in $A$ is the same as the percentage change in $X$; values of $|SC_X|$ greater or less than one indicate a greater or lesser sensitivity to a change in $X$.

Table IV.1 gives the results for an instantaneous spill of 90 m$^3$ of benzene on an unbounded lake. (This sensitivity analysis had to be conducted before data from the tests were available to establish the empirical constants. Therefore, the absolute magnitudes of slick radius and evaporation time presented in the table may be in error in places, but the trends of the sensitivity coefficients, since they are computed as ratios, are generally correct.) From the table, the relative importance of the independent parameters is evident. For the slick size, for example, the chemical density and the spill volume are the dominant parameters. For evaporation, the order of relative
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Independent Variable</th>
<th>Units</th>
<th>Value</th>
<th>Slick Radius* (m)</th>
<th>Sensitivity Coefficient</th>
<th>Evaporation Time (min)</th>
<th>Sensitivity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wind Velocity (Ref.)</td>
<td>m/s</td>
<td>10.</td>
<td>175.13</td>
<td>0</td>
<td>23.66</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Wind Velocity</td>
<td>m/s</td>
<td>9.</td>
<td>175.82</td>
<td>-0.0394</td>
<td>25.31</td>
<td>-0.697</td>
</tr>
<tr>
<td>3</td>
<td>Wind Velocity</td>
<td>m/s</td>
<td>11.</td>
<td>174.45</td>
<td>-0.0388</td>
<td>22.29</td>
<td>-0.579</td>
</tr>
<tr>
<td>4</td>
<td>Current</td>
<td>m/s</td>
<td>1.80</td>
<td>175.00</td>
<td>0.0074</td>
<td>23.36</td>
<td>0.127</td>
</tr>
<tr>
<td>5</td>
<td>Current</td>
<td>m/s</td>
<td>2.20</td>
<td>175.27</td>
<td>0.0080</td>
<td>23.96</td>
<td>0.127</td>
</tr>
<tr>
<td>6</td>
<td>Wave Height</td>
<td>m</td>
<td>1.35</td>
<td>174.76</td>
<td>0.0211</td>
<td>22.88</td>
<td>0.330</td>
</tr>
<tr>
<td>7</td>
<td>Wave Height</td>
<td>m</td>
<td>1.65</td>
<td>175.45</td>
<td>0.0183</td>
<td>24.39</td>
<td>0.309</td>
</tr>
<tr>
<td>8</td>
<td>Spill Volume</td>
<td>m³</td>
<td>81.</td>
<td>167.99</td>
<td>0.408</td>
<td>23.11</td>
<td>0.233</td>
</tr>
<tr>
<td>9</td>
<td>Spill Volume</td>
<td>m³</td>
<td>99.</td>
<td>181.87</td>
<td>0.385</td>
<td>24.15</td>
<td>0.207</td>
</tr>
<tr>
<td>10</td>
<td>Density</td>
<td>kg/m³</td>
<td>791</td>
<td>181.40</td>
<td>-0.358</td>
<td>19.72</td>
<td>1.665</td>
</tr>
<tr>
<td>11</td>
<td>Density</td>
<td>kg/m³</td>
<td>967.</td>
<td>156.78</td>
<td>-1.048</td>
<td>32.33</td>
<td>3.664</td>
</tr>
<tr>
<td>12</td>
<td>Diffusivity in Air</td>
<td>m²/s</td>
<td>0.783 x 10⁻⁵</td>
<td>175.69</td>
<td>-0.032</td>
<td>24.98</td>
<td>-0.558</td>
</tr>
<tr>
<td>13</td>
<td>Diffusivity in Air</td>
<td>m²/s</td>
<td>0.957 x 10⁻⁵</td>
<td>174.58</td>
<td>-0.031</td>
<td>22.53</td>
<td>-0.478</td>
</tr>
<tr>
<td>14</td>
<td>Diffusivity in Water</td>
<td>m²/s</td>
<td>0.918 x 10⁻⁹</td>
<td>175.13</td>
<td>0</td>
<td>23.66</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>Diffusivity in Water</td>
<td>m²/s</td>
<td>1.122 x 10⁻⁹</td>
<td>175.13</td>
<td>0</td>
<td>23.66</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>Vapor Pressure</td>
<td>mb</td>
<td>90.23</td>
<td>175.93</td>
<td>-0.0457</td>
<td>25.63</td>
<td>-0.833</td>
</tr>
<tr>
<td>17</td>
<td>Vapor Pressure</td>
<td>mb</td>
<td>110.29</td>
<td>174.30</td>
<td>-0.0474</td>
<td>22.01</td>
<td>-0.697</td>
</tr>
<tr>
<td>18</td>
<td>Spreading Coefficient</td>
<td>N/m</td>
<td>15.26 x 10⁻³</td>
<td>177.99</td>
<td>0.0227</td>
<td>23.11</td>
<td>-0.032</td>
</tr>
<tr>
<td>19</td>
<td>Spreading Coefficient</td>
<td>N/m</td>
<td>2.46 x 10⁻³</td>
<td>171.37</td>
<td>0.0297</td>
<td>24.46</td>
<td>-0.047</td>
</tr>
<tr>
<td>20</td>
<td>Solubility</td>
<td>%</td>
<td>0.1586</td>
<td>175.13</td>
<td>0</td>
<td>23.66</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>Solubility</td>
<td>%</td>
<td>0.1938</td>
<td>175.13</td>
<td>0</td>
<td>23.66</td>
<td>0</td>
</tr>
</tbody>
</table>

* At 15 min.
importance of parameters is density, vapor pressure, wind speed, diffusivity in air, wave height, spill volume, and current. Similar results were obtained for continuous spills. The effects previously shown in Figures III.6 to III.12 display the same trends graphically. The sensitivity analysis results were used in formulating the test plans.

IV.1.3 Test Plan

Spill Tests - As mentioned earlier, instantaneous and continuous spill tests were planned for a large outdoor basin, and continuous spill tests in a current were planned for a large channel. The final test plan is shown in Tables IV.2 through IV.6. Altogether, 102 spreading tests were planned and conducted. (Some preliminary tests that were conducted to help establish feasible limits on spill sizes, discharge rates, and chemical properties are not included in the plan.)

No tests were conducted using volatile chemicals in a current because of the hazardous vapors that would have been liberated indoors.

Evaporation and Dissolution Tests - Two series of tests for evaporation and dissolution were planned for the experimental program. The first group of tests was to be conducted in a wind tunnel at SwRI with a test section designed for these experiments. The primary objective was to measure transfer rates on a variety of chemicals over a range of wind velocities. The chemicals were selected to cover a range of physical properties important to evaporation and dissolution: Schmidt number, vapor pressure, and solubility. In addition, a range of interfacial tensions was also included since this property is likely to be important in controlling droplet dispersion in water. The chemicals were also selected to minimize health and safety hazards. A secondary objective for these experiments was to perfect experimental techniques for the second group of tests.

A second group of tests was planned for a wind-wave channel at Flow Research, Inc., at Kent, Washington. The purpose of these tests was to measure mass transfer rates for two chemicals exposed to controlled
TABLE IV.2 SUMMARY OF TEST CONDITIONS FOR SPREADING TEST SERIES I
NON-VOLATILE INSTANTANEOUS SPILLS IN BASIN

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Chemical</th>
<th>Specific Gravity</th>
<th>Spreading Coefficient (dyne/cm)</th>
<th>Spill Volume (liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1-1</td>
<td>Octane</td>
<td>0.703</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>1.1-2</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>1.1-3</td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>1.1-4</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>1.2-1</td>
<td>Kerosene</td>
<td>0.795</td>
<td>-2.7</td>
<td>5</td>
</tr>
<tr>
<td>1.2-2</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
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<tr>
<td>1.2-3</td>
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<td>20</td>
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<tr>
<td>1.2-4</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>1.3-1</td>
<td>n-Hexanol</td>
<td>0.819</td>
<td>39.75</td>
<td>5</td>
</tr>
<tr>
<td>1.3-2</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>1.3-3</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>1.4-1</td>
<td>Naphtha</td>
<td>0.785</td>
<td>7.8</td>
<td>5</td>
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<tr>
<td>1.4-2</td>
<td></td>
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<td>1.4-4</td>
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<td>40</td>
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<tr>
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<td>m-Xylene</td>
<td>0.864</td>
<td>7.0</td>
<td>5</td>
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<td>1.5-2</td>
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<td>10</td>
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<td>1.5-3</td>
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<tr>
<td>1.5-4</td>
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<td>40</td>
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## TABLE IV.3 SUMMARY OF TEST CONDITIONS FOR SPREADING TEST SERIES II

### NON-VOLATILE CONTINUOUS SPILLS IN BASIN

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Chemical</th>
<th>Specific Gravity</th>
<th>Spreading Coefficient (dyne/cm)</th>
<th>Discharge Rate (liters/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II.1-1</td>
<td>Octane</td>
<td>0.703</td>
<td>0.3</td>
<td>0.50</td>
</tr>
<tr>
<td>II.1-2</td>
<td></td>
<td></td>
<td></td>
<td>0.82</td>
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<td></td>
<td></td>
<td></td>
<td>1.26</td>
</tr>
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<td>II.2-1</td>
<td>Kerosene</td>
<td>0.795</td>
<td>-2.7</td>
<td>0.50</td>
</tr>
<tr>
<td>II.2-2</td>
<td></td>
<td></td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>II.2-3</td>
<td></td>
<td></td>
<td></td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.26</td>
</tr>
<tr>
<td>II.3-1</td>
<td>n-Hexanol</td>
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<td>Vapor Pressure (millibars)</td>
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TABLE IV.5 SUMMARY OF TEST CONDITIONS FOR SPREADING TEST SERIES IV
VOLATILE CONTINUOUS SPILLS IN BASIN

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Chemical</th>
<th>Specific Gravity</th>
<th>Spreading Coefficient (dyne/cm)</th>
<th>Discharge Rate (liters/sec)</th>
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<tr>
<td>IV.1-1</td>
<td>n-Pentane</td>
<td>0.626</td>
<td>6.5</td>
<td>0.50</td>
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<tr>
<td>Run Number</td>
<td>Chemical (Sp.Gravity)</td>
<td>Spreading Coefficient (dyne/cm)</td>
<td>Discharge Rate (liters/sec)</td>
<td>Current m/sec</td>
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<tr>
<td>V.1-1</td>
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<td>0.038</td>
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<td>0.189</td>
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<td>0.290</td>
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<td>V.2-3</td>
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<td>0.241</td>
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<td>V.2-4</td>
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<td></td>
<td>0.149</td>
<td>0.290</td>
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<td>0.038</td>
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<td>V.3-3</td>
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<td>V.3-4</td>
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<td>0.149</td>
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<td>V.4-4</td>
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</table>
wind and wave conditions that simulate the spill environment. The primary variables for these experiments were Reynolds number and wave roughness.

The test plan is summarized in Tables IV.7 through IV.10. Some minor alterations occurred in the test plan during the course of the experiments. The test chemicals for the wind-wave experiments were selected on the basis of test experience gained at SwRI during the first group of tests. In addition, some wave measurements for water only were taken for comparison to waves with a chemical slick.

IV.2 Test Facilities, Procedures, and Instrumentation

IV.2.1 Basin Tests: Spreading and Evaporation

Environmental Spill Facility. The concrete basin pictured in Figure IV.1, used for conducting the continuous and “instantaneous” spreading experiments was a 18.3 m (60 ft) x 18.3 m (60 ft) x 0.3 m (1 ft) deep square pool located at SwRI. The basin was filled with fresh water through a 17.8 cm (7 inch) diameter water inlet in the middle of the basin. The basin was filled to a depth of 0.3 m (1 ft) for each test. The basin could be emptied through a 15.2 cm (6 inch) diameter drain that was located at its center.

For the purpose of data collection, a rake assembly to measure spill diameters was constructed in the spill facility as shown in Figure IV.1. There were four rakes that spanned the basin along its diagonals. The rakes were numbered 1, 2, 3, and 4. Rake 1 is located in the upper lefthand corner of Figure IV.1. The remaining rakes were sequentially numbered in a clockwise direction. Each rake consisted of a 3.8 cm (1.5 inch) by 7.6 cm (3.0 inch) piece of wood that was secured to the bottom of the basin on which wooden pegs were mounted that extended through the water surface. The diameter of each peg was 0.64 cm (0.25 in). The center-most peg on each rake was located 0.6 m (2 ft) from the center of the basin. The next ten pegs were at 0.3 m (1 ft) intervals and the next 5 were at 0.6 m (2 ft) intervals.
<table>
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<th>Run Number</th>
<th>Chemical</th>
<th>Schmidt Number</th>
<th>Vapor Pressure (mb)</th>
<th>Wind Speed (m/s)</th>
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### Table IV.8 Summary of Test Conditions for Evaporation Test Series VII

**Wind-Wave Channel Tests**

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<th>Schmidt Number</th>
<th>Vapor Pressure (mb)</th>
<th>Wind Speed (m/s)</th>
<th>Mechanical Waves</th>
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TABLE IV.9 SUMMARY OF TEST CONDITIONS FOR DISSOLUTION TEST SERIES VIII WIND TUNNEL TESTS

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<th>Schmidt Number</th>
<th>Solubility (ppm)</th>
<th>Wind Speed (m/s)</th>
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TABLE IV.10 SUMMARY OF TEST CONDITIONS FOR DISSOLUTION TEST SERIES IX WIND-WAVE CHANNEL TESTS

<table>
<thead>
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<th>Chemical</th>
<th>Schmidt Number</th>
<th>Solubility (ppm)</th>
<th>Wind Speed (m/s)</th>
<th>Mechanical Waves</th>
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<td>Hexanol(n)</td>
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<td>6,000</td>
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FIGURE IV.1 RAKE ASSEMBLY IN OUTDOOR TEST BASIN
Test Apparatus, Procedures and Instrumentation - Continuous Spill Experiments. For the continuous spill experiments a platform was built and placed in the center of the basin. Each platform leg was placed so that it bisected the angle formed by the rakes to minimize any disturbance in the area along the rakes.

The platform supported a holding tank, pump, a stroboscope, and the discharge tube. Each tested chemical was mixed with Red B. Automate Liquid Dye in the holding tank and held until the test began. To conduct a test, the pump was set at the speed pre-selected from the pump calibration curve to give the desired discharge rate. The valve to the holding tank was then opened. The rotational rate of the pump was determined by a stroboscope. The discharge rates were 0.5 l/s (8 gpm), 0.82 l/s (13 gpm), 1.01 l/s (16 gpm), and 1.26 l/s (20 gpm). The chemical was discharged through 7.62 cm (3 inch) diameter PVC pipe that ran along the platform, down a leg, along the basin bottom, then straight up at the center of the basin. The pipe extended out of the water 6.4 mm (0.25 inch). The chemical was discharged vertically with negligible vertical momentum.

During discharge of the chemical and dye mixture, the test data were recorded on a strip chart using a Honeywell Visicorder. A common voltage supply was utilized with four triggers that fed into four separate channels on the Visicorder. When the edge of the spill arrived at each peg on one of the rakes, the trigger for that rake was pushed. The events for each rake were marked on the strip chart recorder's light sensitive paper.

The event times for each rake were tabulated and used as input to obtain curves of slick radius vs. time. Then, the radius values of opposite rakes (1 and 3, 2 and 4) were added to obtain two graphs of diameter vs. time. The graph of the diameter least affected by any wind was used for comparison with the computer model predictions.

*Red B. Automate Liquid Dye, Morton Chemical Co.
Test Apparatus, Procedures, and Instrumentation - Instantaneous Spill Experiments. The same four-legged platform used for the continuous spill experiments was also used for these instantaneous spill experiments with some minor modifications. Replacing the holding tank, pump, stroboscope, and discharge tube was a system to approximate an "instantaneous" spill. This instantaneous spill apparatus consisted of an open tank without a bottom that was attached to the rod of a pneumatic cylinder as shown in Figure IV.2. The pneumatic cylinder was set so that in its fully extended position the spill tank was just off the basin bottom. While the cylinder was in its lowest position, the chemical/dye mixture was metered into the spill tank from the open top. Care was taken not to allow any chemical to be discharged at the bottom of the open spill tank. This procedure was possible because all of the chemicals studied were lighter than water and relatively immiscible and insoluble. To spill the chemical, a remote valve was used to activate the pneumatic cylinder and raise the spill tank in less than one second; as the tank was raised, the chemical was automatically released into the water without any significant momentum.

The procedures for data collection and reduction were the same as described above for the continuous spill experiments.

IV.2.2 Channel Spreading Tests

Flow Channel Facility. The flow channel used for the experiments of a continuous spill in a current is a 13.7m (45 ft) long, 2.4m (8 ft wide), and 1.5m (5 ft) deep channel with a 1.5m (5 ft) long, 3m (10 ft) deep sump at one end, located at SwRI. Water flow was achieved by pumping water from the sump area through a 20 cm (8 inch) diameter PVC pipe to the head of the channel. The water channel inlet area was constructed using a combination of a diffuser, weirs, fire bricks, screens, and rubberized hogs hair (shown in Figure IV.3) to yield a uniform flow field across the width of the channel. A weir was constructed at the upstream edge of the sump to limit the water depth and also isolate the sump from the rest of the flow channel. After allowing for the area necessary for flow straightening and sump isolation, the test section dimensions were 6.7m (22 ft) long by 2.4m (8 ft) wide. To aid in the flow visualization and
FIGURE IV.2 INSTANTANEOUS SPILL APPARATUS

FIGURE IV.3 CHANNEL INLET AREA OF INDOOR CHANNEL
data collection, the channel floor was striped as shown in Figure IV.4 using graphic slit tape. For the first 3.05 m (10 ft) of the test section, the stripes were spaced every 30.5 cm (1 ft) downstream and 15.2 cm (0.5 ft) cross-stream. For the last 3.65 m (12 ft) of the test section, the stripes were spaced every 61 cm (2 ft) downstream and 30.5 cm (1 ft) cross-stream.

Water velocities in the channel from 12.0 cm/sec (0.39 ft/sec) to 29.0 cm/sec (0.95 ft/sec) were obtained by the use of an Aurora centrifugal pump driven by a hydraulic motor. Since the weir at the upstream edge of the sump was permanently installed, the water depth varied from about 15 cm (6 inches) to 23 cm (9 inches) over the range of flow rates necessary to achieve the water velocities mentioned above. It was determined that this change in depth had no significant impact on the experiments because only surface phenomena were of concern.

Test Apparatus, Procedures and Instrumentation. For the continuous spill experiments in the flow channel, various chemicals were mixed with "Red B. Automate Liquid Dye" and discharged from a discharge port located at the water surface in the upstream center of the channel width. The port was formed from either 2 cm or 5.5 cm diameter pipe configured to give a discharge aligned with the flow direction. The spill setup for these spills is shown in Figure IV.5. The chemical and dye were premixed in the pictured container and then pumped to the port at the discharge rates specified in the test plan using a variable speed motor and a 1/4" rotary gear pump.

During discharge of the chemical and dye mixture, the tests were filmed on video-tape. The films were then analyzed to determine the "thick slick" plume width as a function of distance from the discharge port. This information was graphed to yield a reproduction of the spreading of the chemical on the water surface, and thus to serve as a basis for comparison to the computer model predictions. Only data for that part of the spreading where the channel walls did not affect the results were analyzed. Thus, these tests simulate the spreading of a continuous spill in "open water" with a current.
FIGURE IV.4 WATER CHANNEL WITH STRIPES FOR FLOW VISUALIZATION

FIGURE IV.5 CONTINUOUS SPILL SETUP FOR CHANNEL EXPERIMENTS
IV.2.3 Wind Tunnel Tests: Evaporation

Theory. In the past, mass transfer by evaporation has been measured as the weight loss of chemical from a pan in a wind tunnel. The work of Pasquill [43] is a frequently referenced example of such experiments, and more recently pan evaporation experiments have been reported by Reijnhart and Rose [44] for pentane and toluene. In the present research, evaporation and wind shear stress were determined by measurement of the logarithmic profiles.

Experimentally, velocity and vapor concentration were measured as a function of height above the liquid surface. The relevant mass transfer constants were determined by a linear regression of the profile data in the following form:

\[ U = a \ln z + b \]  
\[ C = a_C \ln z = b_C \]  

where \( U, C, \) and \( z \) are measured quantities and the \( a \)'s and \( b \)'s are the slopes and intercepts from linear regression analysis. In non-dimensional form these equations are:

\[ u_* = U/U_* = A \ln z_* + B \]  
\[ C_* = C/C_* = A \ln z_* + B_C \]  

where the intercepts are related to the roughness parameters of Equations (III.25) and (III.26) by

\[ z_{0*} = \exp (-kB) \]  

and

\[ z_{0C*} = \exp (-r B_C/5C_F) \]  

75
The constants from boundary layer theory and the linear regression analysis are related as follows:

for velocity: \[ u_* = a \kappa \] (IV.7a)
\[ B = \frac{[b - U_S - a \ln (u_* / \nu)]}{u_*} \] (IV.7b)

for concentration: \[ c_* = a_c \kappa / S_c T \] (IV.8a)
\[ B_c = \frac{(b - C_S)/c_* - A S_c T \ln (u_* / \nu)]}{u_*} \] (IV.8b)

By definition the friction velocity and concentration are:
\[ u_* = \sqrt{\tau_0 / \rho} \] (IV.9)
\[ c_* = J_0 / \rho u_* \] (IV.10)

These quantities are related to wind stress coefficient and Dalton number by
\[ C_f/2 = (u_* / V_w)^2 \] (IV.11)
and
\[ D_a = c_* / (C_{\infty} - C_S) \] (IV.12)

where the saturation concentration, \( C_S \), is a physical property calculated from the barometric pressure and liquid surface temperature.

Wind Tunnel. The wind tunnel for the pan evaporation experiments consisted of the following components:

a. bell mouth entrance;
b. rectangular test section with dimensions of 30.5 cm height, 51.0 cm width, and 484 cm length (12 x 24 x 190.5 inches);
c. contraction section;
d. Buffalo centrifugal blower which is rated at 4.7 m³/s (10,000 cfm) and is driven by a Dennison hydraulic motor;

e. 20.3 cm (8 inch) diameter PVC plastic pipe; and

f. evaporation pan with dimensions of 3.8 cm depth, 40.6 cm width, and 121.9 cm length (1.5 x 16 x 48 inches) and with a volume of 18.9 liters (5 gals).

Air for the wind tunnel was ingested at the bellmouth in the laboratory and exhausted by the blower to the outside air. The inlet to the blower was connected to the wind tunnel via the plastic pipe, and the air was transported from the blower outlet to the exterior of the laboratory by plastic pipe. Figure IV.6 shows the tunnel and instrumentation for the pan evaporation experiments.

This arrangement of the tunnel had three primary advantages. First, laboratory personnel were not exposed to the chemical vapors, and thus, the health hazard was reduced. Second, the concentration measurements were not contaminated from chemical vapors which would accumulate in the laboratory otherwise. The tunnel was sealed to minimize any leakage. Third, this design provided an additional method for the measurement of evaporation.

Mass transfer from evaporation was measured from an air sample taken from the plastic pipe downstream from the blower outlet. From the definition of Dalton number and conservation of mass, the Dalton number measured at the blower outlet is:

\[ \alpha_o = (A_t/A_p) (C_o/C_s) \]  \hspace{1cm} (IV.13)

where \( A_t \) is the cross-sectional area of the test section, \( A_p \) is the surface area of the liquid in the evaporation pan, and \( C_o \) is the concentration measured at the blower outlet. The following assumptions are inherent in Equation (IV.13):

a. The flow was well mixed at the sampling station.

b. Any air leakage in the wind tunnel between the sampling station and pan was small.
c. Boundary layer displacement effect on the tunnel cross-sectional area was small; however, an effective area could have been applied.

The tunnel was constructed primarily of wood; however, the two sides of the test section at the pan location were Plexiglas. The pan was constructed of stainless steel sheet metal. A manual gravity feed and drain system was connected to the pan which included 6.4 mm (0.25 inch) diameter stainless steel tubing, fittings, ball valves, 19 liter (5 gal) reservoir, and sight gage. During an experiment the liquid level in the pan was maintained manually to within ±0.5 mm. The liquid surface was typically 5 mm below the tunnel floor.

A set of eight baffles was installed in the pan below the liquid surface for the prevention of surface waves on the chemicals. The baffles were not necessary for water whose surface tension is more than twice that of the chemicals tested. A 35 mm square horse-hair filter was also installed across the width of the pan at its downstream edge for damping surface waves. Figure IV.7 shows close-up views of the pan and test section area during a typical experiment.

**Instrumentation.** The following is a list of the commercial equipment for the evaporation experiments.

- a. TSI 1050 constant temperature anemometer.
- b. DISA traversing mechanism including a DISA 52B01 sweep drive unit, DISA 55E40 traversing unit, and stepper motor.
- c. TSI 1076 rms voltmeter.
- d. MKS Baratron model 170 with a 1 Torr pressure transducer.
- e. TSI 1125 calibrator.
- f. DISA 55P05 boundary layer probe.
- g. Century OVA-128 organic vapor analyzer.

The first six items were primarily for the measurement and calibration of velocity. The organic vapor analyzer (OVA) and the DISA traversing system were used in the measurement of concentration profiles.
The wind tunnel speed was set by dynamic pressure measurements with the MKS Baratron. The velocity was calculated from Bernoulli's equation

\[ V_a = \sqrt{2 \left( \frac{P_a - P_i}{P_a} \right)} \]  

where \( P_a \) is the barometric pressure which in the present case is the same as the total pressure, and \( P_i \) is the tunnel wall static pressure at station \( i \). Since the MKS has a differential pressure transducer, \( P_a - P_i \) was measured directly. Experimentation indicated that velocities from this method at station 3 were closer to the hot-wire measurements than those from a Pitot-static probe. Table IV.11 is a list of transducer locations and the pan location relative to the test section entrance. A scale drawing of the test section with static pressure hole and hot-wire locations is shown in Figure IV.8. Also, the nondimensional pressure gradient for low over octane is presented in this figure for the test section.

The pressure gradient is defined as:

\[ \frac{1}{\rho} \frac{dp}{dx} = -C_p/\Delta x \]  

where the pressure coefficient, \( C_p \) is

\[ C_p = \frac{(P_{i+1} - P_i)}{\rho} \]  

\( P_i \) is the pressure at station \( i \), \( \rho \) is the dynamic pressure, \( \frac{1}{\rho} V_w^2/2 \), and \( \Delta x = x_{i+1} - x_i \). The physical properties which were not measured directly such as density and viscosity were computed by the methods in Appendix A from the measured temperatures and barometric pressure. Room air temperature and liquid surface temperature were measured with Type T thermocouples while barometric pressure was monitored with an aneroid barometer from Weathermeasure Corporation. The error in velocity from errors in temperature and barometric pressure was less than 0.5%.

The velocity profiles were measured with a TSI 1050 constant temperature anemometer and DISA 55P05 hot-wire probe. The hot-wire anemometer was calibrated with a TSI 1125 calibration jet. Voltages from the
TABLE IV.11 TRANSDUCER LOCATIONS

<table>
<thead>
<tr>
<th>Station (cm)</th>
<th>x (in)</th>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>274.3</td>
<td>108</td>
<td>No. 1 static pressure hole</td>
</tr>
<tr>
<td>302.3</td>
<td>119</td>
<td>Inside leading edge of pan</td>
</tr>
<tr>
<td>335.3</td>
<td>132</td>
<td>No. 2 static pressure hole</td>
</tr>
<tr>
<td>396.2</td>
<td>156</td>
<td>No. 3 static pressure hole</td>
</tr>
<tr>
<td>408.9</td>
<td>161</td>
<td>Hot-wire sensor</td>
</tr>
<tr>
<td>408.9</td>
<td>161</td>
<td>Pitot-static probe tip</td>
</tr>
<tr>
<td>408.9</td>
<td>161</td>
<td>Pan thermocouple</td>
</tr>
<tr>
<td>411.8</td>
<td>162.1</td>
<td>Liquid sampling probe tip</td>
</tr>
<tr>
<td>413.4</td>
<td>162.8</td>
<td>Gas sampling probe tip</td>
</tr>
<tr>
<td>415.3</td>
<td>165.5</td>
<td>DISA traversing mechanism guide tube</td>
</tr>
<tr>
<td>424.2</td>
<td>167</td>
<td>Inside trailing edge of pan</td>
</tr>
<tr>
<td>457.2</td>
<td>180</td>
<td>No. 4 static pressure hole</td>
</tr>
</tbody>
</table>
FIGURE IV.8 WIND TUNNEL PRESSURE GRADIENT MEASUREMENTS FOR FLOW OVER OCTANE(n)
anemometer were measured with a TSI 1076 voltmeter. King's law in the
following form was applied to the calibration data:

\[ E_b^2 = A + B V_w^n \tag{IV.17} \]

where A, B, and n are constants determined by linear regression analysis
and \( E_b \) is the bridge voltage. Usually the exponent n has a value of
\( 0.45 < n < 0.5 \). The exponent n was selected so that the correlation
coefficient returned in the linear regression analysis was a maximum. A
typical calibration curve is shown in Figure IV.9. The hot-wire was oper-
ated at 200°C which was below the ignition temperature of the chemicals
being tested. The relative turbulence intensity was computed from a linear
perturbation of Equation (IV.17)

\[ \frac{\sigma_u}{V_w} = 2 \sigma_e \frac{E_b}{[n(E_b^2 - A))]}, \tag{IV.18} \]

where \( \sigma_u \) is the rms or standard deviation of the velocity \( u \), and \( \sigma_e \)
is the measured rms voltage.

Concentration measurements were taken with a Century OVA-128 total
hydrocarbon analyzer which has a hydrogen flame ionization detector. The
OVA was calibrated for each chemical used. The calibration was of the form

\[ X = A X_0^n \tag{IV.19} \]

where X is the volume fraction in ppm (parts per million), \( X_0 \) is the
OVA measurement, and A and n are constants determined by linear re-
gression analysis. Table IV.12 is a table of calibration constants, and
Figure IV.10 is a typical calibration curve. The meter for the OVA was
analog with a linear range of 0 to 10 and a resolution of 0.1. The in-
strument included a scale factor of 1, 10, and 100 ppm, or it had a maxi-
mum range of 1000 ppm. For those measurements outside the range of the
OVA, a diluter was used which was also calibrated. The volume fraction,
\( X \) in Equation (IV.19) is related to the mass fraction, \( C \), in Equa-
tions (III.19) and (III.26) by
\[ E_b = A + BV_w^n \]

- \( A = 3.4777 \)
- \( B = 0.30234 \)
- \( n = 0.4358 \)

**FIGURE IV.9** TYPICAL CALIBRATION CURVE FOR DISA 55P05 BOUNDARY-LAYER PROBE WITH AN OPERATING TEMPERATURE OF 200°C. STRAIGHT LINE IS A LINEAR REGRESSION WITH A CORRELATION OF 3.999989
### Table IV.12 Calibration Constants for Century OVA-123 Organic Vapor Analyzer

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Date</th>
<th>Coefficient A</th>
<th>Exponent</th>
<th>Correlation Coefficient</th>
<th>Dilution Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl Acetate</td>
<td>07-16-82</td>
<td>1.276</td>
<td>0.9468</td>
<td>0.9992</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>09-07-82</td>
<td>1.082</td>
<td>1.004</td>
<td>0.9995</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>09-08-82</td>
<td>0.018</td>
<td>1.018</td>
<td>0.9996</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>09-08-82</td>
<td>1.302</td>
<td>0.9523</td>
<td>0.9987</td>
<td>11.5</td>
</tr>
<tr>
<td>Hexane</td>
<td>11-30-82</td>
<td>1.272</td>
<td>0.9366</td>
<td>0.9992</td>
<td>12.54</td>
</tr>
<tr>
<td>Hexanol</td>
<td>09-21-82</td>
<td>1.120</td>
<td>1.100</td>
<td>0.9974</td>
<td></td>
</tr>
<tr>
<td></td>
<td>02-24-83</td>
<td>1.037</td>
<td>1.078</td>
<td>0.9995</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>1.144</td>
<td>1.078</td>
<td>0.9967</td>
<td></td>
</tr>
<tr>
<td>Octane</td>
<td>07-08-82</td>
<td>0.684</td>
<td>0.9700</td>
<td>0.9946</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>10-05-82</td>
<td>1.097</td>
<td>0.9416</td>
<td>0.9978</td>
<td>11.43</td>
</tr>
<tr>
<td></td>
<td>02-24-83</td>
<td>0.8438</td>
<td>0.9946</td>
<td>0.9971</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-05-82 &amp; 02-24-83</td>
<td>1.015</td>
<td>0.9574</td>
<td>0.9971</td>
<td>11.43</td>
</tr>
<tr>
<td>Octanol</td>
<td>10-26-82 &amp; 12-03-82</td>
<td>1.593</td>
<td>0.8909</td>
<td>0.9793</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE IV.10 TYPICAL CALIBRATION CURVE OF CENTURY OVA-128 ORGANIC VAPOR ANALYZER FOR OCTANE(n). STRAIGHT LINE IS A LINEAR REGRESSION WITH A CORRELATION OF 0.9978
\[ X = \frac{C M_a}{M} \quad (IV.20) \]

where \( M_a \) is the molecular weight of air, and \( M \) the molecular weight of the chemical.

A schematic of the gas sampling system for the concentration profile measurements is shown in Figure IV.11. A gas sample was withdrawn from the wind tunnel through the sampling probe by a Metal Bellows Corp. pump. The flowrate was adjusted by a needle valve and measured by a calibrated Matheson rotameter. The sample gas was collected in two-liter plastic bags and analyzed with the OVA. The flowrate of the sampling system was adjusted to the local mean velocity on the basis of velocity profile measurements with the hot-wire anemometer. The vertical position for the concentration and velocity profile measurements was set by the DISA traversing system which has a resolution of 0.02 mm.

The gas sampling probe was designed and built specifically for this project. The probe consisted of three stainless-steel tubes with an outside diameter of 1.91 mm (0.075 in) and inside diameter of 1.36 mm (0.0535 in). The tubes were separated by 19.1 mm (0.75 in) horizontally with the entrances in the same plane. The three tubes were routed through a 6 mm (0.237 in) diameter stainless steel tube and manifolded by teflon tubing at the exit of the main probe shaft. The sampling tubes were bent so that their lengths between the probe tip and main shaft were the same and, consequently, so that the pressure drops were nearly the same.

IV.2.4 Wind Tunnel Tests: Dissolution

Theory. In the present program, only the model for dissolution on lakes and coastal waters was investigated. Measurement of mass transfer by the profile method was not feasible, however, because of the very thin concentration boundary layer in the water for "insoluble" chemicals. The concentration boundary layer thickness, from Shaw and Hanratty [36], is (for large Reynolds number and Schmidt number):

\[ \delta_z^* = \left( \frac{D_a}{\kappa} \frac{Sc}{Re} \right)^{-1} \quad (IV.21) \]
FIGURE IV.11 SCHEMATIC OF GAS SAMPLING SYSTEM FOR CONCENTRATION PROFILE MEASUREMENTS
where the Dalton number is given in Equation (111.34). In their experimental results $K = 0.0889$ and $n = 0.704$. As an estimate, the concentration boundary-layer thickness, $\delta_{C*}$, for $Sc = 1000$ is 1.46, or in physical units is 0.1076 mm (3 mils) on the basis of water boundary-layer measurements by Lin, et al. [45] where $\omega_\infty$ was 1.92 cm/s for a wind speed of 10 m/s and fetch of 6 m. Consequently, a successful verification with available instrumentation would be the detection of no chemical in the water within 6.4 mm of the free surface, the location of the first probe. Significant chemical in the water would indicate that another mechanism is more important than boundary layer processes in dissolution.

Wind Tunnel. Minor modifications were made to the chemical feed system of the evaporation tests. The feed system for the dissolution experiments uniformly dispensed chemical on the water surface upstream and withdrew the chemical at the downstream edge of the pan. This method of chemical dispersal on the water surface was selected after some experimentation. Other methods would have allowed dispersal without removal of the chemicals, but chemical would accumulate downstream and waves would grow. Also, more chemical would be required to cover the surface. Removal of the chemical downstream allowed a more uniform slick thickness through control of both the inflow and outflow, and consequently, the spill was modeled more accurately.

The chemical was dyed with a mixture of one part per 5,000 of the red dye from the spreading experiments. The dye served two purposes. First, the dye indicated when the surface was completely covered by the chemical, and second, the dye aided visually in the separation of the chemical from the water during recovery of the chemical at the downstream end of the pan.

Instrumentation. A liquid sampling probe was built from the same tubing as the gas sampling probe. The probe was a conventional rake arrangement of four tubes with their entrances in a vertical plane at 6.4 mm (0.25 inch) intervals, with the top probe positioned 6.4 mm below the free surface. Liquid samples of 8 cm$^3$ each were withdrawn through Teflon tubing by a 10 cm$^3$ glass hypodermic syringe. Samples were withdrawn at 15-minute intervals for one hour. Preliminary testing showed that the top probe had to be at least 6.4 cm below the surface in order to avoid surface disturbances.
The liquid samples were then analyzed for chemical concentration. The differences in solubilities of the chemicals tested required two analysis methods. Water samples with ethyl acetate and hexanol were analyzed with a Beckman Carbonaceous Analyzer (NDIR) which is a total organic carbon combustion-infrared device. The octane and hexane, whose solubilities are quite low, were analyzed by the microextraction method and a gas chromatograph.

IV.2.5 Wind-Wave Channel Tests: Dissolution and Evaporation

Wind-Wave Channel. Evaporation and dissolution experiments were performed in the wind-wave channel at Flow Industries, Inc., in Kent, Washington. The theory and experimental methods for these experiments were essentially the same as described in the previous two sections. The wind-wave channel consisted of a wave tank with dimensions of 9.1m length, 1.2m width, and 0.9m depth, and it included a mechanical wave maker. A wind tunnel of equal width was located above the wave tank with a variable height test section which was set at 65 cm for these experiments. The test station was 5.5m from the wind tunnel entrance. Additional details on the channel, its performance, and instrumentation are contained in Lin, et al. [45].

The chemical feed system was slightly different from that described in [45]. The system was originally designed as a once-through system for the chemical. It was modified so that chemical could be continuously fed through the system. A slight amount of dye was added to the chemical to make the water/chemical interface readily visible in the recovery tanks.

Instrumentation. The instrumentation for the wind-wave channel experiments was similar to that previously described. The liquid and gas sampling systems were the same; however, the liquid sampling probe was replaced by a larger rake. The rake consisted of six sampling tubes with 3.2mm (1/8 in.) outside diameter. The vertical spacing between tube center-lines was 25.4mm (1 in.).

All probes for the traverse in air were mounted on one traversing mechanism. The probes included the following:
a. Two TSI 1210 hot-wire probes (Tungsten T1.5 sensor)
b. Thermistor for air temperature
c. Pitot-static probe
d. Gas sampling probe

The hot-wire anemometer was a TSI 1054B. The water surface temperature was monitored with a thermistor. The flow of chemical onto the water surface was controlled and measured with a Dwyer rotameter. The tunnel speed and hot-wire calibration were determined by a Dwyer micromanometer and Pitot-static probe.

The wave heights were measured with a photodiode wave height gauge which consisted of the following components:

a. Reticon Model LC600V256-1 camera
b. Reticon RS605 Line Scan Controller
c. Spectra Physics 164 argon ion laser

The laser was operated at approximately 3 Watts of power, and the water was dyed with a fluorescent dye. Since only the water was illuminated, the wave heights were actually measured at the chemical/water interface. The resolution of the gauge for these experiments was 0.25 mm.

All data were processed with a digital data acquisition system and computer. The data provided included the mean and rms values in physical units of the following:

a. Velocities from two hot-wires
b. Air and water surface temperatures
c. Position of traversing mechanism, and
d. Wave height.

Approximately 30 seconds of data were averaged. All measurements but wave height were simultaneous. Since the wave height measurements were digital and the other measurements analog, two different software routines were required for the data acquisition. Plots of the data (signal vs. time) were also provided by the data acquisition system.
IV.3 Data Collection (Typical Results)

IV.3.1 Spreading Tests

Only a general overview of these experiments mainly based on flow visualization will be presented in this section. For detailed information about the results of each experiment, see Appendices A through E of the Test Data Volume of the Final Report.

Instantaneous Spills in Basin. The series of photographs labeled Figure IV.12 show a time lapse sequence of a 60 liter instantaneous spill of naphtha. As can be seen, the chemical spreads axisymmetrically from the spill point. The outer edge of the thick slick was very easy to distinguish at the beginning of the spill. Later, when the slick was considerably thinner, a thin slick began forming which made it more difficult to distinguish the edge of the thick slick as shown in Figure IV.13. At that point, the data collection was stopped. From the data obtained, a graph of slick diameter as a function of time was drawn as shown in Figure IV.14, for comparison with the computer model predictions.

These results are typical of the non-volatile instantaneous spills studied. The results for all of the non-volatile instantaneous spills in the basin are contained in Appendix A of the Test Data Volume of the Final Report.

Continuous Spills in Basin. The series of photographs labeled Figure IV.15 show a time lapse sequence of a continuous spill of naphtha at a spill rate of 0.95 liters/second. The slicks spread much the same as the instantaneous spills described above. The major difference was that a thin slick formed almost immediately on the outer edges of the slick. This made it more difficult to document the thick slick spreading rate. From the data obtained, a graph of slick diameter as a function of time was drawn, as shown in Figure IV.16, for comparison with the computer model predictions.
FIGURES IV.12 (a,b) 60-LITER NON-VOLATILE INSTANTANEOUS NAPHTHA SPILL
FIGURES IV.12 (c,d) 60-LITER NON-VOLATILE INSTANTANEOUS NAPHTHA SPILL
FIGURE IV.13 FINAL SPREADING STAGE OF AN INSTANTANEOUS SPILL
I.4-5 GO. LITER NON-VOLATILE
INSTANTANEOUS NAPHTHA SPILL

FIGURE IV.14 INCREASE OF SLICK SIZE WITH TIME
Figures IV.15 (a,b) 0.95 LITER/SECOND NON-VOLATILE CONTINUOUS NAPHTHA SPILL
FIGURES IV.15 (c,d) 0.95 LITER/SECOND NON-VOLATILE CONTINUOUS NAPHTHA SPILL
II.4-3 0.95 L/SEC NON-VOLATILE CONTINUOUS NAPHTHA SPILL

FIGURE IV.16 INCREASE OF SLICK SIZE WITH TIME
These results are typical of the non-volatile continuous spills studied. The results for all of the non-volatile continuous spills in the basin are contained in Appendix B of the Test Data Volume of the Final Report.

**Continuous Spills in Channel.** Figures IV.17 are photographs of the development of four different continuous spills of m-Xylene in the channel. The table below summarizes the flow conditions for the pictures in this figure.

<table>
<thead>
<tr>
<th>Flow Conditions</th>
<th>River Speed (cm/sec)</th>
<th>Discharge Flowrate (liter/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13.4</td>
<td>0.038</td>
</tr>
<tr>
<td>B</td>
<td>18.9</td>
<td>0.050</td>
</tr>
<tr>
<td>C</td>
<td>24.1</td>
<td>0.100</td>
</tr>
<tr>
<td>D</td>
<td>29.0</td>
<td>0.149</td>
</tr>
</tbody>
</table>

These river speed/discharge flowrate combinations were chosen to maximize the length of the channel over which spreading could occur without any influence of the walls. Data collection of this slick width downstream of the spill location was stopped when the thin slick hit the channel walls. The thin slick is indistinguishable in the photographs of Figure IV.17. From the data obtained, a graph of slick width vs. downstream distance was drawn for comparison with the computer model predictions. Figures IV.18 through IV.21 show these graphs for the four m-Xylene spills discussed above.

These results are typical of the continuous spills in the channel that were studied. The results for all of the continuous spills in the channel are contained in Appendix E of the Test Data Volume of the Final Report.
FIGURES IV.17 (A,B) CONTINUOUS SPILLS OF m-XYLENE IN A FLOWING RIVER
FIGURES IV.17 (C,D) CONTINUOUS spills of m-XYLENE IN A FLOWING RIVER

103
Current = 13.4 m/sec  
Chemical Discharge = 0.038 liter/sec

FIGURE IV.18 SLICK SPREADING OF m-XYLENE FOR FLOW CONDITION A
FIGURE IV.19 SLICK SPREADING OF m-XYLENE FOR FLOW CONDITION B

Current = 18.9 cm/sec
Chemical Discharge = 0.050 cm³/sec

Distance from centerline, meters

1.22 0.61 0 0.61 1.22

Downstream Distance, meters

1.83 2.44 3.05 3.66 4.27
Current = 24.1 cm/sec
Chemical Discharge = 0.100 cm³/sec

FIGURE IV.20 SLICK SPREADING OF m-XYLENE FOR FLOW CONDITION C
Current = 29.0 cm/sec  
Chemical Discharge = 0.149 cm³/sec

FIGURE IV.21 SLICK SPREADING OF m-XYLENE FOR FLOW CONDITION D
IV.3.2 Evaporation Tests

Velocity Profile Measurements. Since the friction velocity and boundary layer thickness were required for calculation of Dalton number in Equation (III.27), the velocity profiles were measured for model validation. The results of the velocity profile measurements are summarized in Table IV.13. The data in the table includes the wind velocity, friction velocity, friction coefficient, intercept, roughness parameter, the correlation coefficient for the linear regression, the average coefficient for the 1/7 power-law velocity profile, and the boundary layer thickness. The results are compared to those of a standard smooth flat plate. The boundary layer thickness was computed from the 1/7 power-law profile where \( u/V_w = 0.99 \).

Representative velocity profiles are presented in Figures IV.22 and IV.23 for the pan evaporation and wind-wave experiments, respectively. For the pan evaporation experiments, the surface velocity, \( U_s \), was assumed to be zero. In the wind-wave experiments, the surface velocity was assumed to be

\[
U_s/u_* = 0.55 \quad \text{(IV.22)}
\]

in accordance with the recommendation of Street, et al. [46]. Another possible method is from conservation of momentum across the air-water interface for a 1/7 power-law velocity profile. The result is

\[
V_w/U_s = (\rho/\rho_a)^{\frac{1}{7}} (u/v_a)^{\frac{1}{7}} \quad \text{(IV.23)}
\]

At standard pressure and a temperature of 20°C, the surface velocity is

\[
V_w/U_s = 30.96 \quad \text{(IV.24)}
\]

Either result is consistent with previous experiments in the wind-wave channel [45].

The velocity profiles were typical of flow over a smooth surface with some exceptions. The profiles over the mechanically driven wave.
<table>
<thead>
<tr>
<th>Surface</th>
<th>Facility</th>
<th>$V_W$ (cm/s)</th>
<th>$u_*$ (cm/s)</th>
<th>$10^3 C_f/2$</th>
<th>B</th>
<th>$z_0+$</th>
<th>Correlation Coefficient</th>
<th>$u_*/y_+^{1/7}$</th>
<th>$\delta_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>SwRI</td>
<td>446</td>
<td>23.6</td>
<td>2.782</td>
<td>3.96</td>
<td>0.20</td>
<td>0.9963</td>
<td>7.88</td>
<td>435</td>
</tr>
<tr>
<td>Hexanol</td>
<td>SwRI</td>
<td>387</td>
<td>15.2</td>
<td>1.548</td>
<td>8.54</td>
<td>0.033</td>
<td>0.9225</td>
<td>10.23</td>
<td>542</td>
</tr>
<tr>
<td>Hexanol/Flow Research</td>
<td>730</td>
<td>44.6</td>
<td>3.740</td>
<td>-6.67</td>
<td>14.4</td>
<td>0.9895</td>
<td>4.09</td>
<td>12,003</td>
<td></td>
</tr>
<tr>
<td>Octane</td>
<td>SwRI</td>
<td>195</td>
<td>10.5</td>
<td>2.913</td>
<td>3.85</td>
<td>0.21</td>
<td>0.9615</td>
<td>7.94</td>
<td>350</td>
</tr>
<tr>
<td>Octane/Flow Research</td>
<td>208</td>
<td>0.92</td>
<td>1.835</td>
<td>5.30</td>
<td>0.12</td>
<td>0.9801</td>
<td>8.59</td>
<td>862</td>
<td></td>
</tr>
<tr>
<td>*357</td>
<td>13.6</td>
<td>1.439</td>
<td>6.10</td>
<td>0.068</td>
<td>0.9981</td>
<td>9.36</td>
<td>1,082</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*519</td>
<td>20.8</td>
<td>1.605</td>
<td>3.97</td>
<td>0.20</td>
<td>0.9985</td>
<td>8.00</td>
<td>2,296</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*482</td>
<td>21.3</td>
<td>1.952</td>
<td>2.35</td>
<td>0.39</td>
<td>0.9904</td>
<td>7.33</td>
<td>2,098</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*729</td>
<td>28.1</td>
<td>1.489</td>
<td>4.97</td>
<td>0.14</td>
<td>0.9954</td>
<td>8.29</td>
<td>2,338</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*725</td>
<td>22.6</td>
<td>0.975</td>
<td>9.94</td>
<td>0.019</td>
<td>0.9490</td>
<td>10.24</td>
<td>2,410</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Monin and Yaglom [49]
(2) Hinze [50]
* Wavemaker
Figure IV.22 Velocity Profiles over Octane in Pan Evaporation Experiments
Figure IV.23 Velocity profiles for chemical slicks in flow research wind-wave channel. Filled symbols are with mechanical wave maker.
were anomalous. In particular, the flow at 725 cm/s with the wavemaker had an exceptionally low friction coefficient. The friction coefficient in this case is possibly in error from a wave induced velocity component.

In other cases, the friction velocities are also apparently low. For example, at 729 cm/s without the wavemaker, the friction velocity is 28.1 cm/s whereas Lin, et al. [45] reported 38 cm/s at a tunnel velocity of 7 m/s.

Another exception is the flow over hexanol at 730 cm/s in the wind-wave channel. Figure IV.24 is a plot of the friction coefficients of all experiments in comparison to a smooth surface. As the figure indicates, the friction coefficient over hexanol in the wind-wave channel was unusually high. However, this result, which implies flow over a rough surface, is also consistent with the wave height measurements and flow visualization experiments. The wave heights were increased in the flow over hexanol whereas the octane dampened the waves. This phenomenon is associated with the spreading coefficient of the chemical on water.

Wave Height Measurements and Slick Thickness. One of the objectives of the wind-wave experiments was to measure the effect of waves in mass transfer from evaporation. The results of the wave height measurements are summarized in Table IV.14. The interesting result in this table is a comparison of the rms wave heights for water, octane, and hexanol at 7.5 m/s for wind waves only. The octane dampens the waves while hexanol increases the wave height.

The wave heights in non-dimensional inner-scale variables are also included in Table IV.14. Both rms and mean wave heights are included in the table. The rms was measured, but the evaporation model, Equation (111.27), contains the mean wave height. According to Street [29], the mean and rms wave heights are related by

$$h_{m+} = (2\pi)^{\frac{1}{3}} h,$$

(IV.25)

The frequency and peak-to-peak amplitude of the mechanically-generated waves were 1.6 Hz and 3 cm, respectively.
\[ C_f/2 = (2.5 \ln \delta_+ + 5.1)^{-2} \]

**Figure IV.24** Skin friction coefficient measurements from profile method. Symbols with slash are for pure chemical while others are for slick on water, and closed symbols are for wave maker. Line is for smooth surface.
## TABLE IV.14 WAVE HEIGHT MEASUREMENTS

<table>
<thead>
<tr>
<th>Surface</th>
<th>$V_w$ (cm/s)</th>
<th>RMS Wave Height $n_+$ (cm)</th>
<th>$n_+$</th>
<th>$h_{m+}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane</td>
<td>208</td>
<td>0.01</td>
<td>0.54</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>342</td>
<td>0.01</td>
<td>0.86</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>* 482</td>
<td>0.916</td>
<td>128.</td>
<td>320.</td>
</tr>
<tr>
<td></td>
<td>519</td>
<td>0.0741</td>
<td>10.2</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>* 357</td>
<td>0.971</td>
<td>86.1</td>
<td>216.</td>
</tr>
<tr>
<td></td>
<td>729</td>
<td>0.0779</td>
<td>14.1</td>
<td>35.4</td>
</tr>
<tr>
<td>Octane</td>
<td>* 725</td>
<td>1.037</td>
<td>151.</td>
<td>379.</td>
</tr>
<tr>
<td>Hexanol</td>
<td>730</td>
<td>0.647</td>
<td>186.</td>
<td>467.</td>
</tr>
<tr>
<td>Water</td>
<td>* 760</td>
<td>1.53</td>
<td>421.</td>
<td>1055.</td>
</tr>
<tr>
<td>Water</td>
<td>760</td>
<td>0.558</td>
<td>153.</td>
<td>385.</td>
</tr>
</tbody>
</table>

* Wavemaker

(1) $h_{m+} = (2\pi)^{\frac{1}{2}} n_+$

(2) Estimated from Lin, et al. [45]
For the wind-wave experiments, slick thickness may be an important parameter in evaporation and dissolution. Slick thickness was estimated by conservation of mass from the following:

\[ h = \frac{Q}{(U_w w)} \]  

(IV.26)

where \( Q \) is the measured flowrate of the chemical onto the water surface, \( w \) is the tunnel width, and the surface velocity, \( U_w \), is estimated from Equation (IV.22) or (IV.24). The primary assumption in Equation (IV.26) is that the slick moves uniformly as slug flow. The average slick thickness with two different estimates of surface velocity is tabulated for all the experiments in Table IV.15.

Normally, both octane and hexanol have positive spreading coefficients. Consequently, they will continue to spread until they form a monolayer. However, in the case of hexanol, a thin layer spreads very rapidly and locally changes the surface tension of the water. Thus, the spreading coefficient of hexanol becomes negative, and hexanol forms lenses. The minimum thickness for an infinitely large slick is given by Equation (111.15). From this equation, the minimum thickness for a hexanol slick is 2 mm. Since the average thickness was estimated to be only 0.04 mm, only a small fraction of the surface was covered by lenses. The surface area covered by lenses could be estimated from [19] if an average lens diameter were assumed.

Slick thickness for these experiments can be controlled by the flowrate of the feed system. The flowrate of hexanol was less than the octane in these experiments because the flowrate was limited by the higher viscosity of the hexanol.

Evaporation Concentration Profiles. The results for the concentration measurements are summarized in Table IV.16. Typical concentration profiles are shown in Figures IV.25 and IV.26 for the pan evaporation experiments and wind-wave experiments, respectively. In general, the curves are relatively linear and yield reasonable values of the Dalton number. No trends have been discovered on the value of the intercept, \( B_c \).
TABLE IV.15 ESTIMATED AVERAGE SLICK THICKNESS FOR WIND-WAVE EXPERIMENTS

<table>
<thead>
<tr>
<th>Surface</th>
<th>$V_w$ (cm/s)</th>
<th>Chemical Flowrate (l/min)</th>
<th>$U_s(1)$ (cm/s)</th>
<th>$h$ (mm)</th>
<th>$U_s(2)$ (cm/s)</th>
<th>$h$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane</td>
<td>208</td>
<td>5.3</td>
<td>4.91</td>
<td>0.15</td>
<td>6.73</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>342</td>
<td>8.8</td>
<td>7.17</td>
<td>0.17</td>
<td>11.0</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>* 482</td>
<td>8.8</td>
<td>11.7</td>
<td>0.10</td>
<td>15.6</td>
<td>0.079</td>
</tr>
<tr>
<td></td>
<td>519</td>
<td>8.8</td>
<td>11.4</td>
<td>0.11</td>
<td>16.8</td>
<td>0.073</td>
</tr>
<tr>
<td></td>
<td>* 357</td>
<td>8.8</td>
<td>7.46</td>
<td>0.16</td>
<td>11.5</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>729</td>
<td>9.7</td>
<td>15.5</td>
<td>0.087</td>
<td>23.5</td>
<td>0.057</td>
</tr>
<tr>
<td>Octane</td>
<td>* 725</td>
<td>10.6</td>
<td>12.4</td>
<td>0.12</td>
<td>23.4</td>
<td>0.063</td>
</tr>
<tr>
<td>Hexanol</td>
<td>730</td>
<td>6.6</td>
<td>24.5</td>
<td>0.037</td>
<td>23.6</td>
<td>0.039</td>
</tr>
</tbody>
</table>

(1) $U_s/U_\ast = 0.55$
(2) $V_w/U_s = 30.96$
* Wavemaker
<table>
<thead>
<tr>
<th>Surface</th>
<th>Facility</th>
<th>$V_w$ (cm/s)</th>
<th>$S_C$</th>
<th>$-X_a$ (ppm)</th>
<th>$D_{a_0}$</th>
<th>$B_C$</th>
<th>$2_{OC^+}$</th>
<th>Correlation Coefficient</th>
<th>$10^3 D_{a_0}$</th>
<th>$D_{a_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl Acetate</td>
<td>SwRI</td>
<td>202</td>
<td>1.82</td>
<td>1856</td>
<td>0.0253</td>
<td>27.1</td>
<td>2.86 x 10^{-6}</td>
<td>0.9362</td>
<td>1.853</td>
<td>0.0343</td>
</tr>
<tr>
<td></td>
<td></td>
<td>202</td>
<td>1.82</td>
<td>2072</td>
<td>0.0282</td>
<td>23.4</td>
<td>1.65 x 10^{-5}</td>
<td>0.9886</td>
<td>1.765</td>
<td>0.0327</td>
</tr>
<tr>
<td></td>
<td></td>
<td>301</td>
<td>1.82</td>
<td>1924</td>
<td>0.0287</td>
<td>22.1</td>
<td>3.02 x 10^{-5}</td>
<td>0.9945</td>
<td>1.944</td>
<td>0.0405</td>
</tr>
<tr>
<td></td>
<td></td>
<td>403</td>
<td>1.82</td>
<td>1512</td>
<td>0.0244</td>
<td>27.2</td>
<td>2.71 x 10^{-6}</td>
<td>0.9918</td>
<td>2.000</td>
<td>0.0394</td>
</tr>
<tr>
<td></td>
<td></td>
<td>501</td>
<td>1.82</td>
<td>1815</td>
<td>0.0321</td>
<td>17.4</td>
<td>2.80 x 10^{-4}</td>
<td>0.9958</td>
<td>1.994</td>
<td>0.0410</td>
</tr>
<tr>
<td>Hexane</td>
<td></td>
<td>203</td>
<td>2.16</td>
<td>2941</td>
<td>0.0290</td>
<td>22.7</td>
<td>2.28 x 10^{-5}</td>
<td>0.9864</td>
<td>3.407</td>
<td>0.0631</td>
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<tr>
<td></td>
<td></td>
<td>302</td>
<td>2.16</td>
<td>4517</td>
<td>0.0495</td>
<td>8.28</td>
<td>2.03 x 10^{-2}</td>
<td>0.9750</td>
<td>2.308</td>
<td>0.0481</td>
</tr>
<tr>
<td></td>
<td></td>
<td>403</td>
<td>2.16</td>
<td>3495</td>
<td>0.0417</td>
<td>10.73</td>
<td>6.42 x 10^{-3}</td>
<td>0.9941</td>
<td>2.374</td>
<td>0.0467</td>
</tr>
<tr>
<td></td>
<td></td>
<td>498</td>
<td>2.16</td>
<td>3258</td>
<td>0.0468</td>
<td>7.67</td>
<td>2.70 x 10^{-2}</td>
<td>0.9953</td>
<td>2.443</td>
<td>0.0502</td>
</tr>
<tr>
<td>Hexanol</td>
<td></td>
<td>201</td>
<td>2.19</td>
<td>34.2</td>
<td>0.0348</td>
<td>16.5</td>
<td>4.28 x 10^{-4}</td>
<td>0.9381</td>
<td>1.521</td>
<td>0.0282</td>
</tr>
<tr>
<td></td>
<td></td>
<td>303</td>
<td>2.19</td>
<td>47.7</td>
<td>0.0415</td>
<td>11.7</td>
<td>4.03 x 10^{-3}</td>
<td>0.9755</td>
<td>1.403</td>
<td>0.0293</td>
</tr>
<tr>
<td></td>
<td></td>
<td>402</td>
<td>2.19</td>
<td>39.4</td>
<td>0.0407</td>
<td>11.9</td>
<td>3.69 x 10^{-2}</td>
<td>0.9959</td>
<td>1.946</td>
<td>0.0383</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>2.19</td>
<td>63.9</td>
<td>0.0655</td>
<td>2.34</td>
<td>0.333</td>
<td>0.9530</td>
<td>2.418</td>
<td>0.0497</td>
</tr>
<tr>
<td>Hexanol/Water</td>
<td>Flow</td>
<td>730</td>
<td>2.19</td>
<td>12.6</td>
<td>0.0177</td>
<td>38.6</td>
<td>1.27 x 10^{-8}</td>
<td>0.9750</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Octane</td>
<td>SwRI</td>
<td>200</td>
<td>2.61</td>
<td>794.</td>
<td>0.0463</td>
<td>9.95</td>
<td>9.27 x 10^{-3}</td>
<td>0.9864</td>
<td>1.561</td>
<td>0.0299</td>
</tr>
<tr>
<td></td>
<td></td>
<td>302</td>
<td>2.61</td>
<td>654.</td>
<td>0.0451</td>
<td>9.71</td>
<td>1.04 x 10^{-2}</td>
<td>0.9913</td>
<td>1.670</td>
<td>0.0350</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400</td>
<td>2.61</td>
<td>602.</td>
<td>0.0497</td>
<td>7.52</td>
<td>2.90 x 10^{-2}</td>
<td>0.9892</td>
<td>1.782</td>
<td>0.0351</td>
</tr>
<tr>
<td></td>
<td></td>
<td>501</td>
<td>2.61</td>
<td>432.</td>
<td>0.0336</td>
<td>16.0</td>
<td>5.46 x 10^{-4}</td>
<td>0.9909</td>
<td>2.312</td>
<td>0.0475</td>
</tr>
<tr>
<td></td>
<td></td>
<td>501</td>
<td>2.61</td>
<td>468.</td>
<td>0.0352</td>
<td>14.7</td>
<td>1.33 x 10^{-6}</td>
<td>0.9896</td>
<td>2.243</td>
<td>0.0460</td>
</tr>
<tr>
<td>Octane/Water</td>
<td>Flow</td>
<td>342</td>
<td>2.60</td>
<td>219</td>
<td>0.0219</td>
<td>31.2</td>
<td>4.28 x 10^{-7}</td>
<td>0.9947</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>357</td>
<td>2.60</td>
<td>222</td>
<td>0.0164</td>
<td>44.7</td>
<td>7.33 x 10^{-10}</td>
<td>0.9742</td>
<td>1.949</td>
<td>0.0400</td>
</tr>
<tr>
<td></td>
<td>SwRI</td>
<td>501</td>
<td>2.60</td>
<td>361</td>
<td>0.0296</td>
<td>20.6</td>
<td>6.06 x 10^{-5}</td>
<td>0.9897</td>
<td>1.949</td>
<td>0.0400</td>
</tr>
<tr>
<td></td>
<td>Flow</td>
<td>520</td>
<td>2.60</td>
<td>290</td>
<td>0.0213</td>
<td>30.9</td>
<td>4.85 x 10^{-7}</td>
<td>0.9969</td>
<td>1.949</td>
<td>0.0400</td>
</tr>
<tr>
<td></td>
<td>Research</td>
<td>482</td>
<td>2.60</td>
<td>232</td>
<td>0.0228</td>
<td>27.0</td>
<td>3.02 x 10^{-6}</td>
<td>0.9975</td>
<td>1.949</td>
<td>0.0400</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>729</td>
<td>2.60</td>
<td>225</td>
<td>0.0157</td>
<td>46.7</td>
<td>2.80 x 10^{-10}</td>
<td>0.9950</td>
<td>1.949</td>
<td>0.0400</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>725</td>
<td>2.61</td>
<td>206</td>
<td>0.0150</td>
<td>50.2</td>
<td>5.54 x 10^{-11}</td>
<td>0.9778</td>
<td>1.949</td>
<td>0.0400</td>
</tr>
<tr>
<td>Octanol</td>
<td>SwRI</td>
<td>202</td>
<td>2.36</td>
<td>1.67</td>
<td>0.0149</td>
<td>52.3</td>
<td>2.62 x 10^{-11}</td>
<td>0.8569</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>301</td>
<td>2.36</td>
<td>2.70</td>
<td>0.0240</td>
<td>29.0</td>
<td>7.11 x 10^{-6}</td>
<td>0.9848</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400</td>
<td>2.36</td>
<td>1.68</td>
<td>0.0143</td>
<td>55.2</td>
<td>5.21 x 10^{-12}</td>
<td>0.8176</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>2.36</td>
<td>2.36</td>
<td>0.0200</td>
<td>35.1</td>
<td>3.64 x 10^{-8}</td>
<td>0.9705</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure IV.26 Concentration profiles for wind-wave channel experiments. Closed symbols are for wavemaker.
The quality of the data was checked through repetition of the experiments. One such check is the two concentration profiles for a wind speed of 5 m/s. Although the repeat data are not within the error bars of the measurement, the data are reasonably close. The error bars are ±2σ, or 20-to-one odds, and the standard deviation of the concentration measurements was established by an average of twenty consecutive measurements at one location. According to Moffat [47], this procedure will determine the accuracy of the standard deviation within ±5%. The standard deviation was measured to be 8% of the mean concentration of octane at two locations, one in the boundary layer and one at the downstream sampling station.

Values of the Dalton number for all pan evaporation experiments are shown in Figure IV.27 in comparison to the theories of Street [29] and Yaglom and Kader [28] for smooth flow. This figure indicates that Schmidt number effects are not discernible in these experiments. Also, no relationship can be identified between the results of the two methods of mass transfer measurement; however, in most cases the results are the same within experimental error.

The results for octane in the pan evaporation experiments are presented in Figure IV.28. The primary purpose of this figure is to indicate the magnitude of uncertainty in the measurements. The error bars are again for ±2σ. The uncertainty for the profile measurements was determined from the standard deviation of the slope in the linear regression analysis. The uncertainty for the downstream concentration measurement was computed from an average of 20 bag samples. The error bars for the two measurements of Dalton number usually overlap. Also, the error bars are smaller for the more volatile chemicals such as ethyl acetate, and larger for the less volatile such as hexanol and octanol. The results for the octane on water experiments are comparable to the pure octane experiments.

Dalton numbers from the the two test facilities are compared in Figure IV.29 for the profile method. The uncertainty in the wind-wave experiments tends to be less, and the Dalton numbers are smaller. The lower Dalton numbers may be associated with slick thickness. The slick thickness of octane on water for the pan evaporation experiments was probably much thicker than in the wind-wave experiments. Since the Dalton number of hexanol is similar to that of octane, the water surface must
### Chemical Schmidt Number

- Ethyl Acetate: 1.82
- Hexanol: 2.19
- Octane: 2.61
- Octanol: 2.36
- Hexane: 2.15

**Figure IV.27** Comparison of Dalton numbers for various chemicals in PAN evaporation experiments. Closed symbols are for profile method; open symbols are from tunnel exhaust measurements; and symbols with slash are chemical on water experiments.

![Graph depicting inner-scale boundary layer thickness](image)
**Figure IV.28** Dalton Number with 2σ error bars for octane in pan evaporation experiments. Solid symbols are from profile method, and open symbols from tunnel exhaust concentration measurements. Symbols with slash are for octane on water experiments.
**Figure IV.29** Comparison of Dalton numbers for pan evaporation and wind-wave experiments. Closed symbols are for wavemaker, and symbols with horizontal slash are pure chemicals.
have been covered in a thin film during lens formation; otherwise, the Dalton number would have been much smaller.

The effect of roughness on Dalton number is emphasized in Figure IV.30. The Dalton number is plotted as a function of wave height for the experimental data and for the theories of Street [29] and Yaglom and Kader [28], in which $\delta_+ = 2000$ and $Sc = 2.61$ were used in Equation (111.27). The data are consistent with the hypothesis that mass transfer will diminish in flows over rough surfaces.

During the pan evaporation experiments, substantial cooling occurred. The liquid temperature attained steady state before data acquisition. The liquid surface temperature was used in the calculation of the saturation concentration. The temperature of the chemicals tested as a function of wind speed is presented in Figure IV.31. This cooling has two important effects: boundary layer stabilization and errors in velocity for the hot-wire. In the concentration calculations for these experiments, the friction velocity from the velocity measurements over octane were used. Cooling was not detected in the wind-wave experiments.

IV.3.3 Spreading and Evaporation Tests in Basin

The procedures used for the spreading and evaporation tests in the basin were similar to the non-volatile spreading tests in the basin discussed earlier in Section IV.3.1. These tests, which included evaporation, differed from the non-volatile tests in two ways:

1) Since a wind was necessary for evaporation, the entire slick tended to move with the wind while spreading. Although the slicks stayed relatively symmetric, they no longer were centered in the basin, and special treatment was necessary to determine the average slick diameters over time.

2) The evaporation of the chemicals caused the outer edges of the slick to form irregular fingers rather than being smooth. Estimation of each average radii was necessary during the data collection to collect meaningful slick diameter data.
Figure IV.30: Dalton number as a function of wave height. Lines are theory for $\delta^+=2000$ and $Sc=2.61$. Closed symbols are for mechanical wave.
FIGURE IV.31 STEADY STATE LIQUID SURFACE TEMPERATURE FOR VARIOUS CHEMICALS FROM EVAPORATIVE COOLING IN PAN EVAPORATION EXPERIMENTS
The data collected for the spreading and evaporation tests in the basin were graphed in the form of average slick diameter as a function of time. The results for all of the volatile instantaneous spills are contained in Appendix C of the Test Data Volume of the Final Report. The results for all of the volatile continuous spills are contained in Appendix D of the Test Data Volume.

IV.3.4 Dissolution Tests

Wind Tunnel. Four chemicals (ethyl acetate, hexane, hexanol, and octane) were tested for dissolution in water in the wind tunnel as a function of wind speed. The measured solubilities are listed in Table IV.17.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Measured Solubility (ppm)</th>
<th>Literature Solubility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl Acetate</td>
<td>64,387</td>
<td>87,000</td>
</tr>
<tr>
<td>Hexane</td>
<td>7</td>
<td>9.5</td>
</tr>
<tr>
<td>Hexanol</td>
<td>6,149</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>6,305</td>
<td>6,305</td>
</tr>
<tr>
<td>Octane</td>
<td>2</td>
<td>0.43 - 0.88</td>
</tr>
</tbody>
</table>

in comparison to values from the literature. The solubilities of hexane and octane were much lower than that listed in Appendix A; however, they are in agreement with those reported by Mackay and Shiu [48]. The results of the dissolution tests are summarized in Table IV.18. Since the concentration profiles were fairly uniform, only an average value (over the 31.7 mm depth of the probe) is presented for each time interval. Octane and hexane were virtually insoluble. A maximum of one percent of the solubility limit for octane was measured in a 60-minute period while 15% was the maximum for hexane. Dissolution rate was a strong function of wind speed for ethyl acetate. Ethyl acetate reached 100% of its solubility in 60 minutes at 5 m/s while hexanol attained 77% saturation under the same conditions.
### TABLE IV.18 RESULTS OF DISSOLUTION TESTS IN SwRI WIND TUNNEL

Average of 4 Concentration Measurements Over a Depth of 25 to 30 mm.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>( V_w ) (m/s)</th>
<th>Saturation (%)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl Acetate</td>
<td>2</td>
<td>20.1</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>29.7</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>38.5</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>44.2</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>46.0</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>72.0</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>89.3</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>100.0</td>
<td>60</td>
</tr>
<tr>
<td>Hexane</td>
<td>5</td>
<td>5.7</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.6</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>14.6</td>
<td>60</td>
</tr>
<tr>
<td>Hexanol</td>
<td>2</td>
<td>38.2</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>58.9</td>
<td>30</td>
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<tr>
<td></td>
<td>2</td>
<td>66.4</td>
<td>45</td>
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<tr>
<td></td>
<td>2</td>
<td>65.7</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>42.5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>62.0</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>68.8</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>77.3</td>
<td>60</td>
</tr>
<tr>
<td>Octane</td>
<td>5</td>
<td>0.7</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.3</td>
<td>30</td>
</tr>
<tr>
<td>Octane</td>
<td>5</td>
<td>0.4</td>
<td>45</td>
</tr>
</tbody>
</table>
Wind-Wave Channel. The more interesting dissolution results were from the wind-wave channel. Again, octane was essentially insoluble, but the hexanol was uniformly dispersed in the upper layer of water. The concentration profiles are shown in Figure IV.32 for a wind speed of 7.5 m/s and with mechanical waves. The profiles were averaged and plotted as a function of time in Figure IV.33. The difference in concentration with its saturated value decays in time like a diffusion process. The time constant is 0.0164 min$^{-1}$.

The dissolution process was investigated further by flow visualization. Sufficient dye was added to the hexanol so that it was readily visible on the water surface. Hexanol lenses formed on the surface with diameters of approximately 5 mm. Hexanol droplets were dispersed into the water by wind waves. Neither mechanical waves nor breaking waves were required for the droplet dispersion. At 7.5 m/s, the drops were dispersed to a depth of 10 to 15 cm. In contrast, the octane formed a uniform sheet on the water surface, and no droplets were formed.
FIGURE IV.32 CONCENTRATION PROFILES OF HEXANOL IN WATER AT
7.5 m/s WIND SPEED WITH A WAVE MAKER
Figure IV.33 Average concentration of hexanol in water to a depth of 17.6 cm at 7.5 m/s wind speed with a hawkmaker

\[ e^{-ax} \]

\[ a = 0.01641 \text{ min}^{-1} \]

\[ \sigma_a = 9.50 \times 10^{-4} \]
V. COMPARISON OF MODELS AND TESTS

V.1 Spreading Models

The tests described in Section IV.3.1 are sufficient to establish
(1) the empirical constants \( K_{10}, K_{20}, K_{11}, \) and \( K_{21} \) in the spreading models
for instantaneous and continuous spills in open water without a current, and
(2) the empirical constants \( K_{12} \) and \( K_{22} \) in the spreading model of continu-
ous spills in open water with a current. Although the empirical constants
in the channel models cannot be established directly by any of the tests,
their values can be inferred from the constants that can be established.
According to the model derivation presented in Section III.2.4, for example,
the lateral spreading of a slick formed by a continuous spill in a current
is identical with the one-dimensional spreading of an instantaneous spill
in a channel without a current; therefore, it is reasonable to assume that
\( C_{10} = K_{12} \) and \( C_{20} = K_{22} \). In addition, as is shown below, there is little
difference between the constants for instantaneous and continuous spills in
open water without a current; it is reasonable to expect the same kind of
relations for spills in a channel, so \( C_{11} \approx C_{10} \) (= \( K_{12} \)) and \( C_{22} \approx C_{20} \)
(= \( K_{22} \)). Finally, if there is a current in a channel, the downstream
spreading of the slick from a continuous spill is mostly due to the current;
thus, there can be little error involved in assuming that \( C_{12} = C_{10} \) and
\( C_{22} = C_{20} \). With these physically reasonable assumptions, all the empirical
constants in the spreading models can be established by the test data.

After a portion of the test data is used to determine the empirical
constants, the rest of the test data is used to verify the models.

Instantaneous Spill in Open Water (Negligible Evaporation). Typical
data (from Test I.2.4) are shown in Figure V.1, in the form of the logarithm
of the observed spill diameter plotted against the logarithm of the elapsed
time. This form of plot is convenient to reveal a power-law type of depen-
dency of the diameter on the time, as expected from Equations (III.3) and
(III.5). It is evident that the data points do fall naturally on two
straight lines, whose slopes are, to within the accuracy of the data measure-
ments, equal to the theoretically-predicted values of 0.50 and 0.25 for
gravity-inertial and gravity-viscous spreading. The fundamental assumptions
Figure V.1. Spreading Regimes for Instantaneous Spill Test 1.2-4

40 LITER SPILL
INSTANTANEOUS KEROSENE
s.g. = 0.795
of the model are therefore confirmed. (It ought to be noted that mass loss due to evaporation and dissolution is negligible for this chemical and test condition; hence, Equations (III.3) and (III.5) are applicable, rather than the more complicated version of the model given in Table III.2.) The time of transition from gravity-inertial to gravity-viscous spreading in Figure V.1 and the slick diameter at that time are used to compute the empirical constants; the result is that $K_{10} = 1.53$ and $K_{20} = 1.21$. Both constants are of order unity as expected. Previous semi-analytical estimates gave $K_{10} = 1.14$ and $K_{20} = 0.98$ [7]. The present values are slightly larger than the previous estimates but the ratio $K_{20}/K_{11}$ is about the same for both.

Figures V.2 through V.4 compare predictions of the model with $K_{10} = 1.53$ and $K_{20} = 1.21$ to test results for a variety of spill sizes and chemical densities. (Again, the evaporative loss of mass from the slick is negligible, so Equations (III.3) and (III.5) can be applied directly.) The predictions match the data very well, especially for the larger spills where any influence of a lack of true "instantaneous" initial conditions is small.

Continuous Spill in Open Water Without a Current (Negligible Evaporation). The test data from a typical test (Test II.4.4) are plotted in log-log form in Figure V.5. Just as for the instantaneous spills, the data points fall on two straight lines whose slopes are in agreement with theory. (Mass loss from the slick is negligible, also as before.) From the observed transition time and diameter, the computed empirical constants are $K_{11} = 1.24$ and $K_{21} = 1.09$. There are no previous data or analyses to which these values can be compared.

Figures V.6 through V.9 show comparisons of the revised model to tests with a variety of discharge rates and chemical densities. The predictions overall match the data well, although the comparison for the hexanol spill shown in Figure V.8 is not good near the end of the discharge period. (In many of the tests, the behavior of hexanol was noticeably different from that of the other chemicals. Although the reasons for the differences could not be isolated, it is believed that the large spreading coefficient of hexanol
Figure V.2 Comparison of Model and Test for Instantaneous Spill Test 1.1-2

10 LITER SPILL
INSTANTANEOUS
OCTANE
s.g. = 0.703

GRAVITY-INERTIAL AND
GRAVITY-VISCOUS
MATCHING POINT

SLICK DIAMETER, METERS

TIME, SECONDS

Model
Figure V.3. Comparison of Model and Test for Instantaneous Spill Test 1.3-3
Figure V.4 Comparison of Model and Test for Instantaneous Spill Test (5-4)
Figure V.5. Spreading Regimes for Continuous Spill Test II.4-4
Figure V.6 Comparison of Model and Test for Continuous Spill Test II.5-1
Figure V.7 Comparison of Model and Test for Continuous Spill Test II.Z-1
Figure V.8  Comparison of Model and Test for Continuous Spill Test II.3-2

0.82 LITER SPILL
CONTINUOUS
HEXANOL
s.g. = 0.819

MODEL

GRAVITY-INERTIAL
AND GRAVITY-VISCOUS
MATCHING POINT

TIME, SECONDS

SPILL DIAMETER, METERS
Figure V.9 Comparison of Model and Test for Continuous Spill Test II.1-4
caused a rapid growth of the thin slick and a subsequent change of the surface spreading properties in the water ahead of the thick slick. There was some tendency noted for hexanol to form lenses in the small-scale spreading tests.)

Continuous Spill in Open Water With a Current (Negligible Evaporation). Although these tests were conducted in a channel, data were measured only during the time when the thick slick was still well away from the channel walls. The test data therefore correspond to a discharge in open water with a current.

The results of a typical test (Test V.1.4) are shown in log-log form in Figure V.10. Once again, the test data points fall on two straight lines having the theoretically-predicted slopes for gravity-inertial and gravity-viscous spreading when mass losses are negligible. Because there was somewhat more scatter in the data from test-to-test than for the open-water, zero-current tests, the data from two tests were used to establish the empirical constants in the spreading model. The best fit to the data gives $K_{12} = 2.37$ and $K_{22} = 3.65$. As mentioned previously, the empirical constants for the one-dimensional spreading of an instantaneous spill are theoretically identical to $K_{12} = K_{22}$. Previous estimates of the constants for one-dimensional spreading of instantaneous spills are $C_{10} = 1.39$ to $1.50$ and $C_{20} = 1.39$ to $1.50$ [7]. The present constants are thus about twice as large as the previous estimates, according to this idea of similarity between the two forms of spreading. The previous estimates, which are based on semi-analytical theories and small-scale test results, may be in error; on the other hand, the two types of spreading may be qualitatively similar, but require different constants.

Figures V.11 through V.14 show comparisons of the revised model to test results for a variety of discharge rates, chemical densities, and currents. The comparisons are sufficiently close to verify the model, although not quite as close as for the tests conducted in the large basin. The slightly poorer correlation is perhaps not surprising considering the scatter in the data inherent in measuring slick widths from video recordings.
Figure V.10  Spreading Regimes for Continuous-Spill-In-A-Current Test V.1-4
Figure V.12 Comparison of Model and Test for Continuous-Spill-in-a-Current Test V.3-2
Figure V.13 Comparison of Model and Test for Continuous-Spill-in-a-Current Test V.4-3
0.15 LITER/SEC SPILL
CONTINUOUS IN CURRENT
M-XYLENE s.g. = 0.864
U_T = 0.29 M/SEC

Figure V.14 Comparison of Model and Test for Continuous-Spill-in-a-Current Test V.5-4
V.2  Evaporation Rate Model

The proposed evaporation model appears to be adequate for the present application without any changes. These experiments are probably the first where mass transfer of a hydrocarbon is measured by the profile method. The differences between theory and experiment are likely within the uncertainties of the experimental methods. In future experiments, the inflow and outflow of chemical from the water surface should be measured, and the effects of slick thickness evaluated. Also, the influence of spreading coefficient on waves should be evaluated since such roughness effects are coupled with mass transfer.

V.3  Dissolution Rate Model

The boundary layer model suggested for dissolution may be adequate for certain classes of highly insoluble hydrocarbons such as hexane and octane. For other chemicals such as hexanol, droplet dispersion in the water may be the dominant mechanism for dissolution, and breaking waves are not required necessarily for droplet dispersion. No models are currently available which adequately describe such a mechanism. Probably the interfacial tension of the chemical with water is an important physical property.

V.4  Spreading Models With Evaporation

As discussed in Section V.1, spreading tests with non-volatile chemicals established the empirical constants in the spreading models, and the wind tunnel and wind-wave tunnel tests discussed in Section V.2 established the empirical constants in the evaporative mass-transfer coefficient correlation. In this section, the effects of spreading and evaporation are combined, and the model predictions are compared to tests of instantaneous and continuous spills of volatile chemicals in the large basin. Spreading tests that adequately demonstrate the effects of evaporation are difficult to conduct since the high wind needed to cause significant evaporation also tends to move the slick to the boundary of the basin rapidly. The wind also distorts the shape of the slick so that it is more difficult to determine the slick area and the average diameter than it is for tests with little or no wind.
Figure V.15 shows a comparison of the data for a large spill of pentane, the most volatile of the test chemicals, to the prediction of the model with evaporation included, as well as to predictions with the evaporation suppressed by setting the wind speed to zero. Although the model fits the data to within the scatter in the tests that were used to establish the empirical spreading coefficients, the comparison is not as close as the typical comparison with non-volatile chemicals. This lack of good comparison is not believed to be a deficiency in the model but, as mentioned above, due to the difficulty in computing an accurate average diameter for a slick that moved a significant distance away from the source during the test.

Figure V.16 shows a typical comparison of model and data for a continuous spill. The spreading model for these test conditions falls into the exceptional category discussed previously in Section III.2.4, namely, the case where $U_T$ is small in comparison to the gravitationally-induced spreading velocity. The model assumes a triangular shape for the slick when $U_T > 0$ (no matter how small $U_T$ is), although the observed slick was elliptical and surrounded the source rather than being totally downwind of it. Thus, a first estimate of the spill size as a function of time was made by setting the wind speed equal to zero in order to predict a radial spreading. Although the model then matches the observed shape very well, evaporative losses are not predicted since the assumed wind speed is zero. Thus, to estimate the mass lost by evaporation, the model of an instantaneous spill of the same total volume was exercised twice, once with the true wind speed and once with the wind speed set equal to zero. The difference in evaporative losses and slick diameters were then applied to the continuous spill results. The comparison to the data is not quite so close as was obtained in general with the non-volatile chemical tests, but in this case the model over-predicts the results.

Altogether, it is concluded that the models adequately predict the effects of evaporation on the spreading of instantaneous and continuous spills.
Figure V.15  Comparison of Model and Test for Instantaneous
Volatile Spill Test III.1-3

MODEL WITHOUT EVAPORATION

MODEL WITH EVAPORATION

40 LITER SPILL
INSTANTANEOUS
PENTANE
s.g. = 0.626
WIND SPEED = 1.83 M/SEC

SLICK DIAMETER, METERS

0 4 8 12 16 20 24 28
TIME, SECONDS
Figure V.16 Comparison of Model and Test for Continuous Volatile Spill Test IV.1-4
VI. DEMONSTRATION CASES

The input and output data for five different examples of the computerized models are presented in this section. Table VI.1 gives a brief description of each of the examples. They show most of the features of the models and were selected to highlight potential difficulties in interpreting the computed results.

Table VI.2a is an exact copy of the user "prompts", the input data, and the input printout of Demonstration Case No. 1 as they would appear on a terminal screen. The data following each ? are the input supplied by the user. Most of the required input is self-explanatory. The "time increment" requested at the fourth prompt is the integration time step; a value of 1.0 second is suggested and has been found to be satisfactory for spills of practical size and duration, but here the spill is quite small so a shorter time step is used. The "run time" requested at the fifth prompt is the maximum length of time that the slick motion will be followed; the computations will cease at this time unless one of the other termination criteria is met first. (The criteria are: slick has evaporated and/or dissolved to zero thickness; the thickness of the thick slick is less than the allowed value given as input; or the slick has reached a lake boundary or a coast.) The "minimum thickness of thick slick" requested at the sixth prompt is the user's estimate of the thickness below which the thick slick begins to spread predominantly in the surface tension-viscous mode (i.e., as a thin slick); computations cease when the thickness falls below the input value, and a notification is printed in the output. The present experiments indicate that 0.0001/meters is an appropriate value for this thickness. The "thickness of thin slick" requested is normally the same as the minimum allowed value of the thick slick thickness although the equality is not specifically required. Later in the input, the requested wind direction is referenced to the positive x-axis. The last input, the printout time step, is the time duration between printouts of the results; only forty printouts are allowed, so the user should make sure that the ratio of run time to printout time step is not larger than forty.
<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>Type of Spill</th>
<th>Waterbody Description</th>
<th>Wind and Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pentane</td>
<td>Instantaneous $V_0 = 0.04 \text{ m}^3$</td>
<td>Circular Lake $R = 20\text{ m}; \text{ depth} = 0.3\text{ m} \quad U_C = 0$</td>
<td>$V_W = 1.83 \text{ m/s}$ Wave height = 0.01m</td>
</tr>
<tr>
<td>2. Pentane</td>
<td>Continuous $\dot{m}/\rho_0 = 0.001 \text{ m}^3/\text{s}$ for 60 sec.</td>
<td>Circular Lake $R = 20\text{ m}; \text{ depth} = 0.3\text{ m} \quad U_C = 0$</td>
<td>$V_W = 1.94 \text{ m/s}$ Wave height = 0.01m</td>
</tr>
<tr>
<td>3. Octane</td>
<td>Continuous $\dot{m}/\rho_0 = 0.0333 \text{ m}^3/\text{s}$ for 30 minutes</td>
<td>Circular Lake $R = 20,000\text{ m}; \text{ depth} = 100\text{ m} \quad U_C = 0.51 \text{ m/s}$</td>
<td>$V_W = 3.0 \text{ m/s}$ at 19.7° Wave height = 0.5m</td>
</tr>
<tr>
<td>4. Octane</td>
<td>Continuous $\dot{m}/\rho_0 = 0.1 \text{ m}^3/\text{s}$ for 60 minutes</td>
<td>Channel $W = 50\text{ m}; \text{ depth} = 10\text{ m} \quad U_C = 1.0 \text{ m/s}$</td>
<td>$V_W = 3 \text{ m/s}$ at 135°</td>
</tr>
<tr>
<td>5. Octane</td>
<td>Continuous $\dot{m}/\rho_0 = 0.05 \text{ m}^3/\text{s}$ for 60 minutes</td>
<td>Irregularly-Shaped Lake $\text{ Depth} = 100\text{ m} \quad U_C \text{ is a function of space and time.}$</td>
<td>$V_W = 2.0 \text{ m/s}$ at 15° Wave height = 0.5m</td>
</tr>
</tbody>
</table>
TABLE V1.2a INTERACTIVE INPUT FOR DEMONSTRATION CASE NO. 1

ENTER THE TITLE FOR THIS RUN..
? DEMO NO. 1

INPUT THE AMBIENT TEMPERATURE IN CELSIUS.
? 20

INPUT THE BAROMETRIC PRESSURE IN MILLIBARS OR ZERO, 0, FOR THE STANDARD SEA LEVEL PRESSURE OF 1013.25 MB.
? 0

INPUT THE TIME INCREMENT IN SECONDS. TRY 1.8.
? 1

INPUT THE DESIRED RUN TIME IN MINUTES
? 1.3333

INPUT MINIMUM ALLOWABLE THICKNESS OF THICK SLICK IN METERS.
? 1.E-4

INPUT THICKNESS OF THIN SLICK IN METERS.
? 1.E-4

***************************************************************************
% WATER BODY DESCRIPTION %
***************************************************************************

IS SPILL IN RIVER OR CHANNEL? Y/N
? N

IS IT A LAKE? Y/N
? Y

IS IT A CIRCULAR LAKE? Y/N
? Y

GIVE THE RADIUS AND DEPTH OF THE CIRCULAR LAKE (UNIT: METER)
? 20,0.3

IS THERE CURRENT? Y/N
? N

IS THERE WIND IN THE AREA? Y/N
? Y

IS WIND SPEED CONSTANT? Y/N
? Y

INPUT WIND SPEED (METER/SEC) AND DIRECTION ANGLE (DEGREES)
? 1.83,0

INPUT MEAN WAVE HEIGHT (METER)
DEFAULT VALUE (EQ. (III.32) OF REPORT) IS USED BY INPUTTING -1.
? -1

GIVE SPILL COORDINATES X AND Y, IN METERS
? 0,0

***************************************************************************
% SPILL TYPE %
***************************************************************************

WE HAVE STANDARD PROPERTIES FOR THE FOLLOWING CHEMICALS
1. ALLYL CHLORIDE 2. BENZENE
3. BUTADIENE (1,2) 4. BUTYL ACETATE (ISO)
5. BUTYL MERCAPTAN (H) 6. CHLOROBUTA-1-3-DIENE
7. CYCLOHEXANE 8. CYCLOHEXENE
9. DIPROPYL ETHER (ISO) 10. ETHYL CHLORIDE
### TABLE VI.2a (CONTD)

<table>
<thead>
<tr>
<th>No.</th>
<th>Chemical Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>ETHYL MERCAPTAN</td>
</tr>
<tr>
<td>12.</td>
<td>HEPTANE (H)</td>
</tr>
<tr>
<td>13.</td>
<td>HEXANE (H)</td>
</tr>
<tr>
<td>14.</td>
<td>METHYL CYCLOHEXANE</td>
</tr>
<tr>
<td>15.</td>
<td>NONANE (H)</td>
</tr>
<tr>
<td>16.</td>
<td>OCTANE (H)</td>
</tr>
<tr>
<td>17.</td>
<td>PENTANE</td>
</tr>
<tr>
<td>18.</td>
<td>TOLUENE</td>
</tr>
<tr>
<td>19.</td>
<td>TRIMETHYLBENZENE</td>
</tr>
<tr>
<td>20.</td>
<td>XYLENE (M)</td>
</tr>
</tbody>
</table>

Enter the no. you want or negative value - if you want to input the properties 99 - if the chemical is not on the list.

? 17

**Barometric Pressure:** 1013.250 Millibar

**Temperature:** 20.000 Degrees C

**Chemical Name is:** PENTANE

**Chemical Density:** 626.00 kg/cu.m.

**Molecular Weight:** 72.151 kg/kg-mole

**Diffusion Coeff (Air):** 7.5000e-05 sq.m./sec

**Diffusion Coeff (Water):** 8.4000e-09 sq.m./sec

**Chemical Vapor Pressure:** 58772.29 Newton/sq.m.

**Solubility in Water:** .36 kg/cu.m.

**The Interface Tension WRT Air:** .16046e-01 Newton/M.

**The Interface Tension WRT Water:** .50200e-01 Newton/M.

**The Spreading Coefficient is:** .65142e-02 Newton/m.

Is spill 1. instantaneous or 2. continuous?

? 1

**Input the total spilled volume (cubic meter):** .04

**Input the printout time step in minutes:** .066667
Table VI.2b shows some of the computed results for Demonstration Case No. 1. (The printout of the input conditions is not given in the table, only the computed results. The actual printout includes the input.) First, the results at the end of the gravity-inertial phase (0.14445 minutes, or 8.7 seconds in this case) are printed. Then the regular printout routine begins at about 12 seconds, which is the first printout time greater than the gravity-inertial spreading time that is an integral multiple of the requested printout time step. (The printout occurs at 12.073 seconds rather than exactly 12 seconds because the time step of the numerical integration scheme rarely coincides with the requested printout time step.) The printout gives information about the thick slick size, thickness, and mass, the position of the center of the slick, and the mass of evaporated and dissolved chemical. Similar printout is given every four seconds (although the results between 16 seconds and 80 seconds are not included here, for brevity) until the requested run time is exceeded. None of the other termination criteria is met.

Table VI.3a shows the input for a continuous spill that is otherwise similar to Demonstration Case No. 1. The computed results are shown in Table VI.3b. Again, the results at the end of the gravity-inertial spreading phase are given first. Note that for a continuous spill, the output includes data about the thin slick. Because there is no current, the transport velocity is due only to the wind and is thus very small. As a result, the triangular slick is much wider (17.0 meters) than it is long (3.55 meters). In reality, the slick formed under such small transport velocity conditions would be roughly elliptical and would enclose the spill source, rather than being entirely downstream of it; this was discussed earlier in Section III. After the discharge stops at 1 minute, a switch is made to an instantaneous model and the form of the printout changes to indicate it. Because of the difference in shape of the slick assumed in the two models, there is a small discrepancy in the predicted slick position at the time of the switch. Moreover, only the location of the center of the slick is printed out for the instantaneous model. In this case, the triangular slick is so wide compared to its length that the instantaneous slick is allowed to spread one-dimensionally (as if it were in a channel) until the shape becomes more "squarish." At that time (which would occur here for a time longer than
TABLE VI.2b - SAMPLE COMPUTED OUTPUT FOR DEMONSTRATION CASE NO. 1

SPREADING MODEL OUTPUT

THICK SLICK HAS SPREAD OVER A CIRCULAR AREA OF \(2.9392 \times 10^2\) SQUARE METERS, WITH A RADIUS OF \(2.7805 \times 10^1\) METERS AFTER THE FIRST \(1.4454 \times 10^0\) MINUTES

<table>
<thead>
<tr>
<th>TIME (0.00 MINUTES)</th>
<th>12.073 SECONDS</th>
<th>THICK SLICK AREA (= 2.8605 \times 10^2) SQ. M.</th>
<th>THICK SLICK THICKNESS (= 1.3357 \times 10^{-2}) METERS</th>
<th>THICK SLICK RADIUS (= 3.0175 \times 10^0) METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>(= 2.9033 \times 10^{-1}) KG.</td>
<td>TOTAL EVAPORATED MASS</td>
<td>(= 2.2006 \times 10^{-1}) KG.</td>
<td>RATE OF EVAPORATION</td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>(= 2.3001 \times 10^{-1}) KG.</td>
<td>RATE OF DISSOLUTION</td>
<td>(= 2.5001 \times 10^{-2}) KG/(SEC-SQ.M.)</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>(= 2.9033 \times 10^{-1}) KG.</td>
<td>THE CENTER OF THE SLICK IS LOCATED AT (x = 7.7325 \times 10^{-1}) METERS AND (y = 0) METERS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIME (1.00 MINUTES)</th>
<th>23.073 SECONDS</th>
<th>THICK SLICK AREA (= 1.2732 \times 10^2) SQ. M.</th>
<th>THICK SLICK THICKNESS (= 1.1959 \times 10^{-2}) METERS</th>
<th>THICK SLICK RADIUS (= 3.2178 \times 10^0) METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>(= 2.4503 \times 10^{-1}) KG.</td>
<td>TOTAL EVAPORATED MASS</td>
<td>(= 5.7504 \times 10^{-2}) KG.</td>
<td>RATE OF EVAPORATION</td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>(= 5.7504 \times 10^{-2}) KG.</td>
<td>RATE OF DISSOLUTION</td>
<td>(= 2.5001 \times 10^{-2}) KG/(SEC-SQ.M.)</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>(= 2.4503 \times 10^{-1}) KG.</td>
<td>THE CENTER OF THE SLICK IS LOCATED AT (x = 1.2955 \times 10^{-1}) METERS AND (y = 0) METERS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIME (2.00 MINUTES)</th>
<th>34.073 SECONDS</th>
<th>THICK SLICK AREA (= 4.3421 \times 10^1) SQ. M.</th>
<th>THICK SLICK THICKNESS (= 4.7049 \times 10^{-2}) METERS</th>
<th>THICK SLICK RADIUS (= 4.7049 \times 10^0) METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>(= 1.6033 \times 10^{-1}) KG.</td>
<td>TOTAL EVAPORATED MASS</td>
<td>(= 8.4009 \times 10^{-2}) KG.</td>
<td>RATE OF EVAPORATION</td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>(= 8.4009 \times 10^{-2}) KG.</td>
<td>RATE OF DISSOLUTION</td>
<td>(= 2.5001 \times 10^{-2}) KG/(SEC-SQ.M.)</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>(= 1.6033 \times 10^{-1}) KG.</td>
<td>THE CENTER OF THE SLICK IS LOCATED AT (x = 1.8124 \times 10^{-1}) METERS AND (y = 0) METERS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE VI.3a INTERACTIVE INPUT FOR DEMONSTRATION CASE NO. 2

ENTER THE TITLE FOR THIS RUN.
? DEMO NO. 2
INPUT THE AMBIENT TEMPERATURE IN CELSIUS.
? 20
INPUT THE BAROMETRIC PRESSURE IN MILLIBARS OR ZERO, 0, FOR THE STANDARD SEA LEVEL PRESSURE OF 1013.25 MB.
? 0
INPUT THE TIME INCREMENT IN SECONDS. TRY 1.0.
? .1
INPUT THE DESIRED RUN TIME IN MINUTES
? 1.33333
INPUT MINIMUM ALLOWABLE THICKNESS OF THICK SLICK IN METERS.
? 1.E-4
INPUT THICKNESS OF THIN SLICK IN METERS.
? 1.E-4

#########################################################
# WATER BODY DESCRIPTION #
#########################################################

IS SPILL IN RIVER OR CHANNEL? Y/N
? N
IS IT A LAKE? Y/N
? Y
IS IT A CIRCULAR LAKE? Y/N
? Y
GIVE THE RADIUS AND DEPTH OF THE CIRCULAR LAKE (UNIT: METER)
? 20, 0.3
IS THERE CURRENT? Y/N
? N
IS THERE WIND IN THE AREA? Y/N
? Y
IS WIND SPEED CONSTANT? Y/N
? Y
INPUT WIND SPEED (METER/SEC) AND DIRECTION ANGLE (DEGREES)
? 1.94, 0
INPUT MEAN WAVE HEIGHT (METER)
DEFAULT VALUE (EQ. (III.32) OF REPORT) IS USED BY INPUTTING -1.
? 0.1
GIVE SPILL COORDINATES X AND Y, IN METERS
? 0, 0

#########################################################
# SPILL TYPE #
#########################################################

WE HAVE STANDARD PROPERTIES FOR THE FOLLOWING CHEMICALS
1. ALLYL CHLORIDE
2. BENZENE
3. BUTADIENE (1,2)
4. BUTYL ACETATE (ISO)
5. BUTYL MERCAPTAN (N)
6. CHLOROBUTA-1,3-DIENE
7. CYCLOHEXANE
8. CYCLOHEXENE
9. DIPROPYL ETHER (ISO)
10. ETHYL CHLORIDE
<table>
<thead>
<tr>
<th>No.</th>
<th>Chemical Name</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>ETHYL MERCAPTAN</td>
<td>ENTER THE NO. YOU WANT OR NEGATIVE VALUE - IF YOU WANT TO INPUT THE PROPERTIES 99 - IF THE CHEMICAL IS NOT ON THE LIST</td>
</tr>
<tr>
<td>12</td>
<td>HEXANE (N)</td>
<td>BAROMETRIC PRESSURE : 1013.250 MILLIBAR</td>
</tr>
<tr>
<td>13</td>
<td>HEXANE (N)</td>
<td>TEMPERATURE : 20.000 DEGREES C</td>
</tr>
<tr>
<td>14</td>
<td>METHYL CYCLOHEXANE</td>
<td>CHEMICAL NAME IS: PENTANE</td>
</tr>
<tr>
<td>15</td>
<td>NONANE (O)</td>
<td>CHEMICAL DENSITY = 626.00 KG/CU.M.</td>
</tr>
<tr>
<td>16</td>
<td>OCTANE (H)</td>
<td>MOLECULAR WEIGHT = 72.151 KG/KG-MOLE</td>
</tr>
<tr>
<td>17</td>
<td>PENTANE</td>
<td>DIFFUSION COEFF (AIR) = .75000E-05 SQ.M./SEC</td>
</tr>
<tr>
<td>18</td>
<td>TOLUENE</td>
<td>DIFFUSION COEFF (WATER) = .84000E-09 SQ.M./SEC</td>
</tr>
<tr>
<td>19</td>
<td>TRIMETHYLBENZENE</td>
<td>CHEMICAL VAPOR PRESSURE = 58772.29 NEWTON/SQ.M.</td>
</tr>
<tr>
<td>20</td>
<td>XYLENE (M)</td>
<td>SOLUBILITY IN WATER = .36 KG/CU.M.</td>
</tr>
</tbody>
</table>

**Interface Tension**
- AIR: .16046E-1 NEWTON/M.
- WATER: .582E-9 NEWTON/M.
- SPREADING COEFFICIENT: .65142E-02 NEWTON/M.

**Spill Type**: 1. INSTANTANEOUS OR 2. CONTINUOUS?

**Input Rate of Discharge**: .80E1 CU.M./SEC

**Total Duration of Spill**: 1.

**Printout Time Step**: .066667
### TABLE VI.3b SAMPLE COMPUTED OUTPUT FOR DEMONSTRATION CASE NO. 2

**SPREADING MODEL OUTPUT**

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
<th>THICK SLICK DOWNSTREAM WIDTH</th>
<th>THIN SLICK AREA</th>
<th>THIN SLICK DOWNSTREAM WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 MINUTES, 0.070 SECONDS</td>
<td>0.35E+02 SQ.M.</td>
<td>1.7E-03 METERS</td>
<td>1.12E+00 METERS</td>
<td>0.24E+03 SQ.M.</td>
<td>1.29E+03 METERS</td>
</tr>
</tbody>
</table>

TOTAL MASS OF THICK SLICK = 0.1940E+02 KG.
TOTAL EVAPORATED MASS = 0.6899E+01 KG.
RATE OF EVAPORATION = 2.43E-02 KG/(SEC-SQ.M.)
TOTAL DISSOLVED MASS = 0.54E+01 KG/SEC-SQ.M.
RATE OF DISSOLUTION = 0.54E-06 KG/SEC-SQ.M.
TOTAL MASS OF THIN SLICK = 0.1965E+02 KG.

THE LEADING EDGE OF THE SLICK IS LOCATED AT X = 2.67E+01 METERS AND Y = 0.

THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORIGIN.

---

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
<th>THICK SLICK DOWNSTREAM WIDTH</th>
<th>THIN SLICK AREA</th>
<th>THIN SLICK DOWNSTREAM WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 MINUTES, 0.070 SECONDS</td>
<td>0.35E+02 SQ.M.</td>
<td>1.7E-03 METERS</td>
<td>1.12E+00 METERS</td>
<td>0.24E+03 SQ.M.</td>
<td>1.29E+03 METERS</td>
</tr>
</tbody>
</table>

TOTAL MASS OF THICK SLICK = 0.2126E+02 KG.
TOTAL EVAPORATED MASS = 0.6899E+01 KG.
RATE OF EVAPORATION = 2.43E-02 KG/(SEC-SQ.M.)
TOTAL DISSOLVED MASS = 0.54E+01 KG/SEC-SQ.M.
RATE OF DISSOLUTION = 0.54E-06 KG/SEC-SQ.M.
TOTAL MASS OF THIN SLICK = 0.1965E+02 KG.

THE LEADING EDGE OF THE SLICK IS LOCATED AT X = 2.67E+01 METERS AND Y = 0.

THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORIGIN.

---

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
<th>THICK SLICK DOWNSTREAM WIDTH</th>
<th>THIN SLICK AREA</th>
<th>THIN SLICK DOWNSTREAM WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 MINUTES, 0.070 SECONDS</td>
<td>0.35E+02 SQ.M.</td>
<td>1.7E-03 METERS</td>
<td>1.12E+00 METERS</td>
<td>0.24E+03 SQ.M.</td>
<td>1.29E+03 METERS</td>
</tr>
</tbody>
</table>

TOTAL MASS OF THICK SLICK = 0.2126E+02 KG.
TOTAL EVAPORATED MASS = 0.6899E+01 KG.
RATE OF EVAPORATION = 2.43E-02 KG/(SEC-SQ.M.)
TOTAL DISSOLVED MASS = 0.54E+01 KG/SEC-SQ.M.
RATE OF DISSOLUTION = 0.54E-06 KG/SEC-SQ.M.
TOTAL MASS OF THIN SLICK = 0.1965E+02 KG.

THE CENTER OF THE SLICK IS LOCATED AT X = 2.67E+01 METERS AND Y = 0.

---

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### TABLE VI.3b (CONT'D)

#### TIME = 1.00 MINUTES 4,030 SECONDS

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>.2049E+02 Kg.</td>
<td>.4022E-03 Meters</td>
</tr>
<tr>
<td>TOTAL EVAPORATED MASS</td>
<td>.1962E+01 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>.26372E-02 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>.3130E+00 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>.54650E-06 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>.2195E+02 Kg.</td>
<td></td>
</tr>
</tbody>
</table>

THE CENTER OF THE SLICK IS LOCATED AT X = .32624E+01 METERS AND Y = 0. METER

#### TIME = 1.00 MINUTES 12,030 SECONDS

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>.2109E+02 Kg.</td>
<td>.4037E-03 Meters</td>
</tr>
<tr>
<td>TOTAL EVAPORATED MASS</td>
<td>.1849E+01 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>.26372E-02 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>.3820E+00 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>.54650E-06 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>.2195E+02 Kg.</td>
<td></td>
</tr>
</tbody>
</table>

THE CENTER OF THE SLICK IS LOCATED AT X = .3546E+01 METERS AND Y = 0. METER

#### TIME = 1.00 MINUTES 16,030 SECONDS

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>.1973E+02 Kg.</td>
<td>.8539E-03 Meters</td>
</tr>
<tr>
<td>TOTAL EVAPORATED MASS</td>
<td>.2220E+01 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>.26372E-02 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>.4601E+00 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>.54650E-06 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>.2195E+02 Kg.</td>
<td></td>
</tr>
</tbody>
</table>

THE CENTER OF THE SLICK IS LOCATED AT X = .38056E+01 METERS AND Y = 0. METER

#### TIME = 1.00 MINUTES 20,030 SECONDS

<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>.1935E+02 Kg.</td>
<td>.9769E-03 Meters</td>
</tr>
<tr>
<td>TOTAL EVAPORATED MASS</td>
<td>.2594E+01 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>.26372E-02 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>.4376E+00 Kg.</td>
<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>.54650E-06 Kg/SEC-SQ.M.</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>.2195E+02 Kg.</td>
<td></td>
</tr>
</tbody>
</table>

THE CENTER OF THE SLICK IS LOCATED AT X = .4022E+01 METERS AND Y = 0. METER
the run time), the instantaneous model is changed to the open-water case, and the slick is assumed to be circular subsequently.

Input for Demonstration Case No. 3 is shown in Table VI.4a. For this case, the current is non-zero and its x and y components are input at the fourteenth prompt. Also, the chemical properties are input separately, rather than taken from the data for the twenty chemicals included as samples in the model. Sample output is shown in Table VI.4b. The change in the form of the output should again be noted when the discharge stops after 30 minutes. In this example, the shape of the slick is such that the instantaneous model is immediately assumed to be the open water case; the slick spreads symmetrically, and the radius of the thick slick is printed out.

Input for Demonstration Case No. 4 is shown in Table VI.5a. The width and depth of the channel are input at the eighth prompt. The bottom roughness is input at the ninth prompt; the computed results are practically independent of bottom roughness for realistic values of channel depth, so the default value can be used with little or no loss of accuracy when the actual bottom roughness is unknown. The wind direction for a channel is referred to the downstream channel direction (the fifteenth prompt). Sample output is given in Table VI.5b. The initial printout for this case is data about the slick at the time it has just spread across the entire channel. During this first 2.09 minutes, the slick is triangular and the leading edge moves downstream at a speed equal to \( U_T \); see Equation (III.17). After the slick extends across the entire channel, the spreading is one-dimensional, and the leading edge is transported downstream at a speed equal to a combination of \( U_T \) and the gravitational spreading velocity. Further, at the time the models are switched, the area of the triangular slick is assumed to be instantaneously spread uniformly across the channel width. For these reasons, there is a small discrepancy at the switch-over time in the position of the leading edge of the slick. (The discrepancy is not apparent in the printout because of the long time between the first 2.09 minutes and the first of the regular printouts at 15 minutes.) Note that after the discharge stops at 60 minutes, the printout form changes and the slick moves bodily downstream.
TABLE VI.4a INTERACTIVE INPUT FOR DEMONSTRATION CASE NO. 3

ENTER THE TITLE FOR THIS RUN.
? DEMO NO. 3
INPUT THE AMBIENT TEMPERATURE IN CELSIUS.
? 20
INPUT THE BAROMETRIC PRESSURE IN MILLIBARS OR ZERO, 0, FOR THE STANDARD SEA LEVEL PRESSURE OF 1013.25 MB.
? 0
INPUT THE TIME INCREMENT IN SECONDS. TRY 1.0.
? 1.
INPUT THE DESIRED RUN TIME 'T' MINTURES
? 60.
INPUT MINIMUM ALLOWABLE THICKNESS OF THICK SLICK IN METERS.
? 1.E-4
INPUT THICKNESS OF THIN SLICK IN METERS.
? 1.E-4

Is SPILL IN RIVER OR CHANNEL? Y/N
? N

Is IT A LAKE? Y/N
? Y

Is IT A CIRCULAR LAKE? Y/N
? Y

Give THE RADIUS AND DEPTH OF THE CIRCULAR LAKE (UNIT: METER)
? 20000.100

Is THERE CURRENT? Y/N
? Y

Is CURRENT CONSTANT? Y/N
? Y

INPUT CONSTANT CURRENT SPEED Ucx AND Ucy (UNIT: METER/SEC)
? 0.5, 0.1

Is THERE WIND IN THE AREA? Y/N
? Y

Is WInd SPEED CONSTANT? Y/N
? Y

INPUT WIND SPEED (METER/SEC) AND DIRECTION ANGLE (DEGREES)
? 3., 30

INPUT MEAN WAVE HEIGHT (METER)
DEFAULT VALUE (EQ. (11.32) OF REPORT) IS USED BY INPUTTING -1.
? 5
GIVE SPILL COORDINATES X AND Y, IN METERS
? 0, 0

SPILL TYPE

WE HAVE STANDARD PROPERTIES FOR THE FOLLOWING CHEMICALS
1. ALLYL CHLORIDE
2. BENZENE
3. BUTADIENE (1,2)
4. BUTYL ACETATE (ISO)
5. BUTYL MERCAPTAN (N)
6. CHLOROBUTA-1-3-DIENE
7. CYCLOHEXANE
8. CYCLOHEXENE
TABLE VI.4a (CONT'D)

9. DIPROPYL ETHER (ISO) 10. ETHYL CHLORIDE
11. ETHYL MERCAPTAN 12. OCTANE (N)
13. HEXANE (N) 14. METHYL CYCLOHEXANE
15. NONANE (N) 16. OCTANE (H)
17. PENTANE 18. TOLUENE
19. TRIMETHYLBENZENE 20. XYLENE (M)

ENTER THE NO. YOU WANT OR NEGATIVE VALUE - IF YOU WANT TO INPUT THE PROPERTIES 99 - IF THE CHEMICAL IS NOT ON THE LIST

? -1

ENTER ITS DENSITY IN KG/CU M.
? 800.

INPUT ITS MOLECULAR WEIGHT IN KG/KG-MOLE.
? 114.32

ENTER DIFFUSION COEFFICIENT OF VAPOR IN AIR IN SQ M/SEC.
? 5.8E-6

ENTER DIFFUSION COEFFICIENT OF LIQUID IN WATER IN SQ M/SEC.
? 6.38E-9

IS PV (VAPOR) 1. A NUMBER OR 2. A FORMULA?
? 1

ENTER CONSTANT PV
? 1391.74

INPUT THE SOLUBILITY LIMIT OF CHEMICAL IN WATER (KG/CU.M.)
? .02

INPUT (1) CHEMICAL/AIR INTERFACE TENSION AND (2) WATER/CHEMICAL INTERFACE TENSION
UNIT : NEWTON/M.
? 2.1618E-2
? 5.08E-2

BAROMETRIC PRESSURE : 1013.250 MILLIBAR

TEMPERATURE : 20.000 DEGREES C

CHEMICAL NAME IS:

COPY

CHEMICAL DENSITY = 800.00 KG/CU.M.
MOLECULAR WEIGHT = 114.320 KG/KG-MOLE
DIFFUSION COEFF (AIR) = .58000E-05 SQ.M./SEC
DIFFUSION COEFF (WATER) = .63800E-08 SQ.M./SEC
CHEMICAL VAPOR PRESSURE = 1391.74 NEWTON/SQ.M.
SOLUBILITY IN WATER = .02 KG/CU.M.

THE INTERFACE TENSION WRT AIR IS .21618E-01 NEWTON/M.
THE INTERFACE TENSION WRT WATER IS .50000E-01 NEWTON/M.
THE SPREADING COEFFICIENT IS .34200E-03 NEWTON/M.

IS SPILL 1. INSTANTANEOUS OR 2. CONTINUOUS?
? 2
TABLE VI.4a (CONTD)

INPUT THE RATE OF DISCHARGE (CU.M./SEC)
? .0333

INPUT THE TOTAL DURATION OF SPILL IN MINUTES
? 30.

INPUT THE PRINTOUT TIME STEP IN MINUTES.
? 10.
TABLE VI.4b  SAMPLE COMPUTED OUTPUT FOR  
DEMONSTRATION CASE NO. 3

*SPREADING MODEL OUTPUT*

THICK SLICK HAS SPREAD OVER AN ELONGATED TRIANGULAR AREA OF .21905E+04 
SQUARE METERS AFTER A TIME OF .29361E+00 MINUTES.
THE THICK SLICK LEADING EDGE IS .47F5E+02 METERS WIDE AND IS .92867E+02 METERS 
DOWNSTREAM.

THE THIN SLICK AREA IS EQUAL TO .17524E+03 SQUARE METERS.

TIME = 10.00 MINUTES .100 SECONDS
THICK SLICK AREA = .15298E+05 SQ. M.  THICK SLICK THICKNESS = .11258E-02 METERS
THICK SLICK DOWNSTREAM WIDTH = .83932E+02 METERS
THIN SLICK AREA = .22478E+05 SQ. M.
THIN SLICK DOWNSTREAM WIDTH = .12274E+03 METERS

TOTAL MASS OF THICK SLICK = .13774E+06 KG.
TOTAL EVAPORATED MASS = .41207E+03 KG.
RATE OF EVAPORATION = .11161E-03 KG/(SEC-SC.P.)
TOTAL DISSOLVED MASS = .33931E+00 KG.
RATE OF DISSOLUTION = .14608E-06 KG/(SEC-SC.P.)
TOTAL MASS OF THIN SLICK = .17482E+04 KG.

TOTAL PASS = .15984E+05 KG.

THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .15466E+03 METERS AND 
Y = .18526E+02 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORIGIN.

TIME = 20.00 MINUTES .164 SECONDS
THICK SLICK AREA = .34112E+05 SQ. M.  THICK SLICK THICKNESS = .47421E-03 METERS
THICK SLICK DOWNSTREAM WIDTH = .10286E+03 METERS
THIN SLICK AREA = .24928E+05 SQ. M.
THIN SLICK DOWNSTREAM WIDTH = .81705E+02 METERS

TOTAL MASS OF THICK SLICK = .27364E+06 KG.
TOTAL EVAPORATED MASS = .22073E+04 KG.
RATE OF EVAPORATION = .11161E-03 KG/(SEC-SC.P.)
TOTAL DISSOLVED MASS = .94604E+01 KG.
RATE OF DISSOLUTION = .14608E-06 KG/(SEC-SC.P.)

TOTAL MASS OF THIN SLICK = .23931E+04 KG.
TOTAL PASS = .31972E+05 KG.

THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .76922E+03 METERS AND 
Y = .16303E+03 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORIGIN.
<table>
<thead>
<tr>
<th>TIME</th>
<th>THICK SLICK AREA</th>
<th>THICK SLICK THICKNESS</th>
<th>THICK SLICK RADIUS</th>
<th>TOTAL MASS OF THICK SLICK</th>
<th>TOTAL EVAPORATED MASS</th>
<th>RATE OF EVAPORATION</th>
<th>RATE OF DISSOLUTION</th>
<th>TOTAL DISSOLVED MASS</th>
<th>TOTAL MASS</th>
<th>THE CENTER OF THE SLICK IS LOCATED AT X =</th>
<th>Y =</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00 MINUTES</td>
<td>0.00347E+05 SQ.M.</td>
<td>0.0027E-03 METERS</td>
<td>0.0035E+00 METERS</td>
<td>0.00347E+05 KG.</td>
<td>0.00347E+05 KG.</td>
<td>0.0010E+00 KG/SEC</td>
<td>0.0010E+00 KG/SEC</td>
<td>0.00347E+05 KG.</td>
<td>0.00347E+05 KG.</td>
<td>X = 0.00 METERS</td>
<td>Y = 0.00 METERS</td>
</tr>
<tr>
<td>30.00 MINUTES</td>
<td>0.00363E+05 SQ.M.</td>
<td>0.0027E-03 METERS</td>
<td>0.0035E+00 METERS</td>
<td>0.00363E+05 KG.</td>
<td>0.00363E+05 KG.</td>
<td>0.0010E+00 KG/SEC</td>
<td>0.0010E+00 KG/SEC</td>
<td>0.00363E+05 KG.</td>
<td>0.00363E+05 KG.</td>
<td>X = 0.00 METERS</td>
<td>Y = 0.00 METERS</td>
</tr>
<tr>
<td>40.00 MINUTES</td>
<td>0.00379E+05 SQ.M.</td>
<td>0.0027E-03 METERS</td>
<td>0.0035E+00 METERS</td>
<td>0.00379E+05 KG.</td>
<td>0.00379E+05 KG.</td>
<td>0.0010E+00 KG/SEC</td>
<td>0.0010E+00 KG/SEC</td>
<td>0.00379E+05 KG.</td>
<td>0.00379E+05 KG.</td>
<td>X = 0.00 METERS</td>
<td>Y = 0.00 METERS</td>
</tr>
</tbody>
</table>

THE CENTER OF THE SLICK IS LOCATED AT X = 0.00 METERS AND Y = 0.00 METERS.
TABLE VI.5a  INTERACTIVE INPUT FOR DEMONSTRATION CASE NO. 4

ENTER THE TITLE FOR THIS RUN...
> DEMO NO. 4

INPUT THE AMBIENT TEMPERATURE IN CELSIUS.
> 20

INPUT THE BAROMETRIC PRESSURE IN MILLIBARS OR ZERO, 0, FOR THE STANDARD SEA LEVEL PRESSURE OF 1013.25 MB.
> 0

INPUT THE TIME INCREMENT IN SECONDS. TRY 1.8.
> 1

INPUT THE DESIRED RUN TIME IN MINUTES
> 120

INPUT MINIMUM ALLOWABLE THICKNESS OF THICK SLICK IN METERS.
> 1.0E-4

INPUT THICKNESS OF THIN SLICK IN METERS.
> 1.0E-4

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
# WATER BODY DESCRIPTION #
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

IS SPILL IN RIVER OR CHANNEL? Y/N
> Y

GIVE THE WIDTH AND DEPTH OF THE CHANNEL (IN METERS)
> 5.0, 1.0

INPUT THE BOTTOM ROUGHNESS (METERS) OF THE CHANNEL.
INPUT ZERO, 0 IF YOU WANT TO USE THE DEFAULT VALUE.
> 0

IS THERE CURRENT IN THE CHANNEL? Y/N
> Y

IS IT TIDAL CURRENT? Y/N
> ?

CURRENT SPEED MUST BE CONSTANT.
INPUT CURRENT SPEED METER/SEC
> 1

IS THERE WIND IN THE AREA? Y/N
> Y

IS WIND SPEED CONSTANT? Y/N
> Y

INPUT WIND SPEED (METER/SEC) AND DIRECTION ANGLE (DEGREES)
> 3.1, 135.

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
# SPILL TYPE #
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

WE HAVE STANDARD PROPERTIES FOR THE FOLLOWING CHEMICALS
1. ALLYL CHLORIDE 2. BENZENE
3. BUTADIENE (1,2) 4. BUTYL ACETATE (ISO)
5. BUTYL MERCAPTAN (N) 6. CHLOROBUTA-1-3-DIENE
7. CYCLOHEXANE 8. CYCLOHEXENE
9. DIPROPYL ETHER (ISO) 10. ETHYL CHLORIDE
11. ETHYL MERCAPTAN 12. HEXANE (N)
13. HEXANE (N) 14. METHYL CYCLOHEXANE
15. NONANE (N) 16. OCTANE (N)
17. PENTANE 18. TOLUENE
19. TRIMETHYLBENZENE 20. XYLENE (M)

ENTER THE NO. YOU WANT OR NEGATIVE VALUE - IF YOU WANT TO INPUT THE PROPERTIES
99 - IF THE CHEMICAL IS NOT ON THE LIST
> 16
TABLE VI.5a (CONT'D)

BAROMETRIC PRESSURE : 1013.250 MILLIBAR

TEMPERATURE : 20.000 DEGREES C

CHEMICAL NAME IS: OCTANE (N)

CHEMICAL DENSITY = 703.00 KG/CU.M.

MOLECULAR WEIGHT = 114.232 KG/KG-MOLE

DIFFUSION COEFF (AIR) = .58000E-05 SQ.M./SEC

DIFFUSION COEFF (WATER) = .63000E-09 SQ.M./SEC

CHEMICAL VAPOR PRESSURE = 1391.74 NEWTON/SQ.M.

SOLUBILITY IN WATER = .02 KG/CU.M.

THE INTERFACE TENSION WRT AIR IS .21618E-01 NEWTON/M.

THE INTERFACE TENSION WRT WATER IS .50880E-01 NEWTON/M.

THE SPREADING COEFFICIENT IS .34180E-03 NEWTON/M.

IS SPILL 1. INSTANTANEOUS OR 2. CONTINUOUS?

? 2

INPUT THE RATE OF DISCHARGE (CU.M./SEC)

? .1

INPUT THE TOTAL DURATION OF SPILL IN MINUTES

? 60.

INPUT THE PRINTOUT TIME STEP IN MINUTES.

? 15.
TABLE VI.5b SAMPLE COMPUTED OUTPUT FOR
DEMONSTRATION CASE NO. 4

SPILLING MODEL OUTPUT

THICK SLICK HAS SPREAD ACROSS THE CHANNEL WIDTH AND COVERS AN AREA OF .29075E+04
SQUARE METERS AFTER A TIME OF .20938E+01 MINUTES.
THE SLICK LEADING EDGE IS .11030E+03 METERS DOWNSTREAM.

TIME = 15.00 MINUTES .626 SECONDS
THICK SLICK AREA = .27494E+05 SQ.M. THICK SLICK THICKNESS = .11169E-02 METERS
THIN SLICK AREA = .23575E+05 SQ.M.
TOTAL MASS OF THICK SLICK = .58259E+05 KG.
TOTAL EVAPORATED MASS = .34025E+04 KG.
RATE OF EVAPORATION = .13604E-03 KG/(SEC-SC.P.)
TOTAL DISSOLVED MASS = .16994E+02 KG.
RATE OF DISSOLUTION = .67966E-06 KG/(SEC-SC.P.)
TOTAL MASS OF THICK SLICK = .16355E+04 KG.
TOTAL MASS = .63316E+05 KG.
THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .12593E+04 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT X = 0.

TIME = 30.00 MINUTES .626 SECONDS
THICK SLICK AREA = .34515E+05 SQ.M. THICK SLICK THICKNESS = .11538E-02 METERS
THIN SLICK AREA = .23271E+05 SQ.M.
TOTAL MASS OF THICK SLICK = .10435E+06 KG.
TOTAL EVAPORATED MASS = .15926E+05 KG.
RATE OF EVAPORATION = .13604E-03 KG/(SEC-SC.P.)
TOTAL DISSOLVED MASS = .17562E+02 KG.
RATE OF DISSOLUTION = .67966E-06 KG/(SEC-SC.P.)
TOTAL MASS OF THICK SLICK = .16355E+04 KG.
TOTAL MASS = .12658E+06 KG.
THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .26962E+04 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT X = 0.

TIME = 60.00 MINUTES .626 SECONDS
THICK SLICK AREA = .26928E+05 SQ.M. THICK SLICK THICKNESS = .11912E-02 METERS
THIN SLICK AREA = .23292E+05 SQ.M.
TOTAL MASS OF THICK SLICK = .16934E+05 KG.
TOTAL EVAPORATED MASS = .15926E+05 KG.
RATE OF EVAPORATION = .13604E-03 KG/(SEC-SC.P.)
TOTAL DISSOLVED MASS = .17562E+02 KG.
RATE OF DISSOLUTION = .67966E-06 KG/(SEC-SC.P.)
TOTAL MASS OF THICK SLICK = .16355E+04 KG.
TOTAL MASS = .23123E+05 KG.
THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .39398E+04 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT X = 0.
TABLE VI.5b (CONT'D)

<table>
<thead>
<tr>
<th>TIME</th>
<th>75.0C MINUTES</th>
<th>6.26A SECONDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>THICK SLICK AREA</td>
<td>2.4905E+06 SQ.M.</td>
<td>THICK SLICK THICKNESS = .9794E-03 METERS</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS OF THICK SLICK</td>
<td>1.5395E+06 G.</td>
<td></td>
</tr>
<tr>
<td>TOTAL EVAPORATED MASS</td>
<td>1.2150E+05 G.</td>
<td></td>
</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>2.1694E+03 KG/SEC-SC.P.</td>
<td></td>
</tr>
<tr>
<td>TOTAL DISSOLVED MASS</td>
<td>2.4593E+03 G.</td>
<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>2.9966E+03 KG/SEC-SC.P.</td>
<td></td>
</tr>
</tbody>
</table>

| TOTAL MASS             | 2.5144E+06 G.  |

THE THICK SLICK HAS MOVED = 35324E+04 METERS.
THE DOWNSTREAM EDGE OF THE SLICK IS AT = 69224E+04 METERS AND THE UPSTREAM EDGE IS AT = 80414E+04 METERS.
Input for Case No. 5, a continuous spill in an irregularly-shaped lake with a current that is a function of both position and time, is shown in Table VI.6a. Figure VI.1 shows the lake graphically as well as the currents in the 3x3 grid at the instant the spill occurs. As shown in Table VI.6a, the shape of the lake is specified (beginning at the twelfth prompt) by ten pairs of x,y coordinates. The coordinates should be input in counterclockwise order, starting with the point having the smallest x-coordinate. (An arbitrarily-shaped coast should also be input starting with the smallest x-coordinate.) The x-coordinates of the current grids are input as a group, starting with the smallest value (which must equal the smallest x-coordinate of the lake) and ending with the largest value (which must equal the largest x-coordinate of the lake). Likewise, the y-coordinates of the grid are input as a group, and the largest and smallest coordinates must satisfy similar conditions. Next, the x and y components of the current in each of the nine boxes of the grid are input. Since the current has been specified as a function of time in the input, the x and y components must be input ten times, one for each of the ten instants of time that are input after the currents are given. The smallest time value must be zero, and the largest must be at least as large as the run time. Sample output is shown in Table VI.6b. When the leading edge of the slick moves from grid to grid, the transport velocity varies and the slick will be predicted to bend and kink. (In this example, the continuous spill ends before the leading edge moves out of the original grid.) Although the correct value of \( U_T \) is used to compute the incremental change in the position of the leading edge during the next integration time step (Equation (III.38)), the shape of the entire slick behind the leading edge is not adjusted to account for the new value of the time-varying current; that is, when the current varies in time, the position of the entire slick is not updated, only the leading edge is. Otherwise, the calculations are similar to a case when the current is constant.
TABLE VI.6a INTERACTIVE INPUT FOR DEMONSTRATION CASE NO. 5

ENTER THE TITLE FOR THIS RUN.
? DEMO NO. 5

INPUT THE AMBIENT TEMPERATURE IN CELSIUS.
? 20.

INPUT THE BAROMETRIC PRESSURE IN MILLIBARS OR ZERO, 0, FOR THE STANDARD SEA LEVEL PRESSURE OF 1013.25 MB.
? 0.

INPUT THE TIME INCREMENT IN SECONDS. TRY 1.0.
? 1.

INPUT THE DESIRED RUN TIME IN MINUTES
? 240.

INPUT MINIMUM ALLOWABLE THICKNESS OF THICK SLICK IN METERS.
? 1.E-4

INPUT THICKNESS OF THIN SLICK IN METERS.
? 1.E-4

***************************************************************************
* WATER BODY DESCRIPTION *
***************************************************************************

IS SPILL IN RIVER OR CHANNEL? Y/N
?

IS IT A LAKE? Y/N
?

IS IT A CIRCULAR LAKE? Y/N
?

IS IT A RECTANGULAR LAKE? Y/N
?

THE SPILL IS IN A LAKE WITH ARBITRARY SHAPE. DESCRIBE THE SHAPE WITH 10 PAIRS OF X,Y COORDINATES (METERS). (0,0) SHOULD BE THE SPILL SITE.
?

\[ X \] \[ Y \]
\[ 1 \] \[-.45000E+04 \] \[ 0 \]
\[ 2 \] \[-.35000E+04 \] \[ -.30000E+04 \]
\[ 3 \] \[-.10000E+04 \] \[ -.40000E+04 \]
\[ 4 \] \[ 0 \] \[ -.50000E+04 \]
\[ 5 \] \[ .20000E+04 \] \[ -.10000E+04 \]
\[ 6 \] \[ .40000E+04 \] \[ -.20000E+04 \]
\[ 7 \] \[ .50000E+04 \] \[ .50000E+03 \]
\[ 8 \] \[ .40000E+04 \] \[ .20000E+04 \]
\[ 9 \] \[ .10000E+04 \] \[ .60000E+04 \]
\[ 10 \] \[ -.30000E+04 \] \[ .30000E+04 \]

INPUT WATER DEPTH
?

100
TABLE VI.6a (CONT'D)

IS THERE CURRENT? Y/N
? Y

IS CURRENT CONSTANT? Y/N
? N

IS CURRENT A FUNCTION OF TIME? Y/N
? Y

IS CURRENT A FUNCTION OF TIME ONLY? Y/N
? N

IF A LAKE, THE X, Y CURRENT MUST BE GIVEN AT CENTER OF 9 RECTANGULAR BOXES (3X3 GRID) THAT COVER LAKE.
IF A COAST, THE X, Y CURRENT MUST BE GIVEN FOR THE 9 Y-SLICES THAT EXTEND OUT FROM THE 10 X, Y POINTS DESCRIBING THE COAST.

GIVE THE 4 X-COORDINATES (METERS) THAT SPECIFY THE HORIZONTAL GRID. THE FIRST AND LAST MUST COINCIDE WITH THE LENGTH OF THE LAKE.

? -4500.
? 5000.

NOW GIVE THE 4 Y-COORDINATES (METERS). THE FIRST AND LAST MUST COINCIDE WITH THE WIDTH OF THE LAKE.

? -5000.
? -2500.
? 2500.
? 5000.

INPUT UX AND UY CURRENTS (M/SEC) FOR EACH OF THE 9 BOXES OR SLICES. BOXES ARE NUMBERED LEFT-TO-RIGHT 1, 2, 3 IN BOTTOM ROW, 4, 5, 6 IN MIDDLE ROW, AND 7, 8, 9 IN TOP ROW. SLICES FOR A COAST ARE NUMBERED 1 TO 9, LEFT-TO-RIGHT. IF THE CURRENTS ALSO DEPEND ON TIME, YOU WILL BE ASKED FOR 10 SUCH SETS OF CURRENTS.

CURRENTS FOR NUMBER 1 TIME.
? 0.1, -0.1
? 0.2, 0.
? 0.1, 0.1
? 0.05, -0.15
? 0.05, 0.
? 0.05, 0.15
? -0.1, -0.1
? -0.2, 0.
? -0.1, 0.1

CURRENTS FOR NUMBER 2 TIME.
? 0.15, -0.15
? 0.3, 0.
? 0.15, 0.15
? 0.075, -0.225
? 0.075, 0.
? 0.075, 0.225
? -0.15, -0.15
? -0.3, 0.
? -0.15, 0.15

CURRENTS FOR NUMBER 3 TIME.
? 0.2, -0.2
? 0.4, 0.
? 0.2, 0.2
? 0.1, -0.3
? 0.1, 0.
? 0.1, 0.3
? -0.2, -0.2
? -0.4, 0.
? -0.2, 0.2

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### TABLE VI.6a (CONTD)

#### CURRENTS FOR NUMBER 4 TIME.
- $0.15, -0.15$
- $0.3, 0$
- $0.15, 0.15$
- $0.075, -0.225$
- $0.075, 0$
- $0.075, 0.225$
- $-0.15, -0.15$
- $-0.3, 0$
- $-0.15, 0.15$

#### CURRENTS FOR NUMBER 5 TIME.
- $0.1, -0.1$
- $0.2, 0$
- $0.1, 0.1$
- $0.05, -0.15$
- $0.05, 0$
- $0.05, 0.15$
- $-0.1, -0.1$
- $-0.2, 0$
- $-0.1, 0.1$

#### CURRENTS FOR NUMBER 6 TIME.
- $0.1, -0.1$
- $0.2, 0$
- $0.1, 0.1$
- $0.05, -0.15$
- $0.05, 0$
- $0.05, 0.15$
- $-0.1, -0.1$
- $-0.2, 0$
- $-0.1, 0.1$

#### CURRENTS FOR NUMBER 7 TIME.
- $0.1, -0.1$
- $0.2, 0$
- $0.1, 0.1$
- $0.05, -0.15$
- $0.05, 0$
- $0.05, 0.15$
- $-0.1, -0.1$
- $-0.2, 0$
- $-0.1, 0.1$

#### CURRENTS FOR NUMBER 8 TIME.
- $0.1, -0.1$
- $0.2, 0$
- $0.1, 0.1$
- $0.05, -0.15$
- $0.05, 0$
- $0.05, 0.15$
- $-0.1, -0.1$
- $-0.2, 0$
- $-0.1, 0.1$

#### CURRENTS FOR NUMBER 9 TIME.
- $0.1, -0.1$
- $0.2, 0$
- $0.1, 0.1$
- $0.05, -0.15$
- $0.05, 0$
- $0.05, 0.15$
- $-0.1, -0.1$
- $-0.2, 0$
- $-0.1, 0.1$

#### CURRENTS FOR NUMBER 10 TIME.
- $0.1, -0.1$
- $0.2, 0$
- $0.1, 0.1$
- $0.05, -0.15$
- $0.05, 0$
- $0.05, 0.15$
- $-0.1, -0.1$
- $-0.2, 0$
- $-0.1, 0.1$
TABLE VI.6a (CONT'D)

NOW GIVE THE TEN TIME INSTANTS IN MINUTES.

10. 30. 60. 90. 120. 140. 160. 190. 240.

TIME= 0. MINUTES
UX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SLICES.

<table>
<thead>
<tr>
<th>9</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>.05</td>
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<td>.05</td>
<td>-.10</td>
<td>-.20</td>
</tr>
<tr>
<td>UY</td>
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<td>0.00</td>
<td>.10</td>
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<td>0.00</td>
<td>.15</td>
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TIME= .30000E+02 MINUTES
UX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SLICES.

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<th>3</th>
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<th>7</th>
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</tr>
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<tbody>
<tr>
<td>UX</td>
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<td>.30</td>
<td>.15</td>
<td>.08</td>
<td>.08</td>
<td>.08</td>
<td>-.15</td>
<td>-.30</td>
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<tr>
<td>UY</td>
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<td>-.23</td>
<td>0.00</td>
<td>.23</td>
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TIME= .60000E+02 MINUTES
UX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SLICES.

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<th>3</th>
<th>4</th>
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<td>.40</td>
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<td>.10</td>
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<tr>
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<td>.20</td>
<td>-.30</td>
<td>0.00</td>
<td>.30</td>
<td>-.20</td>
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TIME= .90000E+02 MINUTES
UX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SLICES.

<table>
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<th>3</th>
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<th>7</th>
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<tbody>
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<td>.15</td>
<td>.08</td>
<td>.08</td>
<td>.08</td>
<td>-.15</td>
<td>-.30</td>
</tr>
<tr>
<td>UY</td>
<td>-.15</td>
<td>0.00</td>
<td>.15</td>
<td>-.23</td>
<td>0.00</td>
<td>.23</td>
<td>-.15</td>
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TIME= 1.00000E+03 MINUTES
UX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SLICES.

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<th>3</th>
<th>4</th>
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<th>6</th>
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<tr>
<td>UX</td>
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<td>.20</td>
<td>.10</td>
<td>.05</td>
<td>.05</td>
<td>.05</td>
<td>-.10</td>
<td>-.20</td>
</tr>
<tr>
<td>UY</td>
<td>-.10</td>
<td>0.00</td>
<td>.10</td>
<td>-.15</td>
<td>0.00</td>
<td>.15</td>
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<td>0.00</td>
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TIME= 1.20000E+03 MINUTES
UX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SLICES.

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<td>.10</td>
<td>.05</td>
<td>.05</td>
<td>.05</td>
<td>-.10</td>
<td>-.20</td>
</tr>
<tr>
<td>UY</td>
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TABLE VI.6a (CONT'D)

TIME = .14000E+03 MINUTES

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<td>.05</td>
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<td>-.20</td>
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<td>.15</td>
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TIME = .16000E+03 MINUTES

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<td>.05</td>
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<td>.15</td>
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TIME = .20000E+03 MINUTES

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<td>.05</td>
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<td>.05</td>
<td>-.10</td>
<td>-.20</td>
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<tr>
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<td>.15</td>
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</table>

TIME = .24000E+03 MINUTES

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<tbody>
<tr>
<td>UX</td>
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<td>.10</td>
<td>.05</td>
<td>.05</td>
<td>.05</td>
<td>-.10</td>
<td>-.20</td>
</tr>
<tr>
<td>UY</td>
<td>-.10</td>
<td>0.00</td>
<td>.10</td>
<td>-.15</td>
<td>0.00</td>
<td>.15</td>
<td>-.10</td>
<td>0.00</td>
</tr>
</tbody>
</table>

IS THERE WIND IN THE AREA? Y/N

IS WIND SPEED CONSTANT? Y/N

INPUT WIND SPEED (METER/SEC) AND DIRECTION ANGLE (DEGREES)

INPUT MEAN WAVE HEIGHT (METER)
DEFAULT VALUE (EQ. (III.32) OF REPORT) IS USED BY INPUTTING -1.

GIVE SPILL COORDINATES X AND Y, IN METERS

WHAT BOX (LAKE) OR SLICE (COAST) DOES THE SPILL ORIGIN LIE IN?

***********
SPILL TYPE
***********

WE HAVE STANDARD PROPERTIES FOR THE FOLLOWING CHEMICALS
1. ALLYL CHLORIDE
   2. BENZENE
   3. BUTADIENE (1,2)
   4. BUTYL ACETATE (ISO)
   5. BUTYL MERCAPTAN (H)
   6. CHLOROBUTA-1,3-DIENE
   7. CYCLOHEXANE
   8. CYCLOHEXANE
   9. DIPROPYL ETHER (ISO)
   10. ETHYL CHLORIDE
   11. ETHYL MERCAPTAN
   12. HEPANE (N)
<table>
<thead>
<tr>
<th>No.</th>
<th>Chemical Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.</td>
<td>HEXANE (N)</td>
</tr>
<tr>
<td>15.</td>
<td>NONANE (H)</td>
</tr>
<tr>
<td>17.</td>
<td>PENTANE</td>
</tr>
<tr>
<td>19.</td>
<td>TRIMETHYL BENZENE</td>
</tr>
<tr>
<td>14.</td>
<td>METHYL CYCLOHEXANE</td>
</tr>
<tr>
<td>16.</td>
<td>OCTANE (N)</td>
</tr>
<tr>
<td>18.</td>
<td>TOLUENE</td>
</tr>
<tr>
<td>20.</td>
<td>XYLENE (M)</td>
</tr>
</tbody>
</table>

Enter the no. you want or negative value - if you want to input the properties 99 - if the chemical is not on the list.

? 16

Barometric Pressure : 1013.250 Millibar

Temperature : 20.000 Degrees C

Chemical Name is: OCTANE (N)

Chemical Density = 703.80 KG/CU.M.

Molecular Weight = 114.232 KG/KG-MOLE

Diffusion Coeff (Air) = 0.50000E-05 SQ.M./SEC

Diffusion Coeff (Water) = 0.63000E-09 SQ.M./SEC

Chemical Vapor Pressure = 1391.74 NEWTON/SQ.M.

Solvability in Water = 0.02 KG/CU.M.

The interface tension wrt air is 0.21618E-01 NEWTON/M. The interface tension wrt water is 0.50000E-01 NEWTON/M.

The spreading coefficient is 0.34180E-03 NEWTON/M.

Is Spill 1. Instantaneous or 2. Continuous?

? 2

Input the rate of discharge (CU.M./SEC)

? 0.05

Input the total duration of spill in minutes

? 60

Input the printout time step in minutes.

? 15
NOTE: Currents are given in Meter/Second

Figure VI.1 Irregularly-Shaped Lake and Current Grid at t = 0
TABLE VI.6b  SAMPLE COMPUTED OUTPUT FOR DEMONSTRATION CASE NO. 5

SPREADING MODEL OUTPUT

THICK SLICK HAS SPREAD OVER AN ELONGATED TRIANGULAR AREA OF .44471E+04 SQUARE METERS AFTER A TIME OF .70944E+01 MINUTES.

THE THICK SLICK LEADING EDGE IS .21947E+03 METERS WIDE AND IS .92255E+02 METERS DOWNSTREAM.

THE THIN SLICK AREA IS EQUAL TO .15738E+05 SQUARE METERS.

TIME = 15.00 MINUTES .449 SECONDS
THICK SLICK AREA = .17094E+05 SQ.M. THICK SLICK THICKNESS = .23930E-02 METERS
THICK SLICK DOWNSTREAM WIDTH = .26411E+03 METERS
THIN SLICK AREA = .3414E+05 SQ.M.
THIN SLICK DOWNSTREAM WIDTH = .6047E+03 METERS

TOTAL MASS OF THICK SLICK = .28399E+05 KG.
TOTAL EVAPORATED MASS = .90152E+03 KG.
RATE OF EVAPORATION = .94970E-04 KG/SEC-SQ.M.
TOTAL DISSOLVED MASS = .1490E+03 KG.
RATE OF DISSOLUTION = .29273E-07 KG/SEC-SQ.M.
TOTAL MASS OF THIN SLICK = .27916E+04 KG.

TOTAL MASS = .31652E+05 KG.

THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .11062E+03 METERS AND Y = .16314E+02 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORIGIN

TIME = 60.00 MINUTES .485 SECONDS
THICK SLICK AREA = .11369E+06 SQ.M. THICK SLICK THICKNESS = .13392E-02 METERS
THICK SLICK DOWNSTREAM WIDTH = .43928E+03 METERS
THIN SLICK AREA = .59423E+05 SQ.M.
THIN SLICK DOWNSTREAM WIDTH = .12498E+03 METERS

TOTAL MASS OF THICK SLICK = .10703E+06 KG.
TOTAL EVAPORATED MASS = .74315E+05 KG.
RATE OF EVAPORATION = .87976E-06 KG/SEC-SQ.M.
TOTAL DISSOLVED MASS = .11357E+01 KG.
RATE OF DISSOLUTION = .24833E-07 KG/SEC-SQ.M.
TOTAL MASS OF THIN SLICK = .40932E+04 KG.

TOTAL MASS = .12656E+06 KG.

THE LEADING EDGE OF THE SLICK IS LOCATED AT X = .91231E+03 METERS AND Y = .59231E+02 METERS
THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORIGIN

TIME = 75.00 MINUTES .449 SECONDS
THICK SLICK AREA = .10894E+06 SQ.M. THICK SLICK THICKNESS = .12827E-02 METERS

TOTAL MASS OF THICK SLICK = .98190E+05 KG.
TOTAL EVAPORATED MASS = .24976E+05 KG.
RATE OF EVAPORATION = .89769E-06 KG/SEC-SQ.M.
TOTAL DISSOLVED MASS = .65172E+01 KG.
RATE OF DISSOLUTION = .24997E-07 KG/SEC-SQ.M.

TOTAL MASS = .12248E+06 KG.

THE CENTER OF THE SLICK IS LOCATED AT X = .48843E+03 METERS AND Y = .59743E+02 METERS
**TABLE VI.6b (CONTD)**

<table>
<thead>
<tr>
<th>TIME</th>
<th>225.00 MINUTES</th>
<th>.485 SECONDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>THICK SLICK AREA</td>
<td>.6008E+03 SQ.M.</td>
<td>.7077E-03 METERS</td>
</tr>
<tr>
<td>TOTAL PASS OF THICK SLICK</td>
<td>.2589E+05 KG.</td>
<td></td>
</tr>
<tr>
<td>TOTAL EVAPORATED PASS</td>
<td>.9254E+05 KG.</td>
<td></td>
</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>.8995E-04 KG/(SEC-SQ.P.)</td>
<td></td>
</tr>
<tr>
<td>TOTAL DISSOLVED PASS</td>
<td>.2614E+02 KG.</td>
<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>.2319E-07 KG/(SEC-SQ.P.)</td>
<td></td>
</tr>
<tr>
<td>TOTAL PASS</td>
<td>.1224E+06 KG.</td>
<td></td>
</tr>
<tr>
<td>THE CENTER OF THE SLICK IS LOCATED AT X = 1.58E+04 METERS AND Y = 2.22E+03 METERS</td>
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</table>

<table>
<thead>
<tr>
<th>TIME</th>
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<td>TOTAL PASS OF THICK SLICK</td>
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<tr>
<td>TOTAL EVAPORATED PASS</td>
<td>.9721E+05 KG.</td>
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</tr>
<tr>
<td>RATE OF EVAPORATION</td>
<td>.8995E-04 KG/(SEC-SQ.P.)</td>
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<tr>
<td>TOTAL DISSOLVED PASS</td>
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<td></td>
</tr>
<tr>
<td>RATE OF DISSOLUTION</td>
<td>.2319E-07 KG/(SEC-SQ.P.)</td>
<td></td>
</tr>
<tr>
<td>TOTAL PASS</td>
<td>.1224E+06 KG.</td>
<td></td>
</tr>
<tr>
<td>THE CENTER OF THE SLICK IS LOCATED AT X = 1.58E+04 METERS AND Y = 2.39E+03 METERS</td>
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</table>
VII. CONCLUSIONS AND RECOMMENDATIONS

The models of spreading, evaporation, dissolution, and movement for spills of buoyant, insoluble chemicals have been completely reformulated and now cover nearly every practical combination of chemical thermophysical properties, discharge rate, total volume spilled, and type of waterway. Eight experimentally-verified models are now available that can be used to assess the hazards of a floating chemical slick from an accidental tank rupture: (1) continuous or (2) instantaneous spills in a steady river; (3) continuous or (4) instantaneous spills in a tidal river; (5) continuous or (6) instantaneous spills in a circular, rectangular, or irregularly-shaped (user-specified) lake; and (7) continuous or (8) instantaneous spills near a straight or irregularly-shaped (user-specified) coast. The wind can be specified as constant or time-varying for all the models, and the currents for the lake and coastal models can be specified as a function of position as well as of time.

The spreading and movement models were adapted from the best state-of-the-art models available. None of the spreading models in the literature accounted for a loss of mass, as would be caused by evaporation of dissolution, and so, the available models had to be modified to include this effect in a realistic way. The final form of the models concentrate on predicting the dynamics of the "gravity-viscous" or "thick slick" phase of the spreading since that phase represents the greatest and most prolonged hazard. The initial, short-duration "gravity-inertial" phase of spreading is included primarily to provide the initial conditions for the gravity-viscous phase. Likewise, the surface tension-viscous or "thin slick" phase of the spreading is included primarily as a small loss-of-mass term in the thick slick equations; evaporation and dissolution from the thin slick are neglected as being very small.

The models for the rate of mass-transfer due to evaporation and dissolution were developed from boundary layer theory and realistically account for the effects of winds and currents. It is recognized that a boundary layer model may not predict all the dissolution processes of floating insoluble chemicals when significant waves are present, but better models are not yet available.

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Large scale instantaneous and continuous spills of a variety of chemicals were used to establish the empirical constants in the spreading models. The spills, organized in accordance with the Test Plan approved by the USCG, were conducted in two facilities—a large outdoor basin, in which spreading could be investigated in water without a current, and an indoor channel, in which spreading in a current could be investigated. Some of the outdoor spills employed volatile chemicals in order to assess the effects of evaporation on spreading. An environmental wind tunnel and a wind-wave tunnel were used to investigate evaporation and dissolution in detail. A variety of different volatile chemicals were employed, and the tests were conducted for many wind speeds and wave characteristics. The predictions of the spreading, evaporation, and dissolution models were then compared to results of tests covering a wide range of conditions of discharge rate, volume spilled, winds, currents, and chemical properties. In all cases, a generally close comparison was found with the test results.

Although the revised models for the spreading, evaporation, dissolution, and movement of floating, insoluble chemicals are now suitable for the Hazard Assessment Computer System, the models could still be extended in several ways. Chemicals of moderate (but low) solubility could be included by further development of the dissolution model to incorporate such mass transfer processes as droplet entrainment by waves; this extension would require additional wind-wave tunnel experiments to acquire the necessary physical insight and data. The continuous-discharge spreading model could be improved by further analysis and testing to make it applicable to conditions of very low transport velocity (e.g., wind without current). All the spreading models could be modified to incorporate the anomalous behavior (e.g., lens formation and slick breakup) observed for some chemicals for some spill conditions. Finally, the long-term movement and potential breakup of the slick in open water could also be included in the model by further research.
REFERENCES


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APPENDIX A

Physical Properties of Chemicals
A.1 Introduction

Some of the chemical properties for spills on water of slightly soluble chemicals with a specific gravity of less than one were included in the revised HACS computer model. Several of these properties, molecular diffusivity for example, were not in the previous HACS model. This appendix describes the models of these physical properties. Tables A.1 through A.4 contain numerical values of various physical properties and their relevant constants for twenty chemicals of interest. The list was expanded to include the seven chemicals in Tables A.5 through A.7; however, this latter list has not been added to the computer code. The physical properties of air and water have also been modeled, but they are not listed in the tables.

Five of the chemicals in Table A.1, butadiene (1,2), chlorobutane-1, 3-diene (2), cyclohexene, methyl cyclohexane, and trimethylbenzene (1,2,3), are not in HACS. Two of these chemicals have boiling points less than 20°C. Butadiene (1,2) and ethyl chloride have boiling points of 10.3 and 12.2°C, respectively. Butadiene (1,2) should not be used with butadiene (1,3), HACS code BD1, which has the same atomic weight but a boiling point of -4.4°C.

A.2 Density

The density of the chemicals in HACS is a linear function of temperature from Potts [A.1]

$$\rho = \rho_0 + \alpha_1 t$$

where $\rho$ is the density in gm/cm$^3$, $t$ is the temperature in °C, and $\alpha_0$ and $\alpha_1$ are constants. Since all chemicals are not in HACS, another model for density was selected. Reid, et al. [A.2] recommend the following formula from Yamada and Gunn [A.3].

$$\rho = \rho_0 z^\phi$$

$$\phi = (1-T_0/T_c)^{2/7} - (1-7/T_c)^{2/7}$$

$$z = 0.29056 - 0.08775 \omega$$

where $\rho_0$ is the reference density at temperature $T_0$ in °K, $T_c$ is the critical temperature in °K, and $\omega$ is the Pitzer acentric factor. The necessary constants for the calculation of density are tabulated in Tables A.1 and A.5. From [A.2], the Pitzer acentric factor is defined as

$$\omega = -\log (p_\phi/p_c) - 1$$
where \( p_c \) is the critical pressure and \( p_v \) is the vapor pressure at \( T = 0.7 T_c \). Values of \( w \) have been compiled by Reid, et al., but those that are not available can be estimated from Eq. A.(3). Critical temperature and pressure are tabulated by Dean [A.4] and Reid, et al. [A.2].

Equations A.(2) are valid over a wider temperature range than the linear approximation of Eq. A.(1). A detailed analysis of the density data has not been done, but spot checks indicate that Eq. A.(1) is accurate within the range of temperatures likely to be encountered in the environment. For example, the difference in density for benzene for Eqs. A.(1) and A.(2) is less than 0.2% between 0 and 40°C. Equations A.(2) appear to be in agreement with the density plots for hydrocarbons from Gallant [A.5, A.6].

The reference values in Tables A.1 and A.3 are all at 20°C although two of the chemicals will vaporize at that temperature. The properties in this table were extrapolated to 20°C by the appropriate formulas for convenience.

A.3 Vapor Pressure and Density

Vapor pressure is required in the calculation of \( w \) in Eq. A.(3) and the vapor density. From [A.4] and [A.1], vapor pressure is related to temperature by

\[
\log p_v = A - B/(C + T)
\]

where \( A, B, \) and \( C \) are constants. The constants from HACS and Dean [A.4] are compared in Table A.2. For the present, the constants from [A.4] are being used in the computer program. Some differences exist, but these may be attributable to the temperature ranges of validity for the constants. Changes in units only affect the constant \( A \) which is

\[
A = \log K + A'
\]

where \( K \) is the conversion constant. For example, if \( A' \) is for \( p_v \) in Torr, then \( K \) must be 1333.2279 for \( p_v \) in dynes/cm². Values of \( A, B, \) and \( C \) are also tabulated by Reid, et al. [A.2] for \( \ln p_v \), but no comparisons have been made since their results must be converted to base 10 logarithm, \( \log \). The conversion formulas are

\[
A = A_e \log e
\]

\[
B = B_e \log e
\]

where \( A_e \) and \( B_e \) are the constants for the natural logarithm, \( \ln \), version of Eq. A.(4).

The mass transfer equation for evaporation from Eq.(III.19) is

\[
J_o = D_{oe} \rho_e u_{oe} (C_o - C_e)
\]
where \( J_0 \) is the mass transfer per unit area, \( D_{at} \) is the Dalton number, \( \rho_a \) is the air density, \( u_{*a} \) is the friction velocity of the air, and \( C_s \) and \( C_a \) are the vapor concentrations at the surface and freestream, respectively. Normally, \( C_a \) is zero. The quantity \( \rho_a C_s \) is the vapor density which is given by the perfect gas law

\[
\rho_v = \frac{M \rho_v}{R_r T_r} \tag{A.(8)}
\]

where \( M \) is the molecular weight of the chemical from Table A.1, \( \rho_v \) is the vapor pressure from Eq. A.(4), \( T_r \) is the absolute surface temperature, and \( R_r \) is the universal gas constant whose value is \( 8.31432 \times 10^7 \) dyne-cm/mole-°K from the U.S. Standard Atmosphere, 1976. [A.7].

### A.4 Diffusivity in Air and Water

Diffusivity is required in the calculation of Dalton number for the mass transfer. The diffusivities in water and air are respectively

\[
D_v = \left( \frac{D_{ow} \mu_{ow}/T_o}{T/T_r} \right) \left( \frac{T}{T_r} \right) \tag{A.(9)}
\]

\[
D_a = \left( \frac{D_{oa} \rho_o/T_0^{3/2}}{T^{3/2}/p} \right) \tag{A.(10)}
\]

where the subscript \( o \) is for the reference value. The reference temperature, \( T_o \), and pressure, \( \rho_o \), are \( 293.15°K \) (20°C) and \( 1.01325 \times 10^6 \) dynes/cm\(^2\), respectively. The reference values of the diffusivities are listed in Table A.1.

The experimental diffusivities of benzene, cyclohexane, pentane, and toluene in water, \( D_{ow} \), are taken from Witherspoon and Bonoli [A.8] and those of benzene, octane, and toluene in air, \( D_{oa} \), are from Gray [A.9]. The remaining diffusivities were estimated by methods described by Park and Dodge [A.30].

Data on the diffusivities in sea water are not available.

### A.5 Surface and Interfacial Tensions

The surface tension and the interfacial tension with water for the various chemicals are required in the spreading model. The surface tension of a liquid as a function of temperature is according to [A.4]

\[
\sigma_o = \sigma_o - a_2 t \tag{A.(11)}
\]

where \( \sigma_o \) and \( a_2 \) are constants and \( t \) is the temperature in °C. Values of the constants from [A.4] are tabulated in Table A.3. Similar information of the interfacial tensions in water as a function of temperature is not available. The surface and interfacial tensions at a specific temperature are also listed in Davies and Rideal [A.10], and Weast and Astle [A.11].

An important parameter in spreading is the net spreading coefficient which is

\[
\sigma = \sigma_w - \sigma_{ow} - \sigma_{oa} \tag{A.(12)}
\]

A-3
where $\gamma_{w}$ is the surface tension of water or the interfacial tension of water and air, $\gamma_{oa}$ is the surface tension of the chemical, and $\gamma_{ow}$ is the interfacial tension of the chemical with water. Estimates of the net spreading coefficient are listed in Tables A.3 and A.7.

The mass transfer equation for dissolution is similar to that of evaporation except that the friction velocity and density are in water. From Eq. A.(7), the mass transfer for dissolution is

$$J_0 = D_{av} \frac{\partial C}{\partial x} (C_s - C_m)$$  \hspace{1cm} A.(13)

The available data on solubility or water concentration at the surface, $C_s$, are contained in Tables A.4 and A.7. The units on solubility are grams of chemical per 100 grams of water. The only data on solubility as a function of temperature are from Guseva and Parnov [A.12] for benzene, toluene, and xylene(m). The best curve fit for benzene and toluene seems to be

$$\log C_s = a_0 + a_1 t$$  \hspace{1cm} A.(14)

whereas the solubility of xylene(m) is nearly constant between 25 and 100^0C. The deviation of experimental data is less than 2% in the temperature range of 0 < t < 50^0C for benzene and -10 < t < 50^0C for toluene. The remaining data in Tables A.4 and A.7 are compiled from [A.4] and [A.13].

A.6 Properties of Air

The necessary physical properties of air are taken from the U.S. Standard Atmosphere, 1976. In particular, air density and viscosity are required in the Reynolds number. The density is computed from the perfect gas law, Eq. A.(8), where the pressure and temperature are the ambient values. The molecular weight of air is 28.9644 while standard pressure and temperature are, respectively, 1.01325 x 10^6 dynes/cm^2 (1013.25 mb) and temperature 288.15 °K (15°C). Viscosity is computed from Sutherland's formula

$$\mu = \frac{\beta T^{3/2}}{(T+S)}$$  \hspace{1cm} A.(15)

where $\beta$ is a constant equal to 1.458 x 10^-5, $S$ is Sutherland's constant equal to 110.4 °K, and $\mu$ is the absolute viscosity in Poise.

A.7 Properties of Water

The density, viscosity, and surface tension of water are required in the spreading model. These quantities are very accurately known for pure water. The density of water from Gildseh, et al. [A.14] is

$$\rho = 1 - [\frac{(t - 3.9863)^2 (t + 288.9414)}{[508929.2 (t + 68.12967)]} + 0.011445 \exp (-374.3/t)]$$  \hspace{1cm} A.(16)
where $\rho$ is in g/ml. Equation A.(16) fits experimental data with a mean absolute deviation of $0.7 \times 10^{-6}$ g/ml for $5 < t < 80^\circ C$.

The viscosity of water has been correlated with temperature within a $\pm 0.05\%$ average deviation by Korosi and Fabus [A.15] with their measurements as

$$\log \frac{\mu_20/\mu}{} = \frac{[A(t - 20) + B(t - 20)^2]/(C + t)}{}$$  

A.(17)

for $20 < t < 150^\circ C$ where $A = 1.37023$, $B = 0.000836$, and $C = 109$. The viscosity at $20^\circ C$, $\mu_20$, has been measured as $0.010019 \pm 0.000003$ Poise by Swindells, et al. [A.16], and the National Bureau of Standards (NBS) has adopted 0.01002 as the standard value. Hardy and Cottington [A.17] proposed the following interpolation formula for their measurements for $0 < t < 40^\circ C$

$$\log \mu = \frac{1301}/[998.333 + 8.1855 (t - 20) - 0.00585 (t - 20)^2] - 3.30233$$  

A.(18)

which has been altered to give the newer value of viscosity at $20^\circ C$.

Similar formulas for the density and viscosity of sea water have not been discovered although tabulated values are available. Cox [A.18] has tabulated the specific gravity anomaly of sea water as a function of temperature and salinity. The viscosity of sea water as a function of temperature for a salinity of 35 o/oo has been compiled by King [A.19]. Cox [A.17] has given the surface tension of sea water as

$$\sigma_{wa} = 75.64 - 0.144 t + 0.0399 C2$$  

A.(19)

where $C2$ is chlorinity in o/oo and chlorinity and salinity are related by

$$S2 = 1.805 C2 + 0.030$$  

A.(20)
APPENDIX A. REFERENCES


TABLE A.1 Properties of Relevant Chemicals at 20°C and 1013.25 mb

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>HACS No.</th>
<th>Dean No.</th>
<th>Reid No.</th>
<th>Molecular Weight</th>
<th>Reference Density $\rho_0$ (g/m$^3$)</th>
<th>Pitzer Acentric Factor $\omega$</th>
<th>Critical Temperature $T_C$ (°K)</th>
<th>Diffusivity in Air $D_{OA}$ (cm$^2$/s)</th>
<th>Diffusivity in Water $D_{OW}$ (cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aliyil Chloride</td>
<td>ALC</td>
<td>202</td>
<td>116</td>
<td>76.526</td>
<td>0.938</td>
<td>0.13</td>
<td>514.15</td>
<td>0.097</td>
<td>1.019</td>
</tr>
<tr>
<td>Benzene</td>
<td>BNZ</td>
<td>656</td>
<td>242</td>
<td>78.114</td>
<td>0.879</td>
<td>0.212</td>
<td>562.09</td>
<td>0.087</td>
<td>1.02</td>
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<tr>
<td>Butadiene (1,2)</td>
<td>1018</td>
<td>152</td>
<td>54.092</td>
<td>0.652</td>
<td>0.255</td>
<td>443.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butyl Acetate (iso)</td>
<td>IBA</td>
<td>1031</td>
<td>267</td>
<td>116.160</td>
<td>0.871</td>
<td>0.479</td>
<td>561.15</td>
<td>0.064</td>
<td>0.712</td>
</tr>
<tr>
<td>Butyl Mercaptan (n)</td>
<td>BTM</td>
<td>1103</td>
<td></td>
<td>90.19</td>
<td>0.841</td>
<td>0.300</td>
<td>562.95</td>
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<td></td>
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<td>Chlorobuta-1,3-diene (2)</td>
<td>CRP</td>
<td>1345</td>
<td></td>
<td>88.54</td>
<td>0.956</td>
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<td></td>
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<td>Cyclohexane</td>
<td>CHX</td>
<td>1601</td>
<td>249</td>
<td>84.162</td>
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<td>0.213</td>
<td>553.45</td>
<td>0.081</td>
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<td>0.810</td>
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<td>560.41</td>
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<td>0.085</td>
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<td>Dipropyl Ether (iso)</td>
<td>IPE</td>
<td>2784</td>
<td>278</td>
<td>102.177</td>
<td>0.725</td>
<td>0.34</td>
<td>500.05</td>
<td>0.063</td>
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<td>Ethyl Chloride</td>
<td>ECL</td>
<td>3015</td>
<td>97</td>
<td>64.515</td>
<td>0.896</td>
<td>0.190</td>
<td>460.35</td>
<td>0.0913</td>
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<td>Ethyl Mercaptan</td>
<td>EMC</td>
<td>3083</td>
<td>104</td>
<td>62.134</td>
<td>0.839</td>
<td>0.190</td>
<td>499.15</td>
<td>0.0983</td>
<td>1.533</td>
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<td>Heptane (n)</td>
<td>HPT</td>
<td>3512</td>
<td>308</td>
<td>100.205</td>
<td>0.684</td>
<td>0.351</td>
<td>540.15</td>
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<td>Hexane (n)</td>
<td>HXN</td>
<td>3603</td>
<td>271</td>
<td>86.178</td>
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<td>0.296</td>
<td>507.35</td>
<td>0.070</td>
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<td>4199</td>
<td>305</td>
<td>98.189</td>
<td>0.769</td>
<td>0.233</td>
<td>572.25</td>
<td>0.072</td>
<td>0.799</td>
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<tr>
<td>Nonane (n)</td>
<td>NAN</td>
<td>4917</td>
<td>389</td>
<td>128.259</td>
<td>0.718</td>
<td>0.444</td>
<td>594.56</td>
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<td>0.597</td>
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<td>Octane (n)</td>
<td>OAN</td>
<td>4944</td>
<td>354</td>
<td>114.232</td>
<td>0.703</td>
<td>0.394</td>
<td>568.76</td>
<td>0.058</td>
<td>0.638</td>
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<tr>
<td>Pentane</td>
<td>PTA</td>
<td>5083</td>
<td>223</td>
<td>72.151</td>
<td>0.626</td>
<td>0.251</td>
<td>469.65</td>
<td>0.075</td>
<td>0.84</td>
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<tr>
<td>Toluene</td>
<td>TOL</td>
<td>5960</td>
<td>286</td>
<td>92.141</td>
<td>0.867</td>
<td>0.257</td>
<td>591.72</td>
<td>0.083</td>
<td>0.85</td>
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<td>Trimethylbenzene(1,2,3)</td>
<td>6253</td>
<td>383</td>
<td>120.195</td>
<td>0.894</td>
<td>0.39</td>
<td>664.45</td>
<td>0.065</td>
<td>0.695</td>
<td></td>
</tr>
<tr>
<td>Xylene (m)</td>
<td>XLH</td>
<td>6457</td>
<td>323</td>
<td>106.168</td>
<td>0.864</td>
<td>0.331</td>
<td>616.97</td>
<td>0.072</td>
<td>0.756</td>
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<table>
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<tr>
<td>Allyl Chloride</td>
<td>ALC</td>
<td>10.84</td>
<td>1540.</td>
<td>273.2</td>
<td>386.91</td>
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<td>17.13</td>
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<td>1877.</td>
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<td>45.07</td>
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<td>9.28640</td>
<td>783.45</td>
<td>179.7</td>
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<td>IPE</td>
<td>10.81</td>
<td>9.9744</td>
<td>1644.</td>
<td>1139.34</td>
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<td>273.2</td>
<td>1350.11</td>
<td>3573.66</td>
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<td>10.03</td>
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<td>1171.17</td>
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<td>202.01</td>
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<td>1064.84</td>
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\[ \log p_v = A - B/(t+C) \] where $p_v$ is the vapor pressure in dynes/cm², and $t$ is the temperature in °C.

References:
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<tr>
<th>Chemical Name</th>
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<th>Constants $^a$</th>
<th>Surface Tension $\sigma_{oa}$</th>
<th>Temperature $t$ ($^\circ$C)</th>
<th>Interfacial Tension $\sigma_{ow}$</th>
<th>Temperature $t$ ($^\circ$C)</th>
<th>Spreading Coefficient $\sigma$ (dynes/cm)</th>
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$^a\sigma_{oa} = n_0 - n_1 t$ where $t$ is temperature in $^\circ$C.

$^b\sigma = \sigma_{ow} - \sigma_{oa} - \sigma_{ow}$
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<th>Chemical Name</th>
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<th>Constants&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Solubility C&lt;sub&gt;s&lt;/sub&gt; (%)</th>
<th>Temperature t (°C)</th>
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<sup>a</sup> log C<sub>s</sub> = a<sub>0</sub> + a<sub>1</sub>t

where C<sub>s</sub> is solubility in g/100g of H<sub>2</sub>O, and t is temperature in °C
### TABLE A.5 Properties of Chemicals with High Spreading Coefficients

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>HACS No.</th>
<th>Dean No.</th>
<th>Reid No.</th>
<th>Molecular Weight</th>
<th>Reference Density $\rho_o$ (gm/cm³)</th>
<th>Pitzer Acentric Factor $\omega$</th>
<th>Critical Temperature $T_c$ (°K)</th>
<th>Diffusivity in Air $D_{oa}$ (cm²/s)</th>
<th>Diffusivity in Water $10^5D_{ow}$ (cm²/s)</th>
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<tr>
<td>Amyl Alcohol (n)</td>
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<td>226</td>
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<td>0.58</td>
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<td>BAN</td>
<td>1034</td>
<td>183</td>
<td>74.123</td>
<td>0.610</td>
<td>0.590</td>
<td>562.93</td>
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<td>0.923</td>
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<td>Ether</td>
<td>EET</td>
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<td>187</td>
<td>74.123</td>
<td>0.713</td>
<td>0.281</td>
<td>466.70</td>
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<td>172</td>
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<td>0.303</td>
<td>523.25</td>
<td>0.083</td>
<td>0.898</td>
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<td>Hexyl Alcohol (n)</td>
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<td>184.27</td>
<td>0.910</td>
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**References:**


TABLE A.6  Vapor Properties of Chemicals with High Spreading Coefficients

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Vapor Pressure, P_v @ 20°C (mb)</th>
<th>Vapor Density, p_v @ 20°C (µg/cm³)</th>
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</thead>
<tbody>
<tr>
<td>Amyl Alcohol (n)</td>
<td>10.30248</td>
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\[ \log P_v = A - B/(t + C) \] where \( P_v \) is the vapor pressure in dynes/cm² and \( t \) is the temperature in °C.

Reference:

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>Constants</th>
<th>Surface Tension, $\sigma_{oo}$ @ 20°C (dynes/cm)</th>
<th>Interfacial Tension, $\sigma_{ow}$ (dynes/cm)</th>
<th>Temperature for $\sigma_{ow}$, t (°C)</th>
<th>Spreading Coefficient $\sigma$ (dynes/cm)</th>
<th>Solubility $c_s$ (o/o)</th>
<th>Temperature for $c_s$, t (°C)</th>
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<tr>
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References:


APPENDIX B

Subroutines, Symbols, and Flow Charts
for Program DMODEL
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<td>SPREAD</td>
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<td>6. DISS</td>
<td>---</td>
<td>INTE</td>
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<tr>
<td>7. EVAP</td>
<td>---</td>
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</tr>
<tr>
<td>24.</td>
<td>UERTST</td>
<td>Calls: UGETIO</td>
</tr>
</tbody>
</table>

TABLE B.1 (CONTD)
TABLE B.1 (CONTD)

25. UGETIO
   Calls: ---
   Called by: UERTST

26. UTPEAK
   Calls: ---
   Called by: SPREAD

27. WATER
   Calls: ---
   Called by: DMODEL

28. WBS
   Calls: WIND
   Called by: DMODEL

29. WIND
   Calls: ---
   Called by: WBS
<table>
<thead>
<tr>
<th>TABLE B.2 INPUT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
</tr>
<tr>
<td><strong>TITLE</strong></td>
</tr>
<tr>
<td><strong>TDC</strong></td>
</tr>
<tr>
<td><strong>PB</strong></td>
</tr>
<tr>
<td><strong>DELT</strong></td>
</tr>
<tr>
<td><strong>TSTOP</strong></td>
</tr>
<tr>
<td><strong>HMIN</strong></td>
</tr>
<tr>
<td><strong>HTN</strong></td>
</tr>
<tr>
<td><strong>TPT</strong></td>
</tr>
<tr>
<td><strong>Chemical Properties</strong></td>
</tr>
<tr>
<td><strong>DEN0</strong></td>
</tr>
<tr>
<td><strong>CMW</strong></td>
</tr>
<tr>
<td><strong>DCA</strong></td>
</tr>
<tr>
<td><strong>DCW</strong></td>
</tr>
<tr>
<td><strong>PV</strong></td>
</tr>
<tr>
<td><strong>CS</strong></td>
</tr>
<tr>
<td><strong>SIGOA</strong></td>
</tr>
<tr>
<td><strong>SIGOW</strong></td>
</tr>
<tr>
<td><strong>Discharge Parameters</strong></td>
</tr>
<tr>
<td><strong>ITYPE</strong></td>
</tr>
<tr>
<td><strong>TEM</strong></td>
</tr>
<tr>
<td><strong>TSPILL</strong></td>
</tr>
</tbody>
</table>
TABLE 8.2 (CONTD)

Water Body (not all are needed, depending on water body)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_0, Y_0$</td>
<td>Coordinates of spill source, meters (open water only)</td>
</tr>
<tr>
<td>$W$</td>
<td>Width of river, meters</td>
</tr>
<tr>
<td>$D$</td>
<td>Depth of river, lake, or coastal water, meters</td>
</tr>
<tr>
<td>$R_O$</td>
<td>Roughness of river bottom, meters</td>
</tr>
<tr>
<td>$U_C$</td>
<td>Current in river, meter/sec</td>
</tr>
<tr>
<td>$U_0, U_1, W_T, A_LPH$</td>
<td>For a tidal river: average current, m/sec; amplitude of sinusoidal current, m/sec; tidal period, minutes; phase of tide with respect to time of spill, minutes</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius of circular lake, meters</td>
</tr>
<tr>
<td>$L_1, L_2$</td>
<td>Width and breadth of rectangular lake, meters</td>
</tr>
<tr>
<td>$X(I), Y(I)$</td>
<td>Ten $x,y$ coordinates describing irregularly-shaped lake or coast, meters</td>
</tr>
<tr>
<td>$X(I), Y(I); X(2), Y(2)$</td>
<td>Two $x,y$ coordinates describing a straight coast line, meters</td>
</tr>
<tr>
<td>$U_X(I), U_Y(I)$</td>
<td>Components of a constant current in open water, meter/sec</td>
</tr>
<tr>
<td>$U_X(I,J), U_Y(I,J)$</td>
<td>Components of a time- or spatial-varying current in open water, meter/sec; $I =$ spatial position; $J =$ time.</td>
</tr>
<tr>
<td>$T_I(I)$</td>
<td>Ten specified time instants for a time-varying current in open water, minutes</td>
</tr>
<tr>
<td>$X_U(I), Y_U(I)$</td>
<td>Four $x,y$ coordinates (lake) or 10 $x,y$ coordinates (coastal water) that describe space grid for a spatially-varying current in open water, meters</td>
</tr>
<tr>
<td>$V_W$</td>
<td>Constant wind speed, meter/second</td>
</tr>
<tr>
<td>$THETA_1$</td>
<td>Direction of constant wind with respect to channel axis or $x$-axis (open water), degrees</td>
</tr>
<tr>
<td>$V_WX(I)$</td>
<td>Magnitude of time-varying wind at time $I$, meter/second</td>
</tr>
<tr>
<td>$THETA(I)$</td>
<td>Direction of time-varying wind with respect to channel axis or $x$-axis (open water), degrees</td>
</tr>
<tr>
<td>$T_T(I)$</td>
<td>Ten specified time instants for a time-varying wind, minutes</td>
</tr>
</tbody>
</table>

B-6
### TABLE B.3 COMPUTED OUTPUT VARIABLES

#### Initial Conditions (not all used for any case)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATK</td>
<td>Thick slick area, m²</td>
</tr>
<tr>
<td>TIIT</td>
<td>Time required for thick slick to spread across channel, minutes</td>
</tr>
<tr>
<td>HTK</td>
<td>Thick slick thickness, meters</td>
</tr>
<tr>
<td>Z</td>
<td>Downstream location of leading edge of thick slick (continuous spill), meters</td>
</tr>
<tr>
<td>DMASS</td>
<td>Mass lost from thick slick, kg</td>
</tr>
<tr>
<td>WTK</td>
<td>Downstream width of triangular slick, meters</td>
</tr>
<tr>
<td>RADIUS</td>
<td>Radius of thick slick, meters</td>
</tr>
</tbody>
</table>

#### Regular Printout (not all used for any case)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP,DIFFT</td>
<td>Time of printout, minutes and seconds</td>
</tr>
<tr>
<td>YY(1)</td>
<td>Thick slick area, m²</td>
</tr>
<tr>
<td>YY(3)</td>
<td>Thick slick thickness, meters</td>
</tr>
<tr>
<td>RAD1</td>
<td>Thick slick radius, meters</td>
</tr>
<tr>
<td>YY(2)</td>
<td>Thin slick area, m²</td>
</tr>
<tr>
<td>RAD2</td>
<td>Thin slick radius, m²</td>
</tr>
<tr>
<td>TOTALM</td>
<td>Mass of thick slick, kg</td>
</tr>
<tr>
<td>TOTALE</td>
<td>Evaporated mass, kg</td>
</tr>
<tr>
<td>TOTALD</td>
<td>Dissolved mass, kg</td>
</tr>
<tr>
<td>EVAPM</td>
<td>Rate of evaporation, kg/second</td>
</tr>
<tr>
<td>DISSOM</td>
<td>Rate of dissolution, kg/second</td>
</tr>
<tr>
<td>TMASS</td>
<td>Mass of thin slick, kg</td>
</tr>
<tr>
<td>TOTS</td>
<td>Mass of thin and thick slicks added to evaporated and dissolved masses, kg</td>
</tr>
<tr>
<td>XW</td>
<td>Downstream width of triangular slick, meters</td>
</tr>
<tr>
<td>Code</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>XC, YC</td>
<td>Location of center of an instantaneous spill (open water), meters</td>
</tr>
<tr>
<td>XC</td>
<td>Movement of an instantaneous spill in a river, meters</td>
</tr>
<tr>
<td>—</td>
<td>Upstream and downstream edges of an instantaneous spill in a river, meters</td>
</tr>
<tr>
<td>TEMP1, TEMP2</td>
<td>Upstream and downstream locations of a continuous spill in a river, meters</td>
</tr>
<tr>
<td>XLE, YLE</td>
<td>Coordinates of leading edge of a triangular spill, meters</td>
</tr>
<tr>
<td>—</td>
<td>Time when slick impacts a coast</td>
</tr>
<tr>
<td>—</td>
<td>Time when thick slick thickness is less than HMIN</td>
</tr>
</tbody>
</table>
FIGURES B.1 TO B.16 ARE THE FLOW CHARTS OF PROGRAM "DMODEL" and ALL SUBROUTINES. THE SUBROUTINES ARE GIVEN IN THE ORDER THEY ARE FIRST ENCOUNTERED IN THE PROGRAM, NOT IN ALPHABETICAL ORDER.
FIGURE B.1 FLOW CHART FOR PROGRAM "DMODEL"

Read in title descriptor of up to 30 characters

Read in following input:
1. Ambient temperature, TDC
2. Barometric pressure, PB
3. Integration time step, DELT
4. Maximum printout time, TSTOP
5. Minimum thickness of thick slick, HMIN
6. Thin slick thickness, HTN

Call AIR
Call WATER
Calculate surface tension of water SIGWA

Initialize all variables

Call WBS
Call SPLOC
Call SPTYPE

Call SPREAD

END

Subroutine "AIR"
This subroutine calculates the density and viscosity of air as a function of pressure and temperature.

Subroutine "WATER"
This subroutine calculates the density and viscosity of water as a function of temperature.
FIGURE B.2 FLOW CHART FOR SUBROUTINE "WBS"

Subroutine "WBS"

Subroutine is used to input description of the water body in which spill occurs

10

Is spill in a river of channel?

Yes

Input width WW and Depth D
Input bottom roughness RO

Input current UC. If UC = 0, set IC = 0 and SHAPE = 1.0; if UC > 0, set IC = 1 and SHAPE = 1.1; if UC is tidal, set IC = 2 and SHAPE = 1.2, and input U0, U1, WT, and \( \alpha \) in description

\[ UC = U0 + U1 \times \sin \left(2\pi \frac{(t+\alpha)}{WT}\right) \]

No

Go to 100

100

Is spill in a lake?

Yes

Go to 140

No

Go to 500

If lake is circular, input radius R and depth D; set SHAPE = 2.1. If lake is rectangular, input length L1, width L2, and depth D; set SHAPE = 2.2. If lake is irregularly shaped, input ten X(I), Y(I) boundary coordinates, and depth D; set SHAPE = 2.3

B-12
FIGURE B.2 (CONT'D)

140 Give depth D of coastal water. If coast line is straight, give X(1), Y(1), and X(2), Y(2) that locate the coast; set SHAPE = 3.1. If coast line is irregular, give ten X(I), Y(I) coordinates; set SHAPE = 3.2.

500 Input current components UCX and UCY. If current is zero, set IC = 0. If current is constant, set IC = 1. If current is function of space only, set IC = 2 and give UCX and UCY at nine locations. If current is function of time only, set IC = 3 and give UCX and UCY at ten time instants. If current is function of time and space, set IC = 4 and give UCX and UCY at nine locations for ten time instants.

600 Is there wind?

Yes

Call "WIND"

Subroutine "WIND"

This subroutine inputs wind speed VW and direction THETA. If VW = 0, set IW = 0. If VW is constant, set IW = 1. If VW is a function of time, set VW = 2 and give VW and THETA at ten time instants. Also used to input wave height H.

If wind and current both equal zero, set transport velocity UTBAR = 0

Return to "DMODEL"

No

If there wind?

Return to "WBS" and then to "DMODEL"
FIGURE B.3 FLOW CHARTS FOR SUBROUTINES "SPLOC" AND "SPTYPE"

Subroutine "SPLOC"

If I, the integer part of SHAPE, is 1 (i.e., if the spill is in a river or channel) the spill is assumed to occur at $x = 0$, and $x > 0$ is the downstream direction. If $I > 2$, the spill source, XO and YO, are input. If the current is a function of space, the grid locating the spill source, ISP, is also input.

Return to "DMODEL"

Subroutine "SPTYPE"

Enter name of chemical and the chemical properties; density DENO, molecular weight CMW, diffusion coefficient in air DCA, diffusion coefficient in water DCW, vapor pressure PV, solubility limit CS, air/chemical interface tension SIGOA, and water/chemical interface tension SIGOW. They can be read in for some chemicals from subroutine CHEMICL. Calculate spreading coefficient SIG, and density difference coefficient, COEF = 1 — DEND/DENW.

Is spill continuous?

Yes

Go to 200

No

100

Input total spilled volume TEM and calculate spilled mass SPILLM = TEM * DENO.

If spill is in river or channel, set STP = 1.1.
If spill is in lake or coastal water, set STP = 1.2

Go to 299

B-14
Input the rate of discharge TEM and total spill duration TSPILL. Calculate mass discharge rate SPILMR = TEM * DENO

If the current and wind are zero, and spill is in a river or channel, set STP = 2.1. If the current and wind are not zero and spill is in a river or channel, set STP = 2.2. If the current and wind are zero, and spill is in open water, set STP = 4.1. If the current and wind are not zero, and spill is open water, set STP = 4.2

Return to "DMODEL"
Subroutine "SPREAD"
This is the main computational block

Input desired printout interval TPT

Compute wind and currents at \( t = 0 \)

Is the spill continuous (integer part of STP = 4)?

Yes

Is the current a function of time or space, or is the wind a function of time?

No

Go to 200

Yes

Compute \( UTBAR = \left| \bar{U}_c + 0.035 \cdot V_w \right| \)

Go to 200

Call UTPEAK
Call CURRT

If average transport velocity at the spill source > 0.3 \(*\) peak transport velocity at the spill source, set \( UTBAR \) equal to average. Otherwise, \( UTBAR = 0 \) and spill type is changed to a continuous spill without a current

200

Call INIT to compute initial conditions

300

Start of Integration Loop
FIGURE B.4 (CONTD)

Is spill continuous?

Yes \(\rightarrow\) No \(\rightarrow\) Go to 350

Is current time TIME greater than TSPILL?

Yes \(\rightarrow\) Go to 350

No \(\rightarrow\)

Call SWITCH to start appropriate instantaneous model

350

Call TRANSP to calculate the transport velocity \(U_T\)

Call INTE to use numerical integration to advance the computations by one time step

Is TIME greater than TSTOP?

Yes \(\rightarrow\) Go to 353

No \(\rightarrow\)

Is spill in a river or channel?

Yes \(\rightarrow\) Go to 351

No \(\rightarrow\)

Call GROUND to determine if slick has impacted on beach

351

If TCHECK < TIME, a subroutine CHECKMS (called elsewhere) has determined that the rate of mass loss equals the rate of discharge (for a continuous spill) or that the spill has evaporated/dissolved completely (for an instantaneous spill). If so, a printout is made, and for a continuous spill, the spill area and mass is held constant until TIME > TSPILL.

8-17
FIGURE B.4 (CONTD)

Call MOVE

If the current TIME is equal to a desired printout time, subroutine PRINTO is called

Is thick slick thickness less than HMIN or TIME > TSTOP?

Yes

Return to "DMODEL"

No

Go to 300

Printout boundary impact information

Return to "DMODEL"
Subroutine "UTPEAK'  
Calculates the maximum value of a time-varying transport velocity

Is spill in river of channel?

Yes  Go to 100

No

Calculate maximum value of $U_C + 0.035 V_W \cos \theta = U_{PEAK}(1)$

Go to 999

100 Calculate maximum value of $[(U_{CX} + 0.035 V_{WX})^2 + (U_{CY} + 0.035 V_{WY})^2]^{1/2} = U_{PEAK}(1)$

999 Return to SPREAD

Subroutine "CURRT'  
Calculated average value of transport velocity over the entire spill duration

Is spill in river or channel?

Yes  Go to 200

No

If current is tidal and the spilling time is greater than one tidal cycle, the average current is taken as the steady part, $U_C = U_0$. Otherwise, the time average value of $UC$ is computed. Then the time average value of $V_{W} \cos \theta$ is computed. The average transport velocity is $U_{BAR}(1) = U_C + 0.035 V_W \cos \theta$.  

B-19
First, calculate average value of wind components \( VWX_1 \) and \( VY_1 \) over the spill duration. If the current is constant, then calculate average transport velocity \( UBAR(1) \) and average wind direction, \( \Theta(1) \). Otherwise, the average current at each spatial location is calculated, and average \( UBAR(I) \) and \( \Theta(I) \) is computed.
FIGURE B.6 FLOW CHART FOR SUBROUTINE "INIT"

Subroutine "INIT"

If spill is instantaneous in a channel, call INT12A.
If spill is continuous in a channel without a current, call INT12A.
If spill is instantaneous in open water, call INT12B.
If spill is continuous in open water without a current, call INT12B.
If spill is continuous in a channel with a current, call INIT4A.
If spill is continuous in open water with a current, call INIT4B.

Return to SPREAD

Subroutine "INT12A"

This subroutine calculates initial conditions for spills in a channel. If the spill is continuous, and the time required for the spill to spread across the channel is greater than TSPILL, the spill is changed to instantaneous. In either case, if the time required for the spill to spread across the channel is greater than the gravity-inertial phase maximum time, the calculations are continued by numerical integration, just as in SPREAD, until the spill spreads across the channel.
Subroutine "INT12B"

This subroutine calculates initial conditions for spills in open water.

Subroutine "INIT4A"

This subroutine calculates initial conditions for continuous spills in a channel with a current. If the time required for the spill to spread across the channel is greater than the gravity-inertial phase maximum time, the calculations are continued by numerical integration, just as in SPREAD, unt. the spill spreads across the channel.

Subroutine "INIT4B"

This subroutine calculates initial conditions for continuous spills in open water without a current.
This subroutine switches a continuous spill model to an appropriate instantaneous spill model when \( \text{TIME} > \text{TSPILL} \). If the spill is in open water, and the slick is wide compared to its length, the slick spreads as if it were in a channel until the slick shape is more regular. Afterwards, it spreads as an instantaneous slick in open water.
Subroutine INTE

Subroutine used to advance solution by one time step

Call EVAP
Call DISS

If spill is instantaneous in a channel, call RUNKUT using subroutine FCN11 for equations. If spill is instantaneous in open water, call RUNKUT using subroutine FCN12 for equations. If spill is continuous in a channel without a current, call RUNKUT with subroutine FCN21 for equations. If spill is continuous in open water without a current, call RUNKUT with subroutine FCN22 for equations. If spill is continuous in a channel with a current, call RUNKUT with subroutine FCN41 for equations. If spill is continuous in open water with a current, call RUNKUT with subroutine FCN42 for equations.

Call CHECKMS, which returns IDEB = 0 or IDEB = 2. If IDEB = 0, TCHECK is computed as TIME - DELT. (In DMODEL, TCHECK was initially set as TSTOP.)

Return to SPREAD, SWITCH, INT12A, or INIT4A
FIGURE B.9 FLOW CHART FOR INTEGRATION EQUATIONS

Subroutine FCN11

This subroutine contains the dA/dt and dh/dt equations for an instantaneous spill in a channel.

Subroutine FCN12

This subroutine contains the dA/dt and dh/dt equations for an instantaneous spill in open water.

Subroutine FCN21

This subroutine contains the dA/dt, dA/dt, and dh/dt equations for a continuous spill in a channel without a current.

Subroutine FCN22

This subroutine contains the dA/dt, dA/dt, and dh/dt equations for a continuous spill in open water without a current.

Subroutine FCN41

This subroutine contains the dA/dt, dA/dt, and dh/dt equations for a continuous spill in a channel with a current.

Subroutine FCN42

This subroutine contains the dA/dt, dA/dt, and dh/dt equations for a continuous spill in open water with a current.
FIGURE B.10 SUBROUTINES FOR MASS TRANSFER COEFFICIENTS

Subroutine EVAP

This subroutine computes the evaporation mass transfer coefficient $\text{EVAP}_M$ as a function of the relative wind speed $\text{UREL}$ over the slick. ($\text{UREL}$ is computed in TRANSP).

Subroutine DISS

This subroutine computes the dissolution mass transfer coefficient $\text{DISS}_M$ as a function of wind, current, wave height, and bottom roughness.
Subroutine TRANSP  
Calculates the velocity used to move the slick

Is spill in river of channel?

Yes  
Go to 100

No

If current is a function of space, the grid in which the leading edge is located is determined. The current and the wind at that location and that time are computed, and the velocity components $UTX$, $UTY$, $UREL$ (relative wind speed), and $VTOT = (UTX^2 + UTY^2)\frac{1}{2}$ are computed

Go to 999

100  
If wind is a function of time, the $VWX$ and $VWY$ components at time of interest are computed as well as the current. Then $UTX$, $UREL$ (relative wind speed), and $UTOT = UTX$ are computed

999  
Return to SPREAD, SWITCH, INT12A, or INIT4A

B-27
Subroutine MOVE  
Calculates movement of slick

Is spill instantaneous?

Yes

Compute motion of center of slick during one time step

Go to 999

No

Go to 200

Using appropriate transport velocity components, calculate the movement of the leading edge during one time step

Return to SPREAD, SWITCH, INT12A, or INIT4A
Subroutine PRINTO
Organizes and prints out spreading, evaporation, dissolution, and movement results

First, the thickness and area of the slicks are printed out, followed by the evaporated and dissolved masses.

The upstream and downstream edge locations of the slick are printed out, or the location of the slick center for an instantaneous spill

Return to SPREAD, SWITCH, INT12A, or !M1f4A
FIGURE B.14 FLOW CHART FOR SUBROUTINE "CHECKMS"

- Subroutine CHECKMS
- Set IDEB = 2
- Is spill continuous?
  - Yes
    - If the rate of evaporation, dissolution, and feeding to thin slick is greater than discharge rate, set IDEB = 0
    - Return to INTE
  - No
    - Go to 10
- 10
  - If the sum of the evaporated and dissolved mass is greater than the spilled mass, set IDEB = 0; likewise, if slick area is zero.
  - Return to INTE
This subroutine performs a Runge-Kutta integration on N simultaneous differential equations FCN from an initial time TIME to final time XEND. It calls subroutines UERTST.

Return to INTE

Subroutine UERTST

Determines if an error has occurred in RUNKUT; also calls UGETIO

Subroutine UGETIO

Manipulates input and output of RUNKUT; called by UERTST
FIGURE B.16 FLOW CHART FOR SUBROUTINE "CHEMICL"

Subroutine CHEMICL

This subroutine contains thermophysical property data for twenty chemicals that can be supplied to describe the spill.

Return to SPTYPE
APPENDIX C

PROGRAM "DMODEL" LISTING

Subroutines of DMODEL are given in alphabetical order
PROGRAM DMODEL  

DIFFUSION AND DISPERSION MODEL  

THIS PROGRAM READS IN THE RUN TITLE AND THE INPUT VALUES FOR: 

- TDC = AMBIENT TEMPERATURE  
- PB = BAROMETRIC PRESSURE  
- DELT = INTEGRATION TIME STEP  
- TSTOP = MAXIMUM TIME FOR PRINTOUT (END OF RUN)  
- HMIN = DES.RED MINIMUM THICKNESS OF THICK SLICK; RUN ENDS WHEN THICKNESS BECOMES LESS THAN HMIN  
- HTN = CONSTANT THICKNESS OF THIN SLICK, USUALLY EQUAL TO HMIN  

THE PROGRAM ALSO CALCULATES THE SURFACE TENSION OF WATER = SIGWA, AND CALLS SUBROUTINES "AIR" AND "WATER" TO CALCULATE AIR AND WATER PROPERTIES. IT Initializes ALL VARIABLES. IT CALLS SUBROUTINES "WBS", "SPLOC", AND "SPTYPE", AND FINALLY CALLS "SPREAD" TO MAKE THE SPREADING CALCULATIONS.

COMMON/SIZE/R, D, WW, LI, L2, H, RO  
COMMON/CHEMI/DENW, DCA, DCW, CS, CMW  
COMMON/WATER/DENW, VISW, QR  
COMMON/ENVOR/PV, VISW, DEMA, TDC  
COMMON/INTER/COEF, SIGWA, SIGOA, SIGOW, SIG  
COMMON/CONST/UC, VW, UBAR, UC, UI, WT, ALPH, THETA1  
COMMON/MLOSS/EVAPM, DISSOM  
COMMON/MOVE/UPSAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK  
COMMON/CURRENT/UBAR(10), DMOVE, UTOT, UTX, UTY, UREL  
COMMON/MASS/TOT, TOTALE, TOTALD, TOTALM, DMASS  
COMMON/CONTOR/X(10), Y(10), XC, IC, IW, ISP, XO, YO  
COMMON/TRANSIT/UX(10, 10), UY(10, 10), VWX(10), VWY(10), WX, WY, THETA(10), T(10), T1, ID, IT, IV  
COMMON/ID/ID1, ID2, ID3  
COMMON/RUNGE/YY(5), C(24), W(5,30)  
COMMON/SPREAD/TII, ATK, HTA, ATN, HTN, HMIN, INDEX, IFLAG  
COMMON/TYPE/SPILLM, SPILLR, TSPILL, WS, STP, SPM  
COMMON/SENSE/EVA(40,10), DIS(40,10), THK(40,10), TIN(40,10), PIP(40), TPT  
COMMON/K/C10, C20, C11, C21, C12, C22, K10, K20, K11, K21, K12, K22  
DIMENSION NAME(30,20)  
REAL K10, K20, K11, K21, K12, K22  

C10-K22 ARE THE CONSTANTS IN THE SPREADING MODELS  

C10=2.37  
C20=3.65  
C11=2.37  
C21=3.65  
C12=2.37
C22 = 3.65
K10 = 1.53
K20 = 1.21
K11 = 1.24
K21 = 1.09
K12 = 2.37
K22 = 3.65
C
IFLAG = 1
INDEX = 0
4
FORMAT(1X,30H ENTER THE TITLE FOR THIS RUN. )
READ (5,7,ERR=4) (NAME(JJ,IFLAG), JJ=1,30)
7
FORMAT(30A1)
WRITE(1,8)(NAME(JJ,IFLAG), JJ=1,30)
8
FORMAT(1H1,30A1,//)
10
WRITE(6,11)
11
FORMAT(1X,41H INPUT THE AMBIENT TEMPERATURE IN CELSIUS. )
READ (5,*,ERR=10) TDC
12
WRITE(6,13)
13
FORMAT(1X, 46H INPUT THE TIME INCREMENT IN SECONDS. TRY 1.0. )
READ(5,*,ERR=23) DELT
14
IF(DELT.LE.0.) DELT=1.0
15
WRITE(6,16)
16
FORMAT(1X, 48H INPUT THE DESIRED RUN TIME IN MINUTES )
READ(5,*,ERR=25) TSTOP
17
TSTOP=TSTOP*60.
18
WRITE(6,19)
19
FORMAT(1X,40H INPUT MINIMUM ALLOWABLE THICKNESS OF THICK SLICK IN METERS. )
READ(5,*,ERR=27) HMIN
20
WRITE(6,21)
21
FORMAT(1X,40H INPUT THICKNESS OF THIN SLICK IN METERS. )
READ(5,*,ERR=31) HTN
22
CALL SUBROUTINE AIR TO CALCULATE AIR PROPERTIES
C
CALL AIR (PB, TDC, DENA, VISA)
C
CALL SUBROUTINE WATER TO CALCULATE WATER PROPERTIES
C
CALL WATER (TDC, DENW, VISW)
C
SIGMA = SURFACE TENSION BETWEEN WATER AND AIR
C
SIGMA = ( 75.64 - 0.144 * TDC ) * 1.E-3
C
SET UP ALL THE INITIAL AND DEFAULT VALUES
C067 \( UC = 0.0 \)
C068 \( VW = 0.0 \)
C069 \( UTBAR = 0.0 \)
C070 \( \ThetaETA1 = 0.0 \)
C071 \( XLE = 0.0 \)
C072 \( YLE = 0.0 \)
C073 \( XTE = 0.0 \)
C074 \( YTE = 0.0 \)
C075 \( XC = 0.0 \)
C076 \( YC = 0.0 \)
C077 \( XO = 0.0 \)
C078 \( YO = 0.0 \)
C079 \( TOTALM = 0.0 \)
C080 \( TOTALE = 0.0 \)
C081 \( EVAPM = 0.0 \)
C082 \( DISSOM = 0.0 \)
C083 \( TOTALD = 0.0 \)
C084 \( SPILLM = 0.0 \)
C085 \( SPILMR = 0.0 \)
C086 \( IC = 0 \)
C087 \( IW = 0 \)
C088 \( ID = 1 \)
C089 \( IT = 1 \)
C090 \( IV = 1 \)
C091 \( DO 30 \ I = 1,10 \)
C092 \( DO 29 \ J = 1,10 \)
C093 \( UX(I,J) = 0.0 \)
C094 \( UY(I,J) = 0.0 \)
C095 \( 29 \) CONTINUE
C096 \( TI(I) = 0.0 \)
C097 \( TT(I) = 0.0 \)
C098 \( UPEAK(I) = 0.0 \)
C099 \( UBAR(I) = 0.0 \)
C100 \( VWX(I) = 0.0 \)
C101 \( VWY(I) = 0.0 \)
C102 \( \ThetaETA(I) = 0.0 \)
C103 \( 30 \) CONTINUE
C104 \( TIME = 0.0 \)
C105 \( TCHECK = TSTOP \)
C106 \( TSPILL = TSTOP \)

CALL SUBROUTINE WBS TO OBTAIN WATER BODY DESCRIPTION

CALL WBS

CALL SUBROUTINE SPLOC TO SPECIFY SPILL LOCATION

CALL SPLOC

CALL SUBROUTINE SPTYPE TO DETERMINE SPILL TYPE AND CHEMICAL PROPERTIES

CALL SPTYPE (PB)
CALL SUBROUTINE SPREAD TO SOLVE SPREADING MODEL

CALL SPREAD

CONTINUE
STOP
END
0001 SUBROUTINE AIR (PB, TDC, DENA, VISA)

0002 C SUBROUTINE AIR IS USED TO DETERMINE AIR PROPERTIES. IT IS CALLED BY PROGRAM DMODEL.

0003 C U. S. STANDARD ATMOSPHERE, 1976

0004 DATA BETA, S, R, A, B, C/1.438E-5, 110.4, 2.87053E+6, 2.64638E-5, 1.245, 4.2.

0005 DATA AO, A1, A2, A3, A4, RPR/1.041707E+1, -4.179207E+2, -9.525310E+3, -9.708879E+4, 3.736121E+5, 8.31432/

0006 TDC = TEMPERATURE (C)

0007 PB = BAROMETRIC PRESSURE (MILLIBAR)

0008 DENA = AIR DENSITY (KG / CU. M)

0009 VI = VISCOSITY OF AIR (POISE)

0010 VISA = KINEMATIC VISCOSITY OF AIR (SQ. M / SEC)

0011 W = MOLECULAR WEIGHT

0012 R = UNIVERSAL GAS CONSTANT

0013 P = PB * 1000.0

0014 T = TDC + 273.15

0015 AIR DENSITY IN UNITS OF GM / CU. CM

0016 DENA = P / (R * T)

0017 CONVERT TO UNITS OF KG / CU. M

0018 DENA = DENA * 1000.0

0019 TR = SQRT(T)

0020 TI = T * TR

0021 VI = BETA * TI / (T + S)

0022 NOTE: 1 POISE = 1 GM / (SEC-CM). CONVERT TO KINEMATIC VISCOSITY

0023 VISA = (VI / 10.0) / DENA

0024 RETURN

0025 END
0001 SUBROUTINE CHEKMS

CCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC

CCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC CCCC

C THIS SUBROUTINE IS CALLED BY "INTE" AND THE INITIAL CONDITION ROUTINES "INTI2A" AND "INIT4A". FOR A CONTINUOUS SPILL, IT DETERMINES IF (EVAPORATION RATE + OTHER LOSSES) > DISCHARGE RATE. OR FOR AN INSTANTANEOUS SPILL, IF SPILL AREA IS ZERO (LOSSES > SPILL MASS). IF EITHER IS TRUE, IT RETURNS 'IDEB'=0. OTHERWISE, IT RETURNS 'IDEB'=-2.

0002 COMMON/MASS/TOTALE, TOTALD, TOTALM, TMASS
0003 COMMON/MLOSS/EVAPM, DISSOM
0004 COMMON/PRIM/YPRIME(5), IDEB, WKK
0005 COMMON/MOVE/UPEAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
0006 COMMON/STYPE/SPILMR, SPILLM, TSTOP, WS, STP, SPM
0007 COMMON/RUNGE/Y(5), C(24), W(5, 30)
0008 COMMON/KEY/DENO, DCA, DCW, CS, CMW
0009 COMMON/SPRINT/TII, ATK, HTK, ATN, HTN, HMIN, INDEX, IFLAG

0010 IDEB= 2
0011 EPSLON= .01
0012 ISTP=STP
0013 IF((ISTP.EQ.1) OR (TSTOP <= EPSLON)) 100 10

** CONTINUOUS SPILL **

0014 YNET1=SPILMR-YPRIME(4)-YPRIME(5)
0015 TEST=SPILMR-YPRIME(4)-VPRIME(5)-DENO*HTN*YPRIME(2)
0016 IF((TEST.LE.EPSLON)) IDEB=0
0017 RETURN

** INSTANTANEOUS SPILL **

0018 10 DISSTM = TOTALD + DELT * DISSOM + Y(1)
0019 EVAPM = TOTALE + DELT * EVAPM + Y(1)
0020 IF((ABS(SPILLM - DISSTM - EVAPM) / SPILLM).LE. EPSLON) THEN
0021 IDEB = 0
0022 RETURN
0023 ELSE
0024 ATMPM = YY(1) + YPRIME(1) * DELT
0025 IF((ATMPM.LE.0)) THEN
0026 IDEB = 0
0027 RETURN
0028 ELSE
0029 RETURN
0030 ENDIF
0031 ENDIF
0032 END
```
SUBROUTINE CHEMCL (ICS, NAME, PB, PHI, DENO, CS, CMW, OCA, DCW, SIGOA, SIGOW)

COMMON/WATER/DENW, VISW, QR
COMMON/ENVOR/PV, VISA, DENA, TDC
COMMON/NAIIE/NC(2, 20)

MATERIAL NO. NAME
* I
1 ALLYL CHLORIDE
2 BENZENE
3 BUTADIENE (1,2)
4 BUTYL ACETATE (ISO)
5 BUTYL MERCAPTAN (N)
6 CHLOROBUTA-1,3-DIENE
7 CYCLOHEXANE
8 CYCLOHEXENE
9 DIPROPYL ETHER (ISO)
10 ETHYL CHLORIDE
11 ETHYL MERCAPTAN
12 METHANE (N)
13 HEXANE (N)
14 METHYL CYCLOHEXANE
15 NONANE (N)
16 OCTANE (N)
17 PENTANE
18 TOLUENE
19 TRIMETHYLBENZENE
20 XYLENE (M)

DIMENSION RHO(20), DOA(20), DOW(20),
1 SL(20), TF1(20), CAO(20), CA1(20), STA(20), SAO(20),
2 SAI(20), TF2(20), STW(20), TF3(20), PAF(20), CTK(20),
3 VPA(20), VPS(20), VPC(20)

DATA NC/'ALLYL CHLORIDE'
1 'BUTADIENE', '(1,2)' 'BUTYL ACETATE', 'ISO'
2 'BUTYL MERCAPTAN', '(N)' 'CYCLOHEXANE'
3 'CYCLOHEXENE'
4 'DIPROPYL ETHER', 'ISO'
5 'ETHYL CHLORIDE'
6 'ETHYL MERCAPTAN', '(N)' 'HEXANE', '(N)
7 'METHANE', '(N)' 'METHYL CYCLOHEXANE'
8 'NONANE', '(N)' 'OCTANE', '(N)
9 'PENTANE', '

RHO IS DENSITY AT REFERENCE TEMPERATURE (20C) - IN GM / CU. CM.

DATA RHO/938. 0. 679. 0. 652. 0. 671. 0. 651. 0. 956. 0. 779. 0. 810. 0.
1 723. 0. 696. 0. 639. 0. 684. 0. 659. 0. 769. 0. 718. 0. 703. 0.
2 626. 0. 867. 0. 894. 0. 864. 0/

WM IS MOLECULAR WEIGHT
```
DATA WM/76.528, 78.114, 54.092, 116, 160.90.19, 88.54, 84.162.
2 82.146, 102.177, 64.515.62, 134, 100.205.86.178.98.189.
3 128.259, 114.232, 72, 151, 92.141, 120.195.106.168/
4 DOA IS DIFFUSIVITY IN AIR AT REFERENCE TEMPERATURE (20°C) -
5 IN SQ. CM. / SEC.
6 DATA DOA/0.097, 0.087, 0.0, 0.0, 0.064, 0.0, 0.0, 0.081, 0.085, 0.063,
7 0.0913, 0.0983, 0.064, 0.070, 0.072, 0.056, 0.056,
8 0.075, 0.063, 0.065, 0.072/
9 DOW IS DIFFUSIVITY IN WATER AT REFERENCE TEMPERATURE (20°C) -
10 (SG. CM. / SEC.) * 1E5
11 DATA DOW/1.019, 1.021, 0.062, 0.712, 0.0, 0.0, 0.84, 0.870, 0.744,
12 1.128, 1.333, 0.700, 0.764, 0.799, 0.397, 0.635, 0.84,
13 0.85, 0.885, 0.756/
14 VPA, VPB AND VPC ARE USED TO CALCULATE VAPOR PRESSURE PV HAS
15 A UNIT OF (NEWTON / SQ. M.)
16
17 DATA VPA/10.84, 10.00355, 31, 11873, 10.15, 11.06, 10 2864,
18 9, 9662, 10, 01107, 9, 9744, 10, 82, 10, 75, 10, 02167,
19 10, 00091, 9, 9479, 10, 06383, 10, 04358, 0, 97786,
20 10, 07954, 10, 16572, 10, 13398/
21 DATA VPB/1540, 1211, 035, 1041, 117, 1343, 1207, 1783, 45, 1201, 53,
22 1229, 973, 1139, 34, 1373, 1461, 1264, 90, 1171, 17,
23 1270.763, 1431.82, 1351.99, 1064.84, 1344.8, 1593.958,
24 1342.666/
25 DATA VPC/273.2, 220.79, 242.274, 207.0, 273.0, 179.7, 222.65,
26 224, 10, 218.7, 273.2, 273.0, 216, 34, 224, 41, 221.42,
27 202.01, 209.15, 233.01, 219.48, 207.08, 215.11/
28 SL IS THE SOLUBILITY IN G / 100 G OF H2O
29 DATA SL/33.175, 0.6, 0.06, 0.013, 0.02, 0.60, 1.50, 0.052,
30 0.14, 0.0, 0.002, 0.063, 0.043, 0.0196/
31 TF1 IS THE REFERENCE TEMPERATURE FOR SOLUBILITY
32 DATA TF1/25, 0.20, 0.20, 0.20, 0.20, 0.20, 0.20, 0.20, 0.20
33 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
34 CAO AND CA1 ARE USED TO CALCULATE TEMPERATURE DEPENDENT
35 SOLUBILITY
36 DATA CAO/0.0, -8213.150, 0.0, -1.57767, 2*0.0 /
37 DATA CA1/0.0, 0.00037, 15*0.0, 0.0114, 2*0.0 /
38 STA IS THE SURFACE TENSION BETWEEN CHEMICAL AND AIR
39 AT REFERENCE TEMPERATURE TF2 - IN DYNE / CM
40 DATA STA/2, 89.2, 888.0, 0.2, 37.2, 61.0, 0.2, 84.2, 2, 678.1, 71.1, 95.2, 35,
41 1.93, 1.84, 2, 365.2, 29.2, 17.1, 40.2, 882.2, 883.2, 860 /
42 DATA TF2/15.0, 7*20, 25, 0.35, 11*20 /
43 SAO AND SA1 ARE USED TO CALCULATE SURFACE TENSION AT
44 DIFFERENT TEMPERATURE
45 DATA SAO/0.0, 31.54, 4*0.0, 27, 62, 29, 23, 19, 89, 0.0, 0.0, 0.0, 22.1,
46 20.44, 26, 11, 24, 72, 23, 32, 18, 29, 30, 30, 90, 30, 91, 31.23 /
47 DATA SA1/0.0, 133.4*0.0, 1188.1223, 1048.2*0.0, 0.089,
48 1022, 113, 0.03470.09509, 11021, 1189, 1040, 1104 /
49 STW IS THE SURFACE TENSION BETWEEN CHEMICAL AND WATER AT
REFERENCE TEMPERATURE TF3 - DYNE / CM

0.023 DATA STW/ 5 71. 3. 5 0.4. 0.3. 0.0 0.5 0.0 0.1. 71 4. 00 2. 50 5. 10

0.024 1 5 11. 0 0. 3. 0. 30. 5 08. 5 02. 3. 61. 0 0. 3. 64/

0.025 1 - 15. 20. 19. 85. 20. 0. 20. 19. 85. 25. 0. 29. 85 /

C PAF IS THE Pitzer ACENTRIC FACTOR

0.026 DATA PAF/ 13. 212. 253. 479. 3. 0. 215 . 213. 34. 19. 19.

C CTK IS THE CRITICAL TEMPERATURE - IN K

0.027 DO 1112 1 = 1. 2

0.028 NAME(I) = NC(IICS)

0.029 1112 CONTINUE

0.030 PHI = (1.0-(293. 15/CTK(IICS))))**(2.0/7.0)-(1.0-(TDC+273. 15)/

0.031 1 CTK(IICS))**(2.0/7.0)

0.032 IF (PHI .EQ. 0.) GO TO 1115

0.033 ZIZ = 29036. - 08775 * PAF(IICS)

0.034 DENO = CHEMICAL DENSITY IN KG/CU. M.

0.035 DENO = (RHO(IICS) * (ZIZ ** PHI))

0.036 GO TO 1116

0.037 1115 DENO = RHO(IICS)

0.038 1116 CONTINUE

C PV = VAPOR PRESSURE - IN NEWTON / SG. M.

0.039 PV = (VPA(IICS) - VPB(IICS) / (TDC + VPC(IICS)))

0.040 PV = (10. ** (PV)) / 10. 0

C CS = SOLUBILITY LIMIT - IN KG / CU. M.

0.041 SL(IICS) = 10. **(CAO(IICS) + CAI(IICS) * TDC)

0.042 CS = SL(IICS) * DENW / 100. 0

CMW = MOLECULAR WEIGHT

0.043 CMW = WM(IICS)

DCA = DIFFUSIVITY IN AIR (SQ. M. / SEC)

0.044 DCA = (DOA(IICS) * (1.01325E6) / 293. 15 ** 1.5) *

(((TDC + 273. 15) ** 1.5 / (PB * 1000. 0))

DCA = DCA * 1. E-4

NOTE : PB IS IN MILLIBAR

1.01325E6 IS THE REFERENCE PRESSURE IN DYNE/CQ. CM.

DCW = DIFFUSIVITY IN WATER (SQ. M. / SEC)

0.045 DCW = (DCW(IICS) * .001002 / 293. 15) * ((TDC + 273. 15) /

0.046 1 (VISW * DENW))

DCW = DCW * 1. E-9

SIGMA = SURFACE TENSION BETWEEN CHEMICAL AND AIR

(IN NEWTON / M.)
IF (SAO(ICS) .EQ. 0.0 .AND. SA1(ICS) .EQ. 0.0) GO TO 1117
SIGOA = (SAO(ICS) - SA1(ICS) * TDC) * (1.0E-3)
GO TO 1118
SIGOA = STA(ICS) * (1.0E-2)
CONTINUE
SIGOW = SURFACE TENSION BETWEEN CHEMICAL AND WATER
(IN NEWTON / M.)
SIGOW = STW(ICS) * (1.0E-2)
RETURN
END
SUBROUTINE CURRENT

THIS SUBROUTINE COMPUTES THE AVERAGE TRANSPORT VELOCITY OVER THE Entire SPILL DURATION.

THIS SUBROUTINE IS CALLED BY "SPREAD". IT CALCULATES THE AVERAGE VALUE OF THE VELOCITY USED IN THE SPREADING MODELS TO COMPARE WITH THE PEAK COMPUTED IN UTPEAK.

** VARIABLE NAME **

UBAR(I) = AVERAGE VALUE OVER TIME OF UC + 0.035*VW (COMPONENTS) IN EACH OF THE 9 SLICES OR BOXES. FOR A RIVER, A DUMMY BOX(I=1) IS USED.

SUBROUTINE CURRT

COMMON/CURRENT/UBAR(IO),DMOVE,UTOT,UTX,UTY,UREL
COMMON/MOVE/UTPEAK(IO),XLE,XTE,YLE,YTE,DELT,TIME,TSTOP,TCHECK
COMMON/CONTUR/SHAPE,X(IO),Y(IO),XC,YC,IC,IC,ISP,XO,YO
COMMON/CONSTANT/UC,VW,UTBAR,UO,U1,WT,ALPH,THETA1
COMMON/TRANSIT/UX(IO,10),UY(IO,10),VWX(IO),VWY(IO)
VWT(10),THETA(IO),T(10),ID,IT,IV
COMMON/STYPE/SPILLM,SPILMR,TSPILL,WS,STP,SPM
COMMON/UAVE/UCXI,UCYI,VWX1,VWY1

0001 IF(IC.EQ.0.AND.IW.EQ.0) GO TO 999
0010 ISHAP = SHAPE
0011 IF (ISHAP.GT.1) GO TO 200

IN RIVERS OR CHANNELS

0012 IF (IC.EQ.1) GO TO 60
0013 IF (TSPILL.GT.WT) GO TO 50

AVERAGE VALUE OF TIDAL VELOCITY OVER ONE TIDAL PERIOD

0014 UC = UO
0015 GO TO 60
0016 CONTINUE

AVERAGE VALUE OF TIDAL VELOCITY OVER DISCHARGE TIME

0017 UC = UO+U1*WT/6+28319*(-COS(6.28318/WT*(TSPILL+ALPH)))
+28319*ALPH/WT))

0018 IF (IW.LE.1) GO TO 70
0019 VWT = 0.
0020 THETAT = 0.
0021 DO 62 I = 1,10
0022 IF (TSPILL.LT.TT(I)) GO TO 63
0023 VWT = VWT +VWX(I)

60CONTINUE
62CONTINUE
63CONTINUE
DECLARE
THETAT = THETAT + THETA(I)
VW = VWX(I-1) + (TSPILL-TT(I-1))*(VWX(I)-VWX(I-1))/
   (TT(I)-TT(I-1))
THETA1 = THETA(I-1) + (TSPILL-TT(I-1))*(THETA(I)-THETA(I-1))
   /(TT(I)-TT(I-1))

C++-----------------------------------------------
C TIME AVERAGE VALUE CALCULATED OF WIND AND WIND ANGLE UP TO
C END OF DISCHARGE TIME
C++-----------------------------------------------
VW = (VWX+VW)/I
THETA1 = (THETAT+THETA1)/I

C++-----------------------------------------------
UBAR(I) = UC + 0.035 * VW * THETA1

C++-----------------------------------------------
GO TO 999

C++-----------------------------------------------
IN OPEN WATER
C++-----------------------------------------------

C++-----------------------------------------------
IF (IW.GT.1) GO TO 210
VWX1 = VWX(1)
VWY1 = VWY(1)
GO TO 300
VWX1 = 0.0
VWY1 = 0.0
DO 240 J = 1,10
IF (TSPILL.LT.TT(J)) GO TO 250
VWXI = VWX1 + VWX(J)
VWY1 = VWY1 + VWY(J)
240 CONTINUE
VWX1 = VWX1 + VWX(J-1)*(TSPILL-TT(J-1))*(VWX(J)-VWX(J-1))
   /(TT(J)-TT(J-1))
VWY1 = VWY1 + VWY(J-1)*(TSPILL-TT(J-1))*(VWY(J)-VWY(J-1))
   /(TT(J)-TT(J-1))

C++-----------------------------------------------
TIME AVERAGE VALUE OF WIND COMPONENTS UP TO END OF DISCHARGE
C++-----------------------------------------------
VWX1 = VWX1/J
VWY1 = VWY1/J

C++-----------------------------------------------
IF (IC.GT.1) GO TO 310
UU1 = UX(1,1) 
UU2 = UY(1,1)

C++-----------------------------------------------
COMPUTE UBAR WHEN CURRENT IS CONSTANT
C++-----------------------------------------------
UBAR(1) = SQRT((UU1+0.035*VWX1)**2+(UU2+0.035*VWY1)**2)
C

THETA(1) = ATAN((UU2+0.035*VWY1)/(UU1+0.035*VWY1))

GO TO 999

DO 310 I = 1, N

IF (IC.GT.2) GO TO 320

UU1 = UX(I,1)

UU2 = UY(I,1)

DO TO 360

UU1 = 0.0

UU2 = 0.0

DO 340 J = 1, IT

IF (TSPILL.LT.TI(J)) GO TO 350

UU1 = UU1 + UX(I,J)

UU2 = UU2 + UY(I,J)

CONTINUE

UU1 = UU1 + UX(I,J-1)+(TSPILL-TI(J-1))*(UX(I,J)-UX(I,J-1))

/(TI(J)-TI(J-1))

1

UU2 = UU2 + UY(I,J-1)+(TSPILL-TI(J-1))*(UY(I,J)-UY(I,J-1))

/(TI(J)-TI(J-1))

C

COMPUTE AVERAGE CURRENT IN EACH BOX OR SLICE

C

C

COMPUTE AVERAGE UBAR IN EACH BOX OR SLICE

C

UBAR(I) = SORT((UU1+0.035*VWX1)**2+(UU2+0.035*VWY1)**2)

THETA(I) = ATAN((UU2+0.035*VWY1)/(UU1+0.035*VWX1))

CONTINUE

RETURN

C-13
SUBROUTINE DISS

THIS SUBROUTINE IS USED TO COMPUTE DISSOLUTION LOSS.

THIS SUBROUTINE IS CALLED BY "INTE". IT CALCULATES THE DISSOLUTION MASS TRANSFER RATE COEFFICIENT. THE RELATIVE WIND IS CALCULATED IN "TRANSPL".

DISSOM = DISSOLUTION MASS TRANSFER RATE COEFFICIENT (KG / SQ. M-}

COMMON SIZE/R, D, WW, L1, L2, H, RO
COMMON CHEM/DENO, DCA, DCW, CS, CMW
COMMON WATER/DENW, VISW, GR
COMMON ENVOR/PV, VISA, DENA, TDC
COMMON INTER/CHEMX, SIGW, SIGGA, SIG3W, SIG3
COMMON CONSTAT/UC, VW, UBAR, VO, UI, WT, ALPH, THETA1
COMMON LOSS/EVAPM, DISSOM
COMMON MOVE/UPEAK(10), XLE, XTE, YLE, YTE, DLT, TIME, TSTOP, TCHECK
COMMON CONTOUR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON TRANSIT/UX(10, 10), UY(10, 10), VWPX(10), VWY(10), THETA(10), TI(10), ID, IT, IV, XU(10), YU(10), TT(10)
COMMON ID/IDI, ID2, ID3
COMMON EVADD/SAN, UX, SCHMIA, CSA, DWN, UXW, SCHMIW, CS
COMMON CURRENT/UBAR(10), DMV, UTOP, UT, UTY, UREL

DATA D1, D2, D3, D4, D5, D6, D7, D8, 85, 1, 2, 35, 8, 065, 55, 2, 11.2/
I = IW+1
J = SHAPE

** SCHMIW = SCHMIDT NO. FOR WATER **

SCHMIW = VISW/DCW
CSW = CS/DENW

GO TO (10,100,100) J

------------------------------------------------------------------------------------------------------------------------
DISSOLUTION IN RIVERS OR CHANNELS
------------------------------------------------------------------------------------------------------------------------
CONTINUE

** DWN = DALTON NO. FOR RIVER **

DWN = 0.06266/(SCHMIW**(2./3.))
K = IC+1
GO TO (11,12,13) K
--- NO CURRENT ---

DISSOM = 0.0
GO TO 999
--- CONSTANT CURRENT ---

C-14
G0 TO 20
--- TIDAL CURRENT ---
UC = UO + UI * SIN(2.0 * 3.14159 / WT * (TIME + ALPH))
UXW = UC / (5.66 * ALOG10(2.0 * D/RO) + 4.92)
GO TO 300

DISSOH IN OPEN WATER

C 100 CONTINUE
GO TO (110, 120, 120) I
C -- NO RELATIVE WIND ---
110 DISSOM = 0.0
GO TO 999
C -- RELATIVE WIND ---
120 IF (UREL.GT.3.064) GO TO 155
C --- UREL . LE . 3.064 METER/SEC ---
UXW = SQRT(DENA/DENW)*UREL*SQRT((1.25E-3)/(UREL**0.5))
GO TO 160
C --- UREL . GT . 3.064 METER/SEC ---
155 UXW = SQRT(DENA/DENW)*UREL*SQRT((D4+D5*UREL)/1000.0)
C 160 IF (UREL.GT.5.0) GO TO 165
C --- UREL . LE . 5.0 METER/SEC ---
BW = 12.5*(SCHMIW**(2./3.)) + 2.125*ALOG(SCHMIW) - 5.3
GO TO 170
C --- UREL . GT . 5.0 METER/SEC ---
165 CONTINUE
C SCT = D1
SCT = D1
044 HPLUS = H + UXW/VISW
045 BW = D6*((SCHMIW**(2./3.)) - D7)*SQRT(HPLUS) -
1 2.5*ST*SCT + D8*ST
C 170 ZW = D2*UXW/VISW
C ** DWN = DALTON NO. FOR OPEN WATER **
047 DWN = 1.0/(2.5*SCT*SCTZ + BW + D3)
C
050 DISSOM = DWN * DENW * UXW * CSW
C
999 RETURN
END

C-15
SUBROUTINE EVAP
C
C THIS SUBROUTINE IS USED TO COMPUTE EVAPORATION LOSS
C
C THIS SUBROUTINE IS CALLED BY "INTE". IT CALCULATES THE
EVAPORATION MASS TRANSFER RATE COEFFICIENT. THE RELATIVE
WIND IS CALCULATED IN "TRANSP".

EVAPM = EVAPORATION MASS TRANSFER RATE COEFFICIENT (KG / SQ. M-SEC)

SUBROUTINE EVAP
COMMON/SIZE/R,D, WW, L1, L2, H, RO
COMMON/CHINFO/DCA, DCM, CS, CMW
COMMON/WATER/DPW, VSW, OR
COMMON/ENVOR/PV, VISA, DENA, DTE
COMMON/INTER/COEF, SIGMA, SIGO, SIGO, SIGO
COMMON/CONST/UC, VW, UBAR, VO, U1, WT, ALPH, THETA1
COMMON/MLOSS/EVAPM, DISSOM
COMMON/MOVE/UPEAK, XLE, XTE, VLE, YTE, DELT, TIME, TSTOP, TCHECK
COMMON/CONTINUE/SHAPE, X(10), Y(10), XCYC, IC, IW, ISP, IO, YO
COMMON/TRANSIT/UX(10,10), UY(10,10), VWX(10), VWV(10), THETA(10), XI(10), IT, IV,
XU(10), YU(10), TT(10)
COMMON/ID/L1, L2, ID3
COMMON/EVADIS/DAN, UXA, SCHMIA, CSA, DWA, UXW, SCHMIW, CSW
COMMON/CURRENT/UXBAR(10), UXO, UTX, UTY, UREL
DATA D1, D2, D3, D4, D5, D6, D7, D8/(8314.32*(TDC+273.15))/DENA
10 IF (UREL.EQ.0.0) THEN
11 EVAPM = 0.0
12 GOTO 999
ELSE
ENDIF
20 IF (UREL .LT. 3.064) GO TO 55
30 UXA = UREL*SQRT((2.5E-3)/(UREL**0.2))
35 GO TO 60
C
40 IF (UREL .GT. 3.064) GO TO 55
50 UXA = UREL*SQRT((D4+D5*UREL)/1000.0)
55 CONTINUE
C
60 HX = H/UXA/VISA
C
** SCHMIA = SCHMIDT NO. FOR AIR **
70 SCHMIA = VISA/DCA
75 CSA = (PV*CMW/8314.32*(TDC+273.15))/DENA
80
90 IF (UREL .GT. 5.0) GO TO 75
95 UREL = 5.0 METER/SEC ---
100 BA = 12.5*(SCHMIA**21.0)+2.125*ALOG(SCHMIA)-5.3
105 GO TO 80
110 UREL = 5.0 METER/SEC ---
BA = D6*(SCHMIA**((2./3.)-D7)*SQRTHX-2.5*SCT*ALOG(HX)) +D6*SCT

CONTINUE

ZA = D2 * UXA / VISA

SCT = D1

** DAN = DALTON NO. FOR AIR **

DAN = 1.0/(2.5*SCT*ALOG(ZA)+BA+D3)

EVAPM = DAN * DENA * UXA * CSA

RETURN

END
SUBROUTINE FCN1

SIMULTANEOUS EQUATIONS FOR MODEL 1.

THIS SUBROUTINE IS CALLED BY "RUNKUT" THROUGH "INTE". IT CONTAINS THE GRAVITY-VISCIOUS SPREADING EQUATIONS FOR AN INSTANTANEOUS SPILL IN A RIVER.

SUBROUTINE FCN1 (N, TIME, YY, YPRIME)

COMMON/SPREAD/TII, ATK, HTK, ATN, HTN, KMIN, INDEX, IFLAG
COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPM
COMMON/CHEMI/DENO, DCA, DCH, CS, CMW
COMMON/WATER/DENW, VISW, GR
COMMON/ENVOR/PV, VIS, DENA, TDC
COMMON/SIZE/R, D, WW, R1, L1, L2, H, RO
COMMON/MLOSS/EVAPM, DISSOM
COMMON/MASS/TOTALM, TOTALD, TOTALM, DMASS
COMMON/INTER/COEF, SIGMA, SIGMA, SIGMA, SIGMA, SIGMA, SIGMA
COMMON/CK/Cl0, C20, C11, C21, C12, C22, K10, K20, K11, K21

REAL YPRIME(5), YY(5)

YPRIME(1) = EVAPM*YY(1)
YPRIME(2) = 2.76*(((SIG*WW*D.W/DENW)**2/VISW)**(1./3.))/(YY(2)**(1./3.))
YPRIME(3) = (YY(3)*YPRIME(1)+DLOSS/DENO)/YY(1)

DO 100 IID=1,5

YPRIME(IID) = YPRIME(IID)

100 CONTINUE

END
SUBROUTINE FCN12
C SIMULTANEOUS EQUATIONS FOR MODEL 1.B
C
C THIS SUBROUTINE IS CALLED BY "RUNKUT" THROUGH "INTE". IT CONTAIN
THE GRAVITY-VISCOUS SPREADING EQUATIONS FOR AN INSTANTANEOUS SP
IN OPEN WATER.

SUBROUTINE FCN12 (N, TIME, YY, YPRIME)
COMMON/SPREAD/TII, ATK, ATK, ATN, HTN, HMIN, INDEX, IFLAG
COMMON/STYPE/SPILLM, EPILMA, TSPILL, WS, STF, SPH
COMMON/CHEMI/DENO, DCA, DCW, CS, CMW
COMMON/WATER/DENWVISI, JCR
COMMON/ENVOR/PV, VISA, DENA, TDC
COMMON/SIZE/R, D, WW, LI, L2, H, RO
COMMON/MLOSS/EVAPM, DISSOM
COMMON/INTER/COEF, SIGWA, SIGOA, SIGOW, SIG
COMMON/CK/C10, C20, C11, C12, C22, K10, K20, K11, K21, K12, K22
COMMON/PRIM/PRIME(5), IDEB, K
REAL YPRIME(5), YY(5)
REAL KL0, K20, K11, K22
PI = ACOS(-1.)
YRE() = EVAPM*YY(1)
YPRIME(5) = DISSOM*YY(1)
DLOSS = YPRIME(4)+YPRIME(5)
YPRIME(2) = 6.02*(((SIG/DENW)**(1./3.))*Y(1)**(4./3.))*(YY(3)**(1./3.))
YPRIME(1) = 0.5*(((PI*(K20*2.))*(SIG/DENW)**2/VISW)**(1./3.))
YPRIME(3) = -(YY(3)*YPRIME(1)+DLOSS/DENO)/YY(1)
DO 100 IID = 1, 5
** PRIME ARE VARIABLES USED IN "CHEKMS" **
PRIME(IID) = YPRIME(IID)
100 CONTINUE
RETURN
END
SUBROUTINE FCN21

SIMULTANEOUS EQUATIONS FOR MODEL 2.A

THIS SUBROUTINE IS CALLED BY "RUNKUT" THROUGH "INTE". IT CONTAINS THE GRAVITY-VISCOS Spreading EQUATIONS FOR A CONTINUOUS SPILL IN A RIVER WITH NO CURRENT OR WIND.

0001 SUBROUTINE FCN21 (NTIME, YY, YPRIME)
0002 COMMON/SPREAD/T11, ATK, HTK, ATM, HTN, HMIN, INDEX, IFLAG
0003 COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPM
0004 COMMON/CHEMI/DENO, DCA, DCW, CS, CMW
0005 COMMON/WATER/DENW, VI SW, CR
0006 COMMON/ENVOR/PY, VISA, DENA, TDC
0007 COMMON/SIZE/R, D, WW, L1, L2, H, RO
0008 COMMON/MLOSS/EVAPM, DISSOM
0009 COMMON/INTER/COEF, SIGW, SIGCA, SIGOW, SIG
0010 COMMON/Ck/C10, C20, C11, C21, C12, C22, K10, K20, K11, K21.

1 COMMON/PRIM/PRIME(5), IDEB, KMK
0012 REAL YPRIME(5), YY(5)
0013 REAL K10, K20, K11, K21, K12, K22
0014 YPRIME(4) = EVAPM*YY(1)
0015 YPRIME(5) = DISSOM*YY(1)
0016 DLOSS = YPRIME(4)+YPRIME(5)
0017 YPRIME(2) = 2.78*(((SIG*WW/DENW)**2/VI SW)**(1./3.))
0018 / (YY(2)**(1.0/3.0))
0019 IF(SPM.LE.0.0) QOTO 998

C YPRIME(1) = 2.38*(C21**(B, /3.) )**((QR*WW+COEF)**2/VI SW)

1 **(1./3.)) *(YY(3)**(4./3. ))/(YY(1)**(1./3. ))
2 -DLOSS/(2.0*DENO*YY(3))
3 -0.5*(HTN/YY(3))*YPRIME(2)
4 + SPILMR/(2.0*DENO*YY(3))

C YPRIME(3) = -(YY(3)*YPRIME(1)+HTN*YPRIME(2)+

DLOSS/DEO+SPILMR/DENO)/YY(1)

0022 998 DO 100 IID=1,5
0023 998 ** PRIME ARE VARIABLES USED IN "CHEKMS" **

C PRIME(IID)=YPRIME(IID)
0024 100 CONTINUE
0025 999 RETURN
0026 END
SUBROUTINE FCN22

SIMULTANEOUS EQUATIONS FOR MODEL 2. B

THIS SUBROUTINE IS CALLED BY "RUNKUT" THROUGH "INTE". IT CONTAIN

THE GRAVITY-VISCOS SPREADING EQUATIONS FOR A CONTINUOUS SPILL
IN OPEN WATER WITH NO CURRENT OR WIND.

SUBROUTINE FCN22 (N, TIME, YY, YPRIME)

COMMON/SPREAD/THI, ATK, HTA, ATN, HTN, HMIN, INDEX, IFLAG
COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPL
COMMON/CHEMI/DENO, DCA, DCW, CS, CMW
COMMON/WATER/DENW, VISW, GR
COMMON/ENVOR/PV, VISW, DENO, TDC
COMMON/SIZE/R, WW, L1, L2, H, RO
COMMON/MLOSS/EVAPM, DISSOM
COMMON/INTER/CHEM, SIGMA, SIGMA, SIGMA, SIGMA
COMMON/CK/C10, C20, C11, C21, C12, C22, K10, K20, K11, K21,
1 K12, K22
COMMON/PRIME(3), IDEB, KKK

REAL YPRIME(5), YY(5)
REAL K1, 2, L1, 2, L2, 2
PI=ACOS(-1.)

YPRIME(4) = EVAPM*YY(1)
YPRIME(5) = DISSOM*YY(1)
DLOSS = YPRIME(4)*YPRIME(5)

YPRIME(2) = 6.02*(((SIGA/DENA)**2/VISW)**(1./3.)
*YY(2)**(1./3.)

SPM=SPILMR-DLOSS-DENO*HTN*YPRIME(2)

DO 100 IID=1,3

YPRIME(IID) = YPRIME(IID)
100 CONTINUE

RETURN
END
SUBROUTINE FCN41

SIMULTANEOUS EQUATIONS FOR MODEL 4A

THIS SUBROUTINE IS CALLED BY "RUNKUT" THROUGH "INTE". IT CONTAINS:

THE GRAVITY-VISCOUS SPREADING EQUATIONS FOR A CONTINUOUS SPILL
A RIVER WITH CURRENT OR WIND.

SUBROUTINE FCN41 (N, TIME, YY, YPRIME)
COMMON/CONST/UC, VW, UTBAR, UO, UI, W, ALPH, THETA1
COMMON/SPREAD/TII, ATK, HTK, ATN, HTN, HMIN, INDEX, IFLAG
COMMON/STYPE/TII, TI, TIP, TSP, TP, TSP, TP
COMMON/FCN41/DC, DCW, CS, CMW
COMMON/WATER/DEN, VISA, VSS, VV, VR
COMMON/ENVOR/PV, VISA, VSS, VV, VR
COMMON/SIZE/R, D, WW, LW, H, RO
COMMON/MLOSS/EVAPM, DISSOM
COMMON/CHEM/DENO, DCA, DCW, CS, CMW
COMMON/INTER/COEF, SIGOA, SIGIA, SIGI, SIGO
COMMON/CK/C10, C20, C11, C21, C12, C22, K10, K20, K11, K21,
K12, K22
COMMON/Prim/PRIME(5), IDEB, KMK
REAL YPRIME(5), YY(5)
REAL K10, K20, K11, K21, K12, K22
YPRIME(4) = EVAPM * YY(1)
YPRIME(5) = DISSOM * YY(1)
DLOSS = YPRIME(4) + YPRIME(5)
SPILLW = WW

YPRIME(2) = 2.76 * (((SIG + WW / DENO) ** 2 / VISH) ** (1. / 3))
1
/(YY(2) ** (1. / 3))
SPILL = SPILLW - DLOSS - DENO * HTN * YPRIME(2)
1
IF (SPILL .LE. 0.0) GOTO 998

YPRIME(1) = 2.38 * (C22 ** (2. / 3.)) * ((GR * WW * COEF) ** 2 / VISH) ** (1. / 3)
1
*(YY(3) ** (4. / 3.)) / (YY(1) ** (1. / 3.))
2
-DLOSS / (2.0 * DENO * YY(3))
3
-0.5 * (HTN / YY(3)) * YPRIME(2)
4
+ SPILLW / (2.0 * DENO * YY(3)) + SPILLW * UTBAR

YPRIME(3) = -(YY(3) * YPRIME(1) + HTN * YPRIME(2) +
DLOSS / DENO - SPILLW / DENO) / YY(1)

DO 100 IID = 1, 5
** PRIME ARE VARIABLES USED IN "CHEKMS" **

998 DO 100 IID = 1, 5

999 CONTINUE

RETURN

END
SUBROUTINE FCN42
C
SIMULTANEOUS EQUATIONS FOR MODEL 4B
C
C THIS SUBROUTINE IS CALLED BY "PUNKUT" THROUGH "INTE". IT CONT
C THE EQUATIONS FOR GRAVITY-VISCOUS SPREADING OF A CONTINUOUS SP
C IN OPEN WATER WITH A CURRENT OR WIND.

0001 SUBROUTINE FCN42 (N, ME, YYPRIME)
0002 COMMON/CONSTAT/UC, WO, UTBAR, UO, UI, WT, ALPH, THETA1
0003 COMMON/SPREAD/TTI, ATX, HTH, ATN, HTN, HMIN, INDEX, IFLAG
0004 COMMON/STYPE/SPILLM, SFILM, TBPILM, WS, STP, SPN
0005 COMMON/CHMI/DENO, LCA, DCW, CS, CMW
0006 COMMON/WATER/DENW, VISW, QR
0007 COMMON/ENVOR/PI, VISA, DEMA, TDC
0008 COMMON/SIZE/R, D, W, L1, L2, H, RD
0009 COMMON/LOSS/EVAP, DISSOM
0010 COMMON/INTER/CDEF, SIGMA, SIGMAO, SIGD, SIG,
0011 COMMON/CK/C11, C20, C11, C21, C12, C22, K10, K20, K21, K22
0012 COMMON/PRIM/PRIME(5), IDEB, K(K1, K2)
0013 REAL YYYYPRIME(5), YYYY(5)
0014 REAL K(10, K20, K11, K21, K12, K22
0015 YYYYPRIME(4) = EVAP*YYYY(1)
0016 YYYYPRIME(5) = DISSOM*YYYY(1)
0017 DLOSS = YYYYPRIME(4) + YYYYPRIME(5)
0018 YYYYPRIME(2) = 2.06*((SIGMA*(UTBAR**2)/DENW)**2/VISW)**(1.71)
0019 YYYYPRIME(2) = YYYYPRIME(2) + YYYYPRIME(3)
0020 SPH = SPILMR - DLOSS*DENO*HTN*YYYYPRIME(2)
0021 IF (SPH.LT.0.0) GO TO 999
0022 YYYYPRIME(1) = ((SIGMA*(UTBAR**2)/DENW)**2/VISW)**(1.71)
0023 YYYYPRIME(1) = YYYYPRIME(1) + YYYYPRIME(2) + YYYYPRIME(1)
0024 DO 100 IID = 1, 5
0025 YYYYPRIME = YYYYPRIME + YYYYPRIME
0026 CONTINUE
0027 999 RETURN

C-23
SUBROUTINE GROUND IS USED TO DETERMINE WHETHER THE SLICK HAS HIT THE BOUNDARY LINE(S). THIS SUBROUTINE IS CALLED BY "SPREAD". IT DETERMINES IF THE SLICK HAS HIT THE COASTLINE. IF IT HAS HIT, IT RETURNS IH=99 OTHERWISE, IT RETURNS IH=0

SUBROUTINE GROUND(IH)

COMMON/SIZE/R, D, WW, LI, L2, H, RD
COMMON/MOVE/UPEEK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
COMMON/CONTOUR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPM
COMMON/RUNGE/IY(5), C(24), W(5,30)
COMMON/CONST/UC, VW, UTBAR, UO, UI, WT, ALPH, THETA1
ISTP = STP
IH = 0

PI = 3.141592
IF (STP. EQ. 4.2) GO TO 7

** IF STP IS NOT 4.2, ALL OPEN WATER SLICKS ARE CIRCULAR **
** SO COMPUTE RADIUS OF SLICK = RAD **
RAD = SQRT(YY(1)/PI)
GO TO 9

** IF STP IS 4.2, SLICK IS TRIANGULAR, SO COMPUTE WIDTH = RAD **
RAD = YY(1)/(UTBAR*TIME)
XC = XLE
YC = YLE
IF (SHAPE. EQ. 3.2 OR SHAPE. EQ. 2.3) GO TO 10
GO TO 100

FOR ARBITRARY LAKE OR COAST, COMPUTE DISTANCE FROM LEADING EDGE (CONT.) OR CENTER (INST.) OF SLICK TO EACH BOUNDARY POINT, AND DETERMINE IF RAD > THE DISTANCE. IF SO, SLICK HAS HIT COAST

DO 20 I=1,10
20 X1 = (XC-X(I))*(XC-X(I))+(YC-Y(I))*(YC-Y(I))
IF ((R**2) GT X1) GO TO 30
GOTO 40

IH = 99
GO TO 999

IH = 0
GO TO 999

IDH = 1
GO TO 25

FOR A STRAIGHT COAST, COMPUTE DISTANCE FROM LEADING EDGE (CONT.
C OR CENTER (INST.) TO STRAIGHT LINE AND DETERMINE IF RAD > DISTANCE.
C IF SO, SLICK HAS HIT COAST.

0029 100 IF (SHAPE.NE.3.1) GO TO 200
0030 120 SS = (Y(2)-Y(1))/(X(2)-X(1))
0031 X1 = (SS*(YC-Y(1))*X(1)+SS*X/C)/(SS*SS+1.0)
0032 Y1 = (SS*(XC-X(1))*YC+SS**2*Y(1))/(SS**2+1.0)
0033 SS = ((XC-X1)*(XC-X1)+(YC-Y1)*(YC-Y1))
0034 IF (((RAD**2).LE.SS) GO TO 999
0035 IH = 99
0036 GO TO 999
0037 200 IF (SHAPE.NE.2.2) GO TO 300
C FOR A RECTANGULAR LAKE, CHECK DISTANCE FROM LEADING EDGE (CONT.)
C OR CENTER (INST.) TO ALL 4 EDGES AND DETERMINE IF RAD > DISTANCE.
C IF SO, SLICK HAS HIT COAST.

0038 DO 220 I=1,4
0039 IF (I.EQ.4) GO TO 214
0040 IF (I.EQ.3) GO TO 213
0041 IF (I.EQ.2) GO TO 212
0042 X1=XC
0043 Y1=0.0
0044 GO TO 215
0045 212 XI=FLOAT(L1)
0046 Y1=YC
0047 GO TO 215
0048 213 XI=XC
0049 Y1=FLOAT(L2)
0050 GO TO 215
0051 214 XI=0.0
0052 Y1=YC
0053 215 SS = ((XC-X1)*(XC-X1)+(YC-Y1)*(YC-Y1))
0054 IF (((RAD**2).LE.SS) GO TO 220
0055 IH = 99
0056 GO TO 999
0057 220 CONTINUE
0058 IH = 0
0059 GO TO 999
0060 300 CONTINUE
C *****************************************************
C IF (RAD + OFFSET OF LEADING EDGE (CONT.) OR CENTER (INST.) OF
C SLICK FROM CENTER OF CIRCULAR LAKE) > RADIUS OF LAKE.
C *****************************************************

0061 X1 = RAD = SORT((XC-XO)+(YC-YO))
0062 IF (X1.LE.R) GO TO 999
0063 IH = 99
0064 999 REJRN
0065 *ND

C-25
SUBROUTINE INIT

THIS SUBROUTINE MANIPULATES AND DETERMINES WHICH SUBROUTINE SHOULD BE USED TO CALCULATE INITIAL CONDITION

THIS SUBROUTINE IS CALLED BY "SPREAD". IT CALLS ONE OF 4 SUBROUTINES TO COMPUTE EITHER THE END OF THE GRAVITY-INERTIAL PHASE OF SPREADING. OR, FOR A RIVER, THE TIME REQUIRED FOR THE SLICK TO SPREAD ALL THE WAY ACROSS THE RIVER WIDTH. IT WILL RETURN WITH

* TII = INITIAL TIME FOR USE IN MAIN INTEGRATION ROUTINE OF GRAVITY-VISCOUS SPREADING
* ATK = INITIAL VALUE OF THICK SLICK AREA
* ATN = INITIAL VALUE OF THIN SLICK AREA
* HTK = INITIAL VALUE OF THICK SLICK THICKNESS

***************

1 SUBROUTINE INIT

0002 COMMON/STYPE/SPILLM, SPILLMR, TSPILL.WS, STP, SPM

0003 IF (STP. EQ. 1. 1. OR. STP. EQ. 2. 1.) GO TO 50

0004 IF (STP. EQ. 1. 1. OR. STP. EQ. 2. 1.) GO TO 40

0005 IF (STP. EQ. 4. 1.) GO TO 30

** CONTINUOUS SPILL IN RIVER, VELOCITY > 0 **

0006 CALL INIT4A

0007 IF (STP. EQ. 1. 1.) GO TO 10

0008 GO TO 99

** CONTINUOUS SPILL IN OPEN WATER, VELOCITY > 0 **

0009 CALL INIT4B

0010 IF (STP. EQ. 1. 2.) GO TO 10

0011 GO TO 99

** INSTANTANEOUS OR CONTINUOUS SPILL IN RIVER. IF CONTINUOUS, VELOCITY = 0. **

0012 CALL INT12A

0013 GO TO 99

** INSTANTANEOUS OR CONTINUOUS SPILL IN OPEN WATER. IF CONTINUOUS, VELOCITY = 0. **

0014 CALL INT12B

0015 RETURN

99 RETURN
SUBROUTINE INT12A

* CALCULATE INITIAL CONDITIONS FOR MODELS 1A & 2A
* INSTANTANEOUS OR CONTINUOUS IN RIVER OR CHANNEL
* IF SPILL IS CONTINUOUS, UBBAR MUST BE ZERO

THIS SUBROUTINE IS CALLED BY "INIT". IT CALCULATES THE INITIAL CONDITIONS FOR INSTANTANEOUS OR CONTINUOUS SPILLS IN A CHANNEL. FOR A CONTINUOUS SPILL, THE CURRENT AND WIND MUST BE ZERO; OTHERWISE, "INIT4A" WILL BE CALLED.

COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPM
COMMON/CHMI/DEN0, DCA, DCW, CS, CMW
COMMON/WATER/DENW, VISW, GR
COMMON/ENVOR/PV, VISA, DENAo TDC
COMMON/INTER/COEF, SIOWA, SIGOA, SIOW, SIG
COMMON/SPREAD/TII, ATK, HTK, ATN, HTN, HMIN, INDEX, IFLAG
COMMON/SIZE/R,, WW, LI, L2, H, RO
COMMON/RUNGE/YY(5), C(24), W(5, 30)
COMMON/MOVE/UPEAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
COMMON/CONTORSHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON/UAVE/UCJ, UCYJ, VWX1, VWY1
COMMON/PRIM/PRIME(5), IDEB, KKK
COMMON/UAVE/UCJ, UCYJ, VWX1, VWY1
COMMON/SENSE/EVA(40, 10), DIS(40, 10), THK(40, 10), TIN(40, 10), PIP(40), TPT
COMMON/CK/C10, C20, C11, C21, C12, C22, K10, K20, K11, K21, K12, K22
COMMON/CONSTAT/UC, VW, UTBAR, UO, U1, WT, ALPH, THETA1
REAL K10, K20, K11, K21, K12, K22

** STP = 1.1 (INST.) OR 2.1 (CONT.) FOR THIS SUBROUTINE (RIVERS)

I = STP
PI = ACOS(-1.)
GO TO (201, 101) I

**** MODEL 2A IS BEING USED ****
(CONTINUOUS SPILL IN THE CHANNEL) ***

TIA = ((SPILMR/(DENW*WW))^2/(GR*COEF*VISW**(3. /2. )))**(2. /3.)

** TIA = END OF GRAVITY-INERTIA SPREADING FOR A CONT. SPILL **

IF (TIA < .0E0, TSPILL) GO TO 110
GO TO 210
WRITE (1, 112)
WRITE (6, 112)
FORMAT (1H1, //1X,

1 50H-----------------------------------------------------------------------------------/
1 1X, 48HTHE SPILL TIME IS SO SHORT THAT AN INSTANTANEOUS, /
2 1X, 31H SPILL WILL GIVE BETTER RESULTS)
** SPILL IS SWITCHED TO INSTANTANEOUS WITH **
** SPILLED MASS - DISCHARGE RATE * DISCHARGE TIME  **

C
0027  STP = 1.1
0028  SPILLM = SPILMR + TSPILL
C
---- MODEL 1A IS BEING USED ----
** (INSTANTANEOUS SPILL IN THE CHANNEL) **

C
0029  CONTINUE
0030  VO = SPILLM/DENW
0031  TIA=((VO/WW)**4./((VISW**3.)*(GR*COEF)**2.))**(1./7.)*
     ((C20/C10)**(24./7.))
C
** TIA = END OF GRAVITY-INERTIA SPREADING FOR AN INST. SPILL **

C
0032  I = STP
0033  GO TO (240, 220)
C
----- CALCULATE TIB AND RIB BY USING MODEL 2B -----
(2A IS THE CURRENT MODEL)

C
***********************************************
FOR A CONTINUOUS SPILL, USE OPEN WATER MODEL TO COMPUTE TIME
FOR SPILL TO SPREAD ACROSS RIVER. FIRST, COMPUTE THE CONDITIONS
AT END OF GRAVITY-INERTIA PHASE FOR OPEN WATER.
***********************************************

C
0034  TIB = SORT(SPILMR/(GR*COEF*DENW*VISW))**((K21/K11)**6.)
C
** TIB = END OF GRAVITY-INERTIA PHASE FOR A CONT. SPILL **
** IN OPEN WATER **

C
0035  AIB = (((SPILMR/DENW)**5/(VISW**3*GR*COEF))**0.25)*
     (PI*C21**2.*(C21/C20)**7.)
0036  RIB = SORT(AIB/PI)
C
** RIB = RADIUS OF GRAVITY-INERTIA PHASE SLICK FOR CONT. SPILL **
** IN OPEN WATER **

C
0037  GO TO 260
C
----- CALCULATE TIB AND RIB BY USING MODEL 1B -----
(1A IS THE CURRENT MODEL)

C
***********************************************
FOR AN INSTANTANEOUS SPILL, USE OPEN WATER MODEL TO COMPUTE TIME
FOR SPILL TO SPREAD ACROSS RIVER. FIRST, COMPUTE THE CONDITIONS
AT END OF GRAVITY-INERTIA PHASE FOR OPEN WATER.
***********************************************

C
0038  TIB = (VO/(GR*COEF*VISW))**((1./3.)*(K20/K10)**4. )
0039  AIB = (VO**((2./3.))*(GR*VO*COEF/(VISW**2)))**((1./6.)*
     (PI*K20**2.*(K20/K10)**2. )
0040  RIB = SORT(AIB/3.141593)
C
** TIB = END OF GRAVITY-INERTIA PHASE FOR INST. SPILL IN **
** OPEN WATER **
** RIB = RADIUS OF GRAVITY-INERTIA PHASE SLICK FOR INST. **
** SPILL IN OPEN WATER **

0041 CONTINUE
0042 IF (RIB.LT.(WW/2.0)) GO TO 400

*******************************************************************************
IF RIB < WW/2, THE SLICK WILL SPREAD SOME MORE AS AN OPEN WATER SLICK, BUT NUMERICAL INTEGRATION IS REQUIRED.
*******************************************************************************

0043 IF (TIB.GE.TIA) GO TO 280

*******************************************************************************
IF TIB > TIA, OPEN-WATER SLICK HAS SPREAD ALL THE WAY ACROSS RIVER, BUT NEED TO REDUCE TIME SOME TO FIND ACTUAL TIME TO SPREAD ACROSS RIVER.
*******************************************************************************

0044 TII = TIA

** TIB < TIA. SO INITIAL TIME TII = TIA **

0045 GO TO (261, 262)

USE MODEL 1A TO COMPUTE INITIAL AREA AND THICKNESS

0046 261 ATK=2.*C20*((C20/C10)**(9./7.))*(VO**4.*WW**2.)*(i./7.)*(GR*COEF*VO/VISW**2.)**(1./7.)
0047 HTK = VO/ATK

*******************************************************************************
ATK AND HTK ARE INSTANTANEOUS SPILL THICK SLICK AREA AND THICKNESS AT TIME SLICK HAS SPREAD ACROSS RIVER.
*******************************************************************************

0048 IF (IC.GE.2) GOTO 265

*******************************************************************************
XC = NEW SPILL CENTER LOCATION XC AFTER BEING TRANSPORTED DOWNSTREAM (INSTANTANEOUS)
*******************************************************************************

0049 XC-XO + (UCXI+0.025*VWX1)*TIA
0050 GOTO 270
0051 265 XC=XC+(VO*TIA-(WT/(2.*PI*TIA)))*(COS(2.*PI*(TIA+ALPH)/WT)-COS(2.*PI*ALPH/WT))+0.035*VWX1)*TIA
0052 GOTO 270

USE MODEL 2A TO COMPUTE INITIAL AREA & THICKNESS

0053 262 ATK = 2.*C21*((C21/C11)**7.)*(SPILMR/(WW*DENW))**(5./3.)/
0054 1 (VISW*(GR*COEF)**(1./3.))
0055 HTK = (SPILMR*TII-DENO*8.0*ATK*HTN)/(DENO*ATK)

*******************************************************************************

C-29
ATK and HTK are continuous spill thick slick area and thickness.

At time slick has spread across river.

0055 270 ATN = 8.0*ATK
** ATN = THIN SLICK AREA **

0056 280 GO TO 300
0057 280 CONTINUE
0058 281 TII = TIB * SQRT(WW/(2.0*RIB))
0059 281 ATK = AIB*TII/TIB
** INITIAL TIME AND AREA WHEN RIB > WW/2 AND TIB > TIA. **

0060 281 GO TO (281, 282)
USE MODEL 1. A TO CALCULATE INITIAL THICKNESS(INSTANTANEOUS)

0061 281 HTK = VO/ATK
0062 281 GO TO 285
USE MODEL 2. A TO CALCULATE INITIAL THICKNESS AND
CORRECT FOR MASS IN THIN SLICK(CONTINUOUS)

0063 282 HTK = (SPILMR*TII-DENO*8.0*ATK*HTN)/(DENO*ATK)
0064 285 CONTINUE
0065 285 ATN = 8.0 * ATK

0066 290 IF (I.EQ.1) GO TO 300
0067 290 IF (TII.LT.TSPILL) GO TO 300
0068 290 WRITE (1,112)

TIME REQUIRED TO SPREAD ACROSS RIVER > DISCHARGE TIME.
SWITCH TO AN INSTANTANEOUS MODEL AND START OVER

0069 300 STP = 1.1
0070 300 SPILLM = SPILMR * TSPILL
0071 300 GO TO 201

0072 300 CONTINUE
0073 301 TII = TII/60.
0074 301 WRITE (1,301) ATK, TII
0075 301 WRITE (6,301) ATK, TII
0076 301 FORMAT (/1H1/1X.

TIME THE THICK SLICK HAS SPREAD OVER THE.
15h CHANNEL WIDTH. /1X.21HIT COVERS AN AREA OF .
15H AFTER A TIME OF,
13H Meters. /1X.15H 7HMINUTES)

0077 C GO TO 699
0078 C CONTINUE
ROUTINE TO NUMERICALLY INTEGRATE OPEN WATER MODELS IN
GRAVITY-VISCOUS PHASE UNTIL SLICK SPREADS ACROSS RIVER

0079 TII = TIB
0080 ATK = A12
0081 GO TO (401, 402) I

USE MODEL 1B TO CALCULATE INITIAL THICKNESS (INSTANTANEOUS)

0082 401 HTK = V0/ATK
0083 GO TO 405

USE MODEL 2B TO CALCULATE INITIAL THICKNESS
(CORRECT FOR MASS IN THIN SLICK) (CONTINUOUS)

0084 402 HTK = (SPILMR*TII-DENO*8.0*ATK*HTN)/(DENO*ATK)
0085 405 CONTINUE

** TEMPORARILY CHANGE TO OPEN WATER MODEL **

0092 IF (STP. EQ. 1.1) STP = 1.2
0093 IF (STP. EQ. 2.1) STP = 2.2
0094 CALL TRANSP

** INTEGRATE OVER ONE TIME STEP **

0095 410 CALL INTE(XEND)

** CHECK FOR EVAPORATION PROBLEMS **

0096 IF (IDEB. EQ. 0) THEN
0097 KKK = 3
0098 IF (STP. EQ. 1.2) STP = 1.1
0099 IF (STP. EQ. 2.2) STP = 2.1
0100 QOTO 699
0101 ELSE
0102 ENDIF

** CHECK TO SEE IF SLICK HAS SPREAD ACROSS RIVER **

0103 IF (SQRT(YY(1)/3.141593).GE. (WW/2.0)) GO TO 420

** SEE IF PRINTOUT TIME HAS OCCURRED **

0104 IJ = TIME
IK = TPT
MD = MOD(IJ, IK)
IF (MD.NE.0) GO TO 410
CALL MOVE
CALL PRINTO
GO TO 410
CONTINUE
TB = TIME
** CHANGE BACK TO INSTANTANEOUS MODEL IN RIVER **
STP = 1.1
GO TO (442,422) I
C
IF (TB.GE.TSPILL) GO TO 424
C
** CHANGE BACK TO CONTINUOUS MODEL IN RIVER **
SPILLM = SPILMR * TB
GO TO 442
CONTINUE
WRITE (1,112)
WRITE (6,112)
C
IF TIME > DISCHARGE TIME, SWITCH TO INSTANTANEOUS MODEL **
STP = 1.1
SPILLM = SPILMR * TSPILL
GO TO 201
CONTINUE
C
** SET INITIAL TIME = TII **
TII = TB
ATK = YY(1)
ATN = YY(2)
HTK = YY(3)
TOTALM = YY(1) * YY(3) * DENO
DMASS = SPILLM - TOTALM
TIIT = TII/60.
WRITE (1,444) ATK, TIIT, DMASS
WRITE (6,444) ATK, TIIT, DMASS
FORMAT (1HI//1X, 2 /1X, 32H THICK SLICK HAS SPREAD OVER ,
3 32H CHANNEL WIDTH AND COVERS AN AREA /1X, 3HOF , E12.5,
4 2X, 29H SQUARE METERS AFTER A TIME OF, E12.5, 2X, 9H MINUTES, /,
3 1X, 3H THE MASS LOST FROM THE SLICK UP TO THIS,
4 8H TIME IS, E12.5, 2X, 9H KILOGRAMS)
RETURN
END
SUBROUTINE INT12B

* INITIAL CONDITIONS FOR MODELS 1.B AND 2.B *
* SPILL IN OPEN WATER. IF SPILL IS *
* CONTINUOUS, CURRENT MUST BE ZERO. *

THIS SUBROUTINE IS CALLED BY "INIT". IT CALCULATES THE
INITIAL CONDITIONS FOR INSTANTANEOUS OR CONTINUOUS SPILLS
IN OPEN WATER. FOR A CONTINUOUS SPILL, THE CURRENT AND WIND
MUST BE ZERO. OR ELSE "INIT4B" WILL BE CALLED.

COMMON/STYPE/SPILLM, SPILMR, TSPIII, WS, STP, SPM
COMMON/CHEMI/DENO, DCA, DCW, CS, CMW
COMMON/WATER/DENW, VISW, OR
COMMON/SPREAD/TII, ATK, HTK, ATN, HTN, HMIN, INDEX, IFLAG
COMMON/ENVOR/PV, VISA, DENA, TDC
COMMON/INTER/COEF, SIOWA, SIGOA, SIGOW, SIG
COMMON/SENSE/EVA(40, 10), DIS(40, 10), THK(40, 10), TIN(40, 10),
PIP(40), TPT
COMMON/CONTOUR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON/UAVE/UCX1, UCY1, VWX1, VWY1
COMMON/CK/CIOC20, CI20, CI21, C20, C21, C12, C22, K10, K20, K11, K21.
1
COMMON/UAVE/UCX1, UCY1, VWX1, VWY1

PI=ACOS(-1.)

** STP = 1.2 (INST.) OR 2.2 (CONT.) -- OPEN WATER **

I = STP
GO TO (10, 110) I

FOR INSTANTANEOUS SPILL IN OPEN WATER

SPI = SPILLM
VO = SPI/DENO
TII = ((K20/K10)**4.)*(VO/(GR*COEF*VISW))** (1.0/3.0)
ATK = PI*((K20**2.)*((K20/K10)**2.)*(VO** (2.0/3.0))) *
(1.0/6.0)
HTK = VO/ATK

TII = END OF GRAVITY-INERTIA PHASE
ATK, HTK = THICK SLICK AREA AND THICKNESS AT END OF
GRAVITY-INERTIA PHASE

XC=XC+(UCX1+0.035*VWX1)*TII
YC=YC+(UCY1+0.035*VWY1)*TII

** XC, YC = NEW VALUES OF SICK CENTER LOCATION **

GO TO 149
FOR CONTINUOUS SPILL

0024 110 TII = ((K21/K11)**6.)*SQRT(SPILMR/(GR*COEF*DENW*VISW))
** TII = END OF GRAVITY-IERTIA PHASE **

0025 IF (TII.LT.TSPILL) GO TO 120
0026 WRITE (1,112)
0027 WRITE (6,112)
0028 112 FORMAT (1H4//IX,
1 30H*********************************************************************,/
2 1X,48HTHE SPILL TIME IS SO SHORT THAT AN INSTANTANEOUS./
3 1X,30HSPILL WILL GIVE BETTER RESULTS)
** SINCE TII > DISCHARGE TIME, SWITCH TO INSTANTANEOUS MODEL **

0029 STP = 1.2
0030 SPILLM = SPILMR * TSPILL
0031 GO TO 10
0032 120 ATK = (PI*K21**2.*(K21/K11)**7.)*((SPILMR/DENW)**5
9 /(VISU**3.*GR*COEF)) ** 0.25
0033 HTK = (SPILMR*TII-DENO*B.0*ATK*HTN)/(DENO*ATK)
0034 ATN = B.0*ATK
** ATK, HTK = THICK SLICK AREA AND THICKNESS AT END OF **
** GRAVITY-INERTIA PHASE **
** ATN = THIN SLICK AREA AT END OF GRAVITY-INERTIA PHASE **

0035 149 CONTINUE
0036 RADIUS = SQRT(ATK/3.141593)
0037 TII = TII/60.
0038 WRITE (1,159) ATK,RADIUS,TII
0039 WRITE (6,159) ATK,RADIUS,TII
0040 159 FORMAT (1X,38HTHICK SLICK HAS SPREAD OVER A CIRCULAR,
1 SH AREA OF,.E12,5.14SQUARE METERS./
2 1X,17HWITH A RADIUS OF,.E12,5.6METERS,
3 16H AFTER THE FIRST,.E12,5.7MINUTES)
0041 RETURN
0042 END
SUBROUTINE INIT4A

*****************************************************************************
* CALCULATE INITIAL CONDITIONS FOR MODEL 4A
* CONTINUOUS IN A CHANNEL WITH A TRANSPORT VELOCITY
* OF UTB4
*****************************************************************************

THIS SUBROUTINE IS CALLED BY "INIT". IT COMPUTES INITIAL
CONDITIONS FOR A CONTINUOUS SPILL IN A RIVER WITH A CURRENT.

COMMON/SIZE/R, D, WW, L1, L2, M, RO
COMMON/STYPE/SPILLM, SPILLR, TSPILL, WS, STP, SPM
COMMON/WATER/DENW, VSW, GR
COMMON/CHIM/DENO, DCA, DCW, CS, CMW
COMMON/SPREAD/TII, ATK, HTK, ATN, HMIN, INDEX, IFLAG
COMMON/RUNGE/YY(5), C(24), W(5,30)
COMMON/CONSTAT/UC, VW, UTBAR, UO, U1, WT, ALPH, THETA1
COMMON/TRAVEL/WTK, Z
COMMON/INTER/COEF, SIGMA, SIGOA, SIGOW, SIG
COMMON/MOVE/UPEAK(10), XLE, XTE, VLE, VTE, DELT, TIME, TSTOP, TCHECK
COMMON/PRIM/PRIME(5), IDEB, KKK
COMMON/CK/CIOC20, CIC21, CI2, C22, K10, K20, K11, K21.

REAL K10, K20, K11, K21, K12, K22

TIB = ((K22/K12)**(24./7.))*(SPILMR/(2.*DENW))**(4./7.)/
     1 (((UTBAR**(4./7.))*(GR*COEF)**(2./7.))*(VSW**(3./7.)))

ATKB = K22*(K22/K12)**(33./7.)*(SPILMR/(2.*DENW))**(9./7.)/
       1/((UTBAR**(2./7.))*(GR*COEF)**(1./7.))*(VSW**(5./7.)))

** TIB = END OF GRAVITY-INERTIA PHASE
** ATKB = THICK SLICK AREA AT END OF GRAVITY-    **
**     INERTIA PHASE

IF (TIB.LT.TSPILL) GO TO 50
WRITE (1,10)
WRITE (6,10)
FORMAT (//5X,44HSPILL TIME IS SO SHORT THAT AN INSTANTANEOUS,
       1/5X,31HMODEL WILL GIVE BETTER RESULTS.)

*****************************************************************************
SINCE TIB > DISCHARGE TIME, SWITCH TO AN INSTANTANEOUS
SPILL (RETURN TO "INIT").
*****************************************************************************

STP = 1.1
SPILLR = SPILMR * TSPILL
GO TO 99

** WTK = WIDTH OF DOWNSTREAM END OF THICK SLICK

WTK = 2.*ATKB/(UTBAR*TIB)
IF (WTK.GT.WW) GO TO 55
GO TO 100

C-35
C SINCE WTK > RIVER WIDTH, TIME AND SLICK AREA NEED TO BE REDUCED ACCORDINGLY TO GET INITIAL CONDITIONS.

C

0028 TII = TIB*(W/WTK)
0029 ATK = ATAB*(TII/TIB)**2

0030 IF (TII, OT, TSPILL) GO TO 90
0031 Z = UBAR*TII
0032 TIIT = TII/60.
0033 WRITE (1,60) ATK, TIIT, Z
0034 WRITE (6,60) ATK, TIIT, Z
0035 FORMAT(/1X,42HTHICK SLICK HAS SPREAD ACROSS THE CHANNEL,
1 27 WIDTH AND COVERS AN AREA OF E12.5/IX,
2 29 PORE METER AFTER A TIME OF E12.5,2X,8 MINUTES,
3 1X.25 THE SLICK LEADING EDGE IS E12.5,2X,
4 18 METERS DOWNSTREAM.)

C 0036 HTK = (SPILMR*TII-DENO*8.0*ATK*HTN)/(DENO*ATK)

C 0037 ATN = 8.0 * ATK

C 0038 GO TO 299

C 0039 CONTINUE

C 0040 TII = TII

C 0041 GO TO 5

C SINCE SLICK WIDTH < RIVER WIDTH AT END OF GRAVITY-INERTIA PHASE, USE INTEGRATION OF OPEN-WATER GRAVITY-VISCOUS MODEL TO CONTINUE UNTIL WIDTH = RIVER WIDTH.

C

0042 TII = TII
0043 ATK = ATKB
0044 HTK = (SPILMR*TII-DENO*8.0*ATK*HTN)/(DENO*8.0*ATK)
0045 TIME = TII
0046 YY(1) = ATK
0047 YY(2) = 8.0 * ATK
0048 YY(3) = HTK

C 0049 CALL TRANSP

C 0050 CALL INTE(XEND)
** CHECK FOR EVAPORATION TROUBLES **

IF (IDEB.EQ.0) THEN
  KKK=3
  STP=4.1
  GOTO 299
ELSE
  ENDIF

** ONCE MORE, CHECK TO SEE IF TIME < DISCHARGE TIME **

IF (TIME.GT. TSPILL) GOTO 5.
IF ((2.0*YY(I))/(UTBAR*TIME)).GT.WW) GOTO 110

** GO TO 110 WHEN WIDTH > RIVER WIDTH **

IJ = TIME
IK = TPT
MD = MOD(IJ, IK)
IF (MD .NE. 0) GO TO 105
CALL MOVE
CALL PRINTO
GO TO 105
STP = 4.1

RETURN WITH INITIAL CONDITIONS TII = TIME, ATK = THICK SLICK AREA, ATN=THIN SLICK AREA, AND ATK = THICK.

TII = TIME
ATK = YY(1)
ATN = YY(2)
HTK = YY(3)
TOTALM = YY(1)*YY(3)*DENO
SPILLM=SPILHR * TIME
DMASS = SPILLM - TOTALM
TIIT = TII/60
Z = UTBAR * TII
WRITE (1,120) ATK, TIIT, Z, DMASS
WRITE (6,120) ATK, TIIT, Z, DMASS
FORMAT(/1X,41THICK SLICK HAS SPREAD ACROSS THE CHANNEL,
1 284 WIDTH AND COVERS AN AREA OF.,/1X,E12 5,
2 14HOURS SQUARE METERS.,/1X,16AFTER A TIME OF .E12 5.8MINUTES ./,
3 23HMETERS SLICK LEADING EDGE IS.E12 5,
4 15METERS DOWNSTREAM ./1X,
5 47HTHE MASS LOST FROM THE SLICK UP TO THIS TIME IS,
6 E12 5.104KILLOGRAMS ;
RETURN
END
SUBROUTINE INIT4B

* CALCULATE INITIAL CONDITIONS FOR MODEL 4B
* CONTINUOUS SPILL IN OPEN WATER WITH A CURRENT
* SPEED (TRANSPORT VELOCITY) OF UTBAR

THIS SUBROUTINE IS CALLED BY "INIT". IT COMPUTES THE INITIAL CONDITIONS FOR A CONTINUOUS SPILL IN OPEN WATER WITH A CURRENT.

0002 COMMON SIZE/R, D, WW, L1, L2, H, RO
0003 COMMON STYPE/SPILLM, SPILMLR, TSPILL, WS, STP, SPM
0004 COMMON WATER/DENW, VISW, OX
0005 COMMON CHEM/DENO, DCA, DCW, CS, CMW
0006 COMMON SPREAD/TII, ATK, HTK, ATN, HMIN, INDEX, IFLAG
0007 COMMON CONSTRAINT/UC, VU, UTBAR, U0, U1, WT, ALPH, THETA1
0008 COMMON TRAVEL/WTK, 2
0009 COMMON INTER/Coeff, SIGMA, SIGMAU, SIGMAO, SIGMA10
0010 COMMON MOVE/UPEAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
0011 COMMON TRANSIT/WX(10, 10), UY(10, 10), VWX(10), VWY(10), THETA(10), TI(10), ID, IT, IV,
0012 COMMON CONTOUR/shape, X(10), Y(10), XC, YC, IW, ISP, XO, YO
0013 COMMON CK/C10, C20, C11, C21, C12, C22, K10, K20, K1, K21.
0014 REAL K10, K20, K11, K21, K12, K22
0015 M=ISP
0016 TII = ((K22/K12)**(24./7.))*((SPILMLR/(2.*DENW))**(9./7.))
0017 IF (TII.E. TSPILL) GO TO 50
0018 IF TII > DISCHARGE TIME, SWITCH TO AN INSTANTANEOUS MODEL **
0019 ATK = K22*(((K22/K12)**(33./7.))*((SPILMLR/(2.*DENW))**(9./7.))
0020 /((UTBAR**((2.*7./)))*((GR*COEF)**(1./7.)))*((VISW**((3./7.))))
0021 HTK = (SPILMLR*ATN+8.*ATK+HTN)/(DENW+ATK)
0022 ATN = 0.0 + ATK
0023 WTK = 2.0 + ATK/(UTBAR*ATK)

ATK = INITIAL THICK SLICK AREA
HTK = INITIAL THICK SLICK THICKNESS
ATN = INITIAL THIN SLICK AREA
WTK = INITIAL THICK SLICK DOWNSTREAM WIDTH

XLE AND YLE ARE DOWNSTREAM COORDINATES OF LEADING EDGE WITH RESPECT TO CURRENT DIRECTION.
C
0022 Z = UTBAR*TII
0023 XLE = XC + (UX(M,1)+0.035*VWX(1))*TII
0024 YLE = YC + (UY(M,1)+0.035*VWY(1))*TII
0025 TIII = TII/60.
0026 WRITE (1,20) ATK, TII, WTK, Z
0027 WRITE (6,20) ATA, TII, WTK, Z
0028 20 FORMAT(/1X,41HTHICK SLICK HAS SPREAD OVER AN ELONGATED ,
1 19HTRIANGULAR AREA OF ,E12.5,/
2 1X,29HSQUARE METERS AFTER A TIME OF,E12.5,0HMINUTES.,/
3 1X,31HTHE THICK SLICK LEADING EDGE IS,E12.5,2X,
4 18HMETERS WIDE AND IS,E12.5,2X,7HMETERS /
5 1X,11HDOWNSTREAM.)
0029 WRITE (1,22) ATN
0030 22 FORMAT(/1X,31HTHE THIN SLICK AREA IS EQUAL TO,E12.5,/
1 1X,14HSQUARE METERS.)
0031 TEMP1 = DENO*(ATK*HTW-ATN*HTN)
0032 TEMP2 = SPILMR*TII
0033 GO TO 99
0034 50 WRITE (1,52)
0035 52 FORMAT(/1X,45HSPIILL TIME IS SO SHORT THAT AN INSTANTANEOUS ,
1 /1X,31HMODEL WILL GIVE BETTER RESULTS.)
0037 ** MAKE SWITCH TO INSTANTANEOUS MODEL **
0038 STP = 1.2
0039 99 RETURN
0040 END
SUBROUTINE TO SOLVE SIMULTANEOUS 1ST ORDER DIFFERENTIAL EQUATIONS BY USING RUNGE-KUTTA METHOD

THIS SUBROUTINE IS CALLED BY "SPREAD" AND THE INITIAL CONDITION SUBROUTINES "INT12A" AND "INIT4A". IT SENDS THE APPROPRIATE GRAVITY-VISCOS MODEL EQUATIONS TO A RUNGE-KUTTA INTEGRATION ROUTINE "RUNKUT" TO COMPUTE THE THICK SLICK AREA AND OTHER VARIABLES AS A FUNCTION OF TIME. AFTER EACH PASS, 'TIME' IS INCREMENTED BY 'DELT'. THE "FCN" SUBROUTINES IN THE "RUNKUT" CALL ARE THE EQUATIONS OF THE GRAVITY-VISCOS MODELS. THE MATRIX 'YY' IN THE CALL IS:
** YY(1) = THICK SLICK AREA, SQ. M
** YY(2) = THIN SLICK AREA, SQ. M
** YY(3) = THICK SLICK THICKNESS, M

THE MATRIX 'YPRIME' IN THE "FCN" SUBROUTINES IS:
** YPRIME(1) = D(YY(1))/DT
** YPRIME(2) = D(YY(2))/DT
** YPRIME(3) = D(YY(3))/DT
** YPRIME(4) = RATE OF EVAPORATION LOSS, KG/SEC
** YPRIME(5) = RATE OF DISSOLUTION LOSS, KG/SEC

--- CALL SUBROUTINE TO CALCULATE EVAPORATION LOSS ---

--- CALL DISS ---

--- MODEL 1.A ---

IF (STP .NE. 1.1) GO TO 20
C---- MODEL 1. A -----
0023 CALL RUNKUT(N, FCN11, TIME, YY, XEND, TOL, IND, C, NW, W, IER)
0024 GO TO 99
0025 20 IF (STP .NE. 1. 2) GO TO 30
C---- MODEL 1. B -----
0026 CALL RUNKUT(N, FCN12, TIME, YY, XEND, TOL, IND, C, NW, W, IER)
0027 GO TO 99
0028 30 IF (STP .NE. 2. 1) GO TO 40
C---- MODEL 2. A -----
0029 CALL RUNKUT(N, FCN21, TIME, YY, XEND, TOL, IND, C, NW, W, IER)
0030 GO TO 99
0031 40 IF (STP .NE. 2. 2) GO TO 70
C---- MODEL 2. B -----
0032 CALL RUNKUT(N, FCN22, TIME, YY, XEND, TOL, IND, C, NW, W, IER)
0033 GO TO 99
0034 70 IF (STP .NE. 4. 1) GO TO 80
C---- MODEL 4. A -----
0035 CALL RUNKUT(N, FCN41, TIME, YY, XEND, TOL, IND, C, NW, W, IER)
0036 GO TO 99
0037 80 CONTINUE
C---- MODEL 4. B -----
0038 CALL RUNKUT(N, FCN42, TIME, YY, XEND, TOL, IND, C, NW, W, IER)
0039 99 CONTINUE
0040 TOTALE = YY(4)
0041 TOTALD = YY(5)
0042 TOTALM = DEN0*YY(1)*YY(3)
0043 ISTP = STP
0044 110 CONTINUE
0045 CALL CHEKMS
0046 IF (IDEB .GT. 1) GO TO 999
C
C******************************************************************************
C IF IDEB = 0, 'TCHECK' IS MADE LESS THAN 'TIME'. OTHERWISE, 'TCHECK' REMAINS EQUAL TO 'TSTOP' AS SPECIFIED IN 'DMODEL'.
C******************************************************************************
C
0047 111 TCHECK = TIME - DELT
0048 999 CONTINUE
0049 RETURN
0050 END
SUBROUTINE MOVE

TRACKING THE MOVEMENT OF THE SLICK

THIS SUBROUTINE IS CALLED BY "SPREAD" AND THE INITIAL CONDITION
SUBRoutines "INIT4A" AND "INT12A". IT COMPUTES THE MOVEMENT
OF THE SLICK FOR EACH TIME STEP. THE TRANSPORT VELOCITIES ARE
COMPUTED IN SUBROUTINE "TRANS".

SUBROUTINE MOVE
COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPH
COMMON/MOVE/UPEAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
COMMON/CONTOR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON/TRANSIT/UX(10, 10), UY(10, 10), VMX(10),
1 VWY(10), THETA(10), TI(10), ID, IT, IV,
2 XU(10), YU(10), TT(10)
COMMON/CONSTAT/UC, VW, UTBAR, UO, Ul, WT, ALPH, THETAI
COMMON/CURRENT/UBAR(10), DMOVE, UTOT, UTX, UTY, UREL

I = STP
J = SHAPE
TBEF = TIME-DELT
IC1 = IC + 1
IW1 = IW + 1
IF(I.GT.1) GO TO 200

INSTANTANEOUS SPILL
(THE WHOLE SLICK IS FREE TO MOVE)

IF (J.LT.2) GO TO 100
*** MOVEMENT MODEL M. 1.0 ***
(IN OPEN WATER)

DMOVE = 1.0
XC = XC + UTX*DELT
YC = YC + UTY*DELT
GO TO 999

*** MOVEMENT MODEL M. 1.1 ***
(IN OPEN WATER AFTER THE SPILL STOPPED)

*** MOVEMENT MODEL M. 2 ***
(IN RIVERS OR CHANNELS)

CONTINUOUS SPILL
(THE SLICK MUST STAY ATTACHED TO THE SPILL ORIGIN)
CONTINUE
IF (J.GT.1) GO TO 400
IF (IC.GT.1 AND IW.GT.1) GO TO 250

** MOVEMENT MODEL M.3.A **
1. IN RIVER OR CHANNEL
2. UC AND VW DO NOT VARY WITH TIME

DMOVE = 3.10
XLE = UTOT*TIME
XTE = 0.0
GO TO 999
CONTINUE
IF (UBAR(1).LT.(0.3*UPEAK(1))) GO TO 300

** MOVEMENT MODEL M.3 (B.1) **
1. IN RIVER OR CHANNEL
2. UBAR .GE. (0.3*UPEAK)

********************************************************************
WHEN UBAR > 0.3 * UPEAK, TIME VARIATION IS NEGLECTED AND
AVERAGE TRANSPORT VELOCITY IS USED TO COMPUTE MOVEMENT
DUE TO CURRENT. CORRECTION FOR APPARENT MOVEMENT DUE TO
SPREADING IS MADE IN "PRINTO".
********************************************************************

DMOVE = 3.21
XLE = (UBAR(1) + 0.035*VW*COS(THETA1))*TIME
XTE = 0.0
GO TO 999

** MOVEMENT MODEL M.3 (B.2) **
1. IN RIVER OR CHANNEL
2. UBAR .LT. (0.3*UPEAK)

********************************************************************
WHEN UBAR < 0.3 * UPEAK, TIME VARYING 'UTOT' IS USED TO
COMPUTE INCREMENTAL MOTION OF LEADING EDGE DUE TO CURRENT.
CORRECTION FOR APPARENT MOVEMENT DUE TO SPREADING IS MADE
IN "PRINTO".
********************************************************************

CONTINUE
DMOVE = 3.22
XLE = XLE + UTOT*DELT
GO TO 999

** OPEN WATER, CONTINUOUS SPILL **

IF (IC.LE.2 AND IW.LE.1) GO TO 455
GO TO 500

** MOVEMENT MODEL M.4.A **
1. IN OPEN WATER
2. UC AND VW DO NOT VARY WITH TIME

DMOVE = 4.10
** SINCE WIND = F(TIME), INTERPOLATE TO FIND WIND SPEED AT **
** CORRECT TIME. **

0050 CONTINUE
0051 DO 510 I = 1,10
0052 IF (TBEF.LE.TT(I)) GO TO 520
0053 CONTINUE
0054 W1 = VWX(I-1)+(VWX(I)-VWX(I-1))*(TBEF-TT(I-1))/
1 (TT(I)-TT(I-1))
0055 W2 = VWY(I-1)+(VWY(I)-VWY(I-1))*(TBEF-TT(I-1))/
1 (TT(I)-TT(I-1))

** W1 AND W2 ARE INTERPOLATED WIND SPEEDS IN X AND Y DIRECTION**

0056 CONTINUE
0057 IF (IC.EQ.1.OR.IC.EQ.3) ISP = 1

** IF CURRENT IS NOT F(SPACE), BOX OR SLICE LOCATION = 1 **

0058 IF (STP.LE.2.2) GO TO 600

*** MOVEMENT MODEL M. 4 (B. 1) ***
1. IN OPEN WATER
2. UT(I) GE. UPEAK(I)
I IS THE REGION NO. WHERE THE LEADING
EDGE WAS........
0059 DMOVE = 4.21
0060 XLE = XLE + UTX*DELT
0061 YLE = YLE + UTY*DELT
0062 GO TO 999

*** MOVEMENT MODEL M. 4 (B. 2) ***
1. IN OPEN WATER
2. UT(I) LT. UPEAK(I)
3. THE SLICK IS CIRCULAR
4. SPREADING MODEL 2.B WAS USED AND UBAR = 0.
0063 CONTINUE
0064 DMOVE = 4.22
0065 XLE = XLE+UTX*DELT
0066 YLE = YLE+UTY*DELT
0067 UO = UTX/SQRT(UTX**2.+UTY**2.)
0068 UI = UTY/SQRT(UTX**2.+UTY**2.)
0069 RETURN
0070 END
SUBROUTINE PRINTO

THIS SUBROUTINE IS CALLED BY "SPREAD" AND BY INITIAL CONDITION
SUBROUTINES "INT12A" AND "INIT4A". IT USES DATA FROM "MOVE"
AND MAKES SOME CORRECTIONS. IT ORGANIZES AND PRINTS OUT RESULT!

SUBROUTINE PRINTO
COMMON/SIZE/R, D, WW, L1, L2, H, RO
COMMON/CHI/DENO, DCA, DCW, CS, CMW
COMMON/WATER/DENW, VISW, GR
COMMON/ENVOR/PV, UIV, UIV, WT, ALPH, THETA1
COMMON/INTER/COEF, SIGWA, SIGOA, SIGOW, SIGO
COMMON/CONSTAT/UC, VW, UBAR, UO, UI, WI, ALPH, THETA1
COMMON/TRANSIT/U.X(10,10), UY(10), VWX(I0),
VWX(10), THETA(I0), TI(10), ID, IT, IV.
COMMON/ID/IDt, ID2, ID3
COMMON/RUNGE/YY(5), C(24), W(5,30)
COMMON/MASS/TOTALE, TOTALD, TOTALM, DMASS
COMMON/SPREAD/MIT, ATN, HTK, ATN, HTN, HTM, INDEX, IFLAG
COMMON/STYFE/SPELL, SPILM, TSPIL, TSUP, WS, STP, SP
COMMON/CURRENT/UBAR(10), DMOVE, UTOT, UTX, UTY, UREL
COMMON/ENSE/eva(40, 10), DIS(40, 10), THK(40, 10), TIN(40, 10).

REAL LTH

I = STP
ITEMP = TIME / 60.
TEMP = FLOAT (ITEMP)
DIFF = TIME - TEMP * 60.
TMASS = DENO*HTN*YY(2)
IF (I.EQ.1) TMASS=0.0
TOTS = TMASS + TOTALM + TOTALD + TOTALE
DECI = STP-0.0001
IF (DECI. LT. 0. 1999') GO TO 100
IF (I.EQ.4) GO TO 50

-------------------------------------------------------------------

SPREADING MODELS 1, B, 2, B
1B = INSTANTANEOUS SPILL IN OPEN WATER;
2B = CONTINUOUS SPILL IN OPEN WATER WITH NO CURRENT)
** ALL SLICKS ARE CIRCULAR **

THE NEXT 3 BLOCKS PRINT OUT DATA ON SLICK AREA, THICKNESS,
MASS, EVAPORATED MASS, AND OTHER NON-MOVEMENT PARAMETERS.

-------------------------------------------------------------------

RAD1 = SGRT(YY(1)/3.14159)
0031 RAD2 = SQRT((YY(1)+YY(2))/3.14159)
0032 WRITE (1.5) TEMP, DIFFT, YY(1), YY(3), RAD1
0033 WRITE (6.5) TEMP, DIFFT, YY(1), YY(3), RAD1
0034 5 FORMAT(///2X,7HTIME =,F10.2,8H MINUTES,2X,F7.3,8H SECONDS/9X,
1 18HTHICK SLICK AREA =,E12.5,6H SQ. M. ,2X,
2 23HTHICK SLICK THICKNESS =,E12.5,7H METERS/9X,
3 20HTHICK SLICK RADIUS =,E12.5,7H METERS)
0035 IF(I.EQ.1) QOTO 9
0036 WRITE (1.6) YY(2),RAD2
0037 WRITE (6,6) YY(2),RAD2
0038 6 FORMAT(9X,
1 18HTHIN SLICK AREA =,E12.5,5H SQ. M. ,/9X,
2 20HTHIN SLICK RADIUS =,E12.5,6H METERS)
0039 9 WRITE (1.7) TOTALM, TOTALE, EVAPM, TOTALD, DISSOM
0040 WRITE (6.7) TOTALM, TOTALE, EVAPM, TOTALD, DISSOM
0041 7 FORMAT(///9X,27HTOTAL MASS OF THICK SLICK =,E12.5,4H KG. ,/9X,
1 27HTOTAL EVAPORATED MASS =,E12.5,4H KG. ,/9X,
3 27HRATE OF EVAPORATION =,E12.5,15H KG/(SEC-SQ.M.),/9X,
4 27HTOTAL DISSOLVED MASS =,E12.5,4H KG. ,/9X,
5 27HRATE OF DISSOLUTION =,E12.5,15H KG/(SEC-SQ.M.))
0042 IF(I.EQ.1) QOTO 10
0043 WRITE(1.8)TMASS
0044 WRITE(6.8)TMASS
0045 8 FORMAT(9X,27HTOTAL MASS OF THIN SLICK =,E12.5,4H KG.)
0046 10 WRITE(1.20)TOTS
0047 20 FORMAT(///9X,27HTOTAL MASS =,E12.5,4H KG.)
0048 20 WRITE(6.20)TOTS
0049 GO TO 300

C C C C C
(CONTINUOUS SPILL IN OPEN WATER WITH CURRENT)
C ELONGATED SLICK
C
0050 CONTINUE
0051 XW = 2.0*YY(1)/(UTBAR*TIME)
0052 XW1 = YY(2)*2.0/(UTBAR*TIME)
0053 WRITE (1.55) TEMP, DIFFT, YY(1), YY(3), XW
0054 WRITE (6.55) TEMP, DIFFT, YY(1), YY(3), XW
0055 WRITE (1.57) YY(2),XW1
0056 WRITE (6.57) YY(2),XW1
0057 55 FORMAT(///2X,7HTIME =,F10.2,8H MINUTES,2X,F7.3,8H SECONDS/9X,
1 18HTHICK SLICK AREA =,E12.5,6H SQ. M. ,2X,
2 23HTHICK SLICK THICKNESS =,E12.5,7H METERS/9X,
3 30HTHICK SLICK DOWNSTREAM WIDTH =,E12.5,1X,6H METERS)
0059 57 FORMAT(///9X,
1 18HTHIN SLICK AREA =,E12.5,5H SQ. M. ,/9X,
2 30HTHIN SLICK DOWNSTREAM WIDTH =,E12.5,1X,6H METERS)
0059 57 FORMAT(///9X,
1 18HTHIN SLICK AREA =,E12.5,5H SQ. M. ,/9X,
2 30HTHIN SLICK DOWNSTREAM WIDTH =,E12.5,1X,6H METERS)
0059 WRITE (1.7) TOTALM, TOTALE, EVAPM, TOTALD, DISSOM
0060 WRITE (6.7) TOTALM, TOTALE, EVAPM, TOTALD, DISSOM
0061 WRITE(1.8)TMASS
0062 WRITE(6.8)TMASS
0063 WRITE(1.20)TOTS
0064 WRITE(6.20)TOTS

C-46
C \text{GO TO 300}

\begin{verbatim}
C SPREADING MODELS 1.A, 2.A
(1A = INSTANTANEOUS SPILL IN RIVER,
2A = CONTINUOUS SPILL IN RIVER WITH NO CURRENT)

C

0066 100 CONTINUE
0067 WRITE (1,105) TEMP, DIFFTYY(1),YY(3)
0068 WRITE (6,105) TEMP, DIFFTYY(0),YY(3)
0069 105 FORMAT (///2X.7HTIME = ,F10.2,8H MINUTES,2X,F7.3,8H SECONDS/9X, 
1 18HTHICK SLICK AREA = ,E12.5,6H SQ.M.,2X, 
2 223HTHICK SLICK THICKNESS = ,E12.5,7H METERS)
0070 IF(I.EG.1) GO TO 1C7
0071 WRITE (1,106) YY(2)
0072 WRITE (6,106) YY(2)
0073 106 FORMAT (9X, 
1 18HTHIN SLICK AREA = ,E12.5,H SQ.M.)
0074 107 WRITE (1,7) TOTALM,TOTALE,EVAPM,TOTALD,DISSOM
0075 WRITE (6,7) TOTALM,TOTALE,EVAPM,TOTALD,DISSOM
0076 IF(I.EQ.1) GO TO 30
0077 WRITE(1,8) TMASS
0078 WRITE(6,8) TMASS
0079 30 WRITE(1,20) TMASS
0080 WRITE(6,20) TMASS
C
0081 300 CONTINUE
0082 IJ = TIME
0083 IK = TPT
0084 IF (IJ.EQ.IK) GO TO 298
0085 MD = MOD(IJ,IK)
0086 IF (MD.NE.0) GO TO 299
0087 298 CONTINUE
0088 INDEX = INDEX + 1
0089 PIP(INDEX) = TIME
0090 EVA(INDEX,IFLAG) = TOTALE
0091 DIS(INDEX,IFLAG) = TOTALD
0092 THK(INDEX,IFLAG) = TOTALM
0093 TIN(INDEX,IFLAG) = TMASS
0094 299 CONTINUE
C
C \text{TRACKING MOVEMENT}

***************
'DMOVE' INDICES ARE DEFINED IN "MOVE"
***************

0095 IF (DMOVE.EQ.1.0. OR. DMOVE.EQ.1.1) GO TO 301
0096 IF (DMOVE.EQ.2.0) GO TO 311
0097 GO TO 321
C
C ** HERE TO 314 PERTAIN TO INSTANTANEOUS SPILLS **

0099 301 WRITE (1,303) XC,YC
\end{verbatim}
WRITE (6,303) XC, YC
FORMAT (/**9X,
1 41MTHE CENTER OF THE SLICK IS LOCATED AT X = ,
2 E12.5,15H METERS AND Y = ,E12.5,7H METERS)
GO TO 500

WRITE (1,313) XC
WRITE (6,313) XC
FORMAT (/**9X,25HTHE WHOLE SLICK HAS Moved,E12.5,
1 6HMETERS)
WRITE (1,314) LTH/2+XC,XC-LTH/2
WRITE (6,314) LTH/2+XC,XC-LTH/2
FORMAT(9X,40HTHE DOWNSTREAM EDGE OF THE SLICK IS AT = ,E12.5,
8 7H METERS, 1X,30H AND THE UPSTREAM EDGE IS AT = ,E12.5,7H METERS)
GO TO 500
CONTINUE
IF (DMOVE.LE.3.215) GO TO 323
IF (DMOVE.LT.3.900) GO TO 325
IF (DMOVE.LT.4.215) GO TO 333
GO TO 335

** REST OF STATEMENTS RELATE TO CONTINUOUS SPILLS **

TEMP1 = XLE
TEMP2 = 0.0
C ** NOW CORRECT IF THERE IS NO CURRENT, SO SLICK IS SPREAD **
C ** OUT SYMMETRICALLY ABOUT SOURCE. **
IF(TEMP1.EQ.0.0) THEN
TEMP1 = YY(1)/(2.0*WW)
TEMP2 = -YY(1)/(2.0*WW)
ELSE
TEMP1=YY(1)/WW
ENDIF
GO TO 327
TEMP1 = XLE+YY(1)/(2.0*WW)
TEMP2 = XLE-YY(1)/(2.0*WW)
C ** IN A TIDAL RIVER, THE TRAILING EDGE CANNOT MOVE **
C ** DOWNSTREAM, JUST UPSTREAM. **
IF (TEMP2.GT.0.0) TEMP2=0.0
WRITE (1,329) TEMP1,TEMP2
WRITE (6,329) TEMP1,TEMP2
FORMAT (/**9X,
1 47HTHE LEADING EDGE OF THE SLICK IS LOCATED AT X = ,
2 E12.5,6HMETERS/
3 9X,
4 48HTHE TRAILING EDGE OF THE SLICK IS LOCATED AT X = ,
5 E12.5,6HMETERS)
GO TO 500
CONTINUE
WRITE (1,334) XLE,YLE
WRITE (6, 334) XLE, YLE
FORMA11 (//9X,
1 4 THE LEADING EDGE OF THE SLICK IS LOCATED AT X = ,
2 E12 5.2X, 10+METERS AND/53X, 3HY = E12 5.2X, 6+METERS/5X,
3 61THE TRAILING EDGE OF THE SLICK IS LOCATED AT THE SPILL ORI
4 )
0135 335 GO TO 500
0136 333 TEMP1 = XLE+UO*SGRT(YY(1)/3 14159)+XC
0137 TEMP2 = YLE+U1*SGRT(YY(1)/3 14159)+YC
0138 TEMP3=(SGRT(XLE**2+YLE**2)-2$GRT(YY(1)/3 14159))U0
0139 TEMP4=(SGRT(XLE**2+YLE**2)-2$GRT(YY(1)/3 14159))U1
0140 IF((TEMP3-XC)GE 0 ) TEMP3=XC
0141 IF((TEMP4-YC)UGE 0 ) TEMP4=YC
0142 337 WRITE (1, 339) TEMP1, TEMP2, TEMP3, TEMP4
0143 WRITE (6, 339) TEMP1, TEMP2, TEMP3, TEMP4
0144 339 FORMAT (//9X,
1 4 THE LEADING EDGE OF THE SLICK IS LOCATED AT X = ,
2 E12 5.2X, 10+METERS AND/53X, 3HY = E12 5.2X, 6+METERS/5X,
3 61THE TRAILING EDGE OF THE SLICK IS LOCATED AT X = ,
4 E12 5.2X, 10+METERS AND 53X, 3HY = E12 5.2X, 6+METERS)
0145 500 CONTINUE
0146 999 RETURN
0147 END
DIFFERENTIAL EQUATION SOLVER

THIS SUBROUTINE IS A STANDARD RUNGE-KUTTA INTEGRATION ROUTINE CALLED BY "INTE". IT CALLS "VERST" AND "UGETO".

**N** = NO. OF SIMULTANEOUS FIRST-ORDER DIFFERENTIAL EQUATIONS

**FCN** = SUBROUTINE WHERE DIFFERENTIAL EQUATIONS ARE GIVEN

**X** = STARTING TIME

**Y** = MATRIX OF DIFFERENTIAL EQUATIONS

**XEND** = STARTING TIME + DELT

**TOL, IND, C, NW, W, IER** = NUMERICAL AND ERROR DATA FOR CHECKING CONVERGENCE

SUBROUTINE RUNKUT(N, FCN, X, YEND, TOL, IND, C, NW, W, IER)

INTEGER N, IND, NW, IER
INTEGER K
DIMENSION Y(N), C(24), W(NW,9)

DATA ZERO/0.0/, ONE/1.0/, TWO/2.0/, THREE/3.0/
DATA FOUR/4.0/, FIVE/5.0/, SEVEN/7.0/
DATA TEN/10.0/, HALF/0.5/, P9/0.9/
DATA C40/1.666667E0/
DATA C50/5.333333E-01/
DATA C82/5.2400000E-01/
DATA C96/1.000000E+00/
DATA C102/2.645823E+00/
DATA C104/3.000000E+00/
DATA C108/5.638528E+00/
DATA C112/9.433082E-01/
DATA C116/2.3240000E-00/
DATA C120/8.648183E+01/
DATA C124/6.976744E+01/
DATA C128/5.648183E+01/
DATA C132/2.033463E+01/
DATA C136/6.976744E+01/
DATA C140/5.648183E+01/
DATA C144/2.033463E+01/
DATA C148/6.976744E+01/
DATA C152/5.648183E+01/
DATA C156/2.033463E+01/
DATA C160/6.976744E+01/
DATA C164/5.648183E+01/
DATA C168/2.033463E+01/
DATA C172/6.976744E+01/
DATA C176/5.648183E+01/
DATA C180/2.033463E+01/
DATA C184/6.976744E+01/
DATA C188/5.648183E+01/
DATA C192/2.033463E+01/
DATA C196/6.976744E+01/
DATA C200/5.648183E+01/
DATA C204/2.033463E+01/
DATA C208/6.976744E+01/
DATA C212/5.648183E+01/
DATA C216/2.033463E+01/
DATA C220/6.976744E+01/
DATA C224/5.648183E+01/
DATA C228/2.033463E+01/
DATA C232/6.976744E+01/
DATA C236/5.648183E+01/
DATA C240/2.033463E+01/
DATA C244/6.976744E+01/
DATA C248/5.648183E+01/
DATA C252/2.033463E+01/
DATA C256/6.976744E+01/
DATA C260/5.648183E+01/
DATA C264/2.033463E+01/
DATA C268/6.976744E+01/
DATA C272/5.648183E+01/
DATA C276/2.033463E+01/
DATA C280/6.976744E+01/
DATA C284/5.648183E+01/
DATA C288/2.033463E+01/
DATA C292/6.976744E+01/
DATA C296/5.648183E+01/
DATA C300/2.033463E+01/
DATA C304/6.976744E+01/
DATA C308/5.648183E+01/
DATA C312/2.033463E+01/
DATA C316/6.976744E+01/
DATA C320/5.648183E+01/
DATA C324/2.033463E+01/
DATA C328/6.976744E+01/
DATA C332/5.648183E+01/
DATA C336/2.033463E+01/
DATA C340/6.976744E+01/
DATA C344/5.648183E+01/
DATA C348/2.033463E+01/
DATA C352/6.976744E+01/
DATA C356/5.648183E+01/
DATA C360/2.033463E+01/
DATA C364/6.976744E+01/
DATA C368/5.648183E+01/
DATA C372/2.033463E+01/
DATA C376/6.976744E+01/
DATA C380/5.648183E+01/
DATA C384/2.033463E+01/
DATA C388/6.976744E+01/
DATA C392/5.648183E+01/
TEMP = ZERO
DO 65 K=1, N
    TEMP = AMAX1(TEMP, ABS(Y(K)))
65 CONTINUE
C(12) = TEMP
DO 115 K=1, N
    IF (C(1).NE. FDA) GO TO 70
    C(12) = ONE
    GO TO 115
30 IF (C(1).NE. THREE) GO TO 85
    DO 80 K=1, N
        TEMP = AMAX1(TEMP, ABS(Y(K))/C(2))
    80 CONTINUE
C(12) = AMINF(TEMP, ONE)
DO 115 K=1,N
    IF (C(1).NE. FOUR) GO TO 95
    TEMP = AMAX1(TEMP, ABS(Y(K))/C(K+30))
90 CONTINUE
C(12) = AMINF(TEMP, ONE)
DO 115 K=1, N
    IF (C(1).NE. FIVE) GO TO 105
    DO 100 K=1, N
        TEMP = AMAX1(TEMP, ABS(Y(K))/C(K+30))
    100 CONTINUE
C(12) = TEMP
    GO TO 115
105 CONTINUE
DO 110 K=1, N
    TEMP = AMAX1(TEMP, ABS(Y(K)))
110 CONTINUE
C(12) = AMINF(TEMP, ONE)
115 CONTINUE
C(13) = TEN*AMAX1(C(11), C(10)*AMAX1(C(12)/TOL, ABS(X)))
120 CONTINUE
C(15) = C(5)
    IF (C(5).EQ. ZERO) C(15) = ONE
132 IF (C(6).NE. ZERO AND C(5).NE. ZERO) C(16) = AMINF(C(6), TWD/C(5))
133 IF (C(6).NE. ZERO AND C(5).EQ. ZERO) C(16) = C(6)
134 IF (C(6).EQ. ZERO AND C(5).NE. ZERO) C(16) = TWD/C(5)
135 IF (C(6).EQ. ZERO AND C(5).EQ. ZERO) C(16) = TWD
136 IF (C(13).LE.C(16)) GO TO 125
137 IND = -2
138 GO TO 9005
139 CONTINUE
140 CONTINUE
142 IF (IND GT. 2) GO TO 130
144 IF (C(4).EQ. ZERO) C(14) = C(16)*TOL**C1D6
143 GO TO 110
130 IF (C(23).GT. ONE) GO TO 135
135 TEMP = TWD*C(14)
136 IF (TOL.LT.C2D96+C(19)) TEMP = P9*(TOL/C .31)**C1D6*C(14)
137 C(14) = AMINF(TEMP, HALF*C(14))
138 GO TO 140
139 CONTINUE
C-52
CONTINUE
C(14) = HALF*C(14)
CONTINUE
C(14) = AMIN1(C(14), C(16))
C(14) = AMAX1(C(14), C(13))
IF (C(8).EQ. ZERO) GO TO 145
IND = 4
GO TO 9005
CONTINUE
IF (C(14).GE. ABS(XEND-X)) GO TO 150
C(14) = AMIN1(C(14), HALF*ABS(XEND-X))
C(17) = X*SIGN(C(14), XEND-X)
GO TO 155
CONTINUE
C(14) = ABS(XEND-X)
C(17) = XEND
CONTINUE
C(18) = C(17)-X
DO 160 K=1, N
W(K) = Y(K) + C(18)*W(K, 1)*R(K(1))
160 CONTINUE
CALL FCN (N, X+C(18)*C1D6, W(1, 9), W(1, 2))
DO 165 K=1, N
W(K) = Y(K) + C(18)*(W(K, 1)*R(K(2)) + W(K, 2)*R(K(3)))
165 CONTINUE
CALL FCN (N, X+C(18)*C4D15, W(1, 9), W(1, 3))
DO 170 K=1, N
W(K) = Y(K) + C(18)*R(K(4)) - W(K, 2)*R(K(5)) + W(K, 3)*R(K(6))
170 CONTINUE
CALL FCN (N, X+C(18)*C2D3, W(1, 9), W(1, 4))
DO 175 K=1, N
W(K) = Y(K) + C(18)*(W(K, 1)*R(K(7)) + W(K, 2)*R(K(8)) - W(K, 3)*R(K(9))
1 + W(K, 4)*R(K(10)))
175 CONTINUE
CALL FCN (N, X+C(18)*C5D6, W(1, 9), W(1, 5))
DO 180 K=1, N
W(K) = Y(K) + C(18)*(W(K, 1)*R(K(11)) - W(K, 2)*R(K(12)) + W(K, 3)*R(K(13))
1 - W(K, 4)*R(K(14)) + W(K, 5)*R(K(15)))
180 CONTINUE
CALL FCN (N, X+C(18), W(1, 9), W(1, 6))
DO 185 K=1, N
W(K) = Y(K) + C(18)*R(K(16)) + W(K, 2)*R(K(17)) - W(K, 3)*R(K(18))
1 + W(K, 4)*R(K(19)) + W(K, 5)*R(K(20)))
185 CONTINUE
CALL FCN (N, X+C(18)*C1D15, W(1, 9), W(1, 7))
DO 190 K=1, N
W(K) = Y(K) + C(18)*(W(K, 1)*R(K(21)) - W(K, 2)*R(K(22)) + W(K, 3)*R(K(23))
1 + W(K, 4)*R(K(24)) + W(K, 5)*R(K(25)) + W(K, 6)*R(K(26)))
190 CONTINUE
CALL FCN (N, X+C(18), W(1, 9), W(1, 8))
DO 195 K=1, N
W(K) = Y(K) + C(18)*R(K(27)) + W(K, 3)*R(K(28)) + W(K, 4)*R(K(29))
1 + W(K, 5)*R(K(30)) + W(K, 7)*R(K(31)) + W(K, 8)*R(K(32)))
195 CONTINUE
CALL FCN (N, X+C(18)*C4D15, W(1, 9), W(1, 3))
DO 199 K=1, N
W(K) = Y(K) + C(18)*R(K(33)) + W(K, 2)*R(K(34)) + W(K, 3)*R(K(35))
1 + W(K, 4)*R(K(36)) + W(K, 5)*R(K(37)) + W(K, 7)*R(K(38)))
199 CONTINUE
C(24) = C(24)*SEVEN
0199      DO 200  K=1,N
 0200      W(K, 2) = W(K, 1)*RK(33)+W(K, 3)*RK(34)-W(K, 4)*RK(35)+W(K, 5)
           +RK(36)+W(K, 6)*RK(37)-W(K, 7)*RK(38)-W(K, 8)*RK(39)
 0201      200 CONTINUE
0202      TEMP = ZERO
0203      IF (C(1).NE.ONE) GO TO 210
0204         DO 205  K=1,N
0205      TEMP = AMAX1(TEMP, ABS(W(K, 2)))
0206      205 CONTINUE
0207      GO TO 260
0208      210 IF (C(1).NE.TWO) GO TO 220
0209      DO 215  K=1,N
0210      IF (Y(K).EQ.ZERO) GO TO 280
0211      TEMP = AMAX1(TEMP, ABS(W(K, 2)/Y(K)))
0212      215 CONTINUE
0213      GO TO 260
0214      220 IF (C(1).NE.TWO) GO TO 230
0215      DO 225  K=1,N
0216      TEMP = AMAX1(TEMP, ABS(W(K, 2))/AMAX1(C(2), ABS(Y(K))))
0217      225 CONTINUE
0218      GO TO 260
0219      230 IF (C(1).NE.FOUR) GO TO 240
0220      DO 235  K=1,N
0221      TEMP = AMAX1(TEMP, ABS(W(K, 2))/AMAX1(C(K+30), ABS(Y(K))))
0222      235 CONTINUE
0223      GO TO 260
0224      240 IF (C(1).NE.FIVE) GO TO 250
0225      DO 245  K=1,N
0226      TEMP = AMAX1(TEMP, ABS(W(K, 2)/C(K+30)))
0227      245 CONTINUE
0228      GO TO 260
0229      250 CONTINUE
0230      DO 255  K=1,N
0231      TEMP = AMAX1(TEMP, ABS(W(K, 2))/AMAX1(ONE, ABS(Y(K))))
0232      255 CONTINUE
0233      260 CONTINUE
0234      C(19) = TEMP*C(14)*C(15)
0235      IND = 5
0236      IF (C(19).GT.TOL) IND = 6
0237      IF (C(9).NE.ZERO) GO TO 9005
0238      265 CONTINUE
0239      IF (IND.EQ.6) GO TO 275
0240      X = C(17)
0241      270 CONTINUE
0242      275 CONTINUE
0243      C(22) = C(22)+ONE
0244      C(23) = ZERO
0245      IF (X.NE.XEND) GO TO 50
0246      IND = 3
0247      C(20) = XEND
0248      C(21) = ONE
0249      250 GO TO 9005
0250      275 CONTINUE
0251      C(23) = C(23)+ONE
0252

C-54
0253 IF (C(14).GT.C(13)) GO TO 50
0254 IND = -3
0255 GO TO 9005
0256 280 CONTINUE
0257 IER = 132
0258 GO TO 9000
0259 285 CONTINUE
0260 IER = 131
0261 GO TO 9000
0262 290 CONTINUE
0263 IER = 130
0264 GO TO 9000
0265 295 CONTINUE
0266 IER = 129
0267 9000 CONTINUE
0268 9005 CONTINUE
0269 RETURN
0270 END
SUBROUTINE SPLOC
SPILL LOCATION DEFINITION

This subroutine is called by "DMODEL". It inputs the spill source location. If the spill is in a river (SHAPE < 2), the spill occurs at X = 0, Y = 0 and X > 0 is downstream. If the spill is in a lake or coast, the X, Y location of source is input. If the current = F(SPACE), the box or slice in which the source lies is also requested.

** X0, Y0 = initial spill location.
** ISP = box or slice no. when current = F(SPACE) in open water.

0001 COMMON/CONTOUR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, X0, Y0
0002 COMMON/TRANSIT/Ux(10, 10), Uy(10, 10), VWX(10), VWY(10), THETA(10), TI(10), ID, IT, IV,
0003 XU(10), YU(10), TT(10)

0004 I = SHAPE
0005 IF (I.EQ.1) GO TO 99
0006 WRITE (6, 10)
0007 FORMAT (5.10)
0008 READ (1, 12) XC, YC
0009 WRITE (1, 12) XC, YC
0010 XO = XC
0011 YO = YC
0012 FORMAT (3X, 30H5. THE SPILL ORIGIN IS AT X = .E12.5, IN METERS.)
0013 IF (IC.EQ.2 OR IC.EQ.4) GO TO 27
0014 ISP = 1
0015 GO TO 99
0016 WRITE (6, 30)
0017 FORMAT (3X, 32HWHAT BOX (LAKE) OR SLICE (COAST) DOES THE SPILL LIE IN?)
0018 READ (5, *, ERR=27) ISP
0019 99 RETURN
0020 END
**SUBROUTINE SPREAD**

*THIS IS THE MAIN COMPUTING BLOCK*

*THIS SUBROUTINE IS CALLED BY "OMODEL". IT ORGANIZES THE CALCULATIONS AND CALLS THE COMPUTING EQUATIONS. IT ASKS FOR INPUT:*  
**TPT** = TIME INTERVAL BETWEEN PRINTOUT OF RESULTS, SEC

```fortran
0001 COMMON/STYPE/SPILLM, SPILMR, TSPILL, WS, STP, SPM
0002 COMMON/CONTOUR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
0003 COMMON/CONSTAT/UC, VW, UBAR, UO, UI, WT, ALPH, THETA1
0004 COMMON/TRANSIT/UX(10, 10), UY(10, 10), VWX(10), 
                  VWY(10), THETA(10), TI(10), ID, IT, IV,
                  XU(10), YU(10), TT(10)
0005 COMMON/MASS/TOTALE, TOTALD, TOTALM, OMASS
0006 COMMON/MOVE/UPEAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
0007 COMMON/SPREAD/TII, ATK, HTK, ATN, HTN, HMIN, INDEX, IFLAG
0008 COMMON/RUNGE/YY(5), C(24), W(5, 30)
0009 COMMON/MLOSS/EVAPM, DISSOM
0010 COMMON/CURRENT/UBAR(10), DMUKE, UTOL, UTX, UTY, UREL
0011 COMMON/EVADIS/DAN, UX, SCHMIA, CSA, DWN, UXW, SCHMIW, CSW
0012 COMMON/SENSE/EVA(40, 10), DIS(40, 10), THK(40, 10), TIN(40, 10), 
        PIP(40), TPT
0013 COMMON/UAVE/UCX1, LCYI, VWX1, VWY1
0014 COMMON/PRIME/PRIME(5), IDEB, KKK
0015 I = STP
0016 IH = 0
0017 J = SHAPE
0018 KKK = 0
0019 IF TSTOP/TPT IS GREATER THAN 40, USER WILL BE ASKED TO REENTER A PRINTOUT TIME STEP (TPT). OTHERWISE, USER CAN INCREASE ARRAY SIZES IN LABELED COMMON /SENSE/ EVA, DIS, THK, TIN, PIP

0020 WRITE (6, 1)
0021 FORMAT (/1X, 10HINPUT THE PRINTOUT TIME STEP IN MINUTES.)
0022 READ (5, *) TPT
0023 TPT = TPT * 60.
0024 TTRY = TSTOP / TPT
0025 IF (TTRY .GT. 40.) THEN
0026 WRITE (6, 6)
0027 FORMAT (1X, 13H47 YOU HAVE EXCEEDED ALLOWABLE NUMBER OF PRINTOUTS / IX, 
           2 42 WITH THIS TIME STEP, THE PROBLEM DURATION / IX, 
           3 56h DIVIDED BY THIS PRINTOUT TIME STEP MUST BE LESS THAN 40. 
           4 / IX, 6HAGAIN, )
0028 QOTO 5
0029 ELSE
0030 ENDIF

*C-*
NEXT 11 STATEMENTS CALCULATE DUMMY VARIABLES NEEDED TO
CALCULATE THE VELOCITY USED IN THE SPREADING MODELS --
UTBAR. AT STATEMENT 100 -- WHEN NEITHER THE CURRENT NOR
THE WIND DEPEND ON TIME.

0031 IF(J.GE.2) M=ISP

ISP = BOX OR SLICE OF SPILL LOCATION WHEN CURRENT = F(SPACE)

0032 IF(J.EQ.1) M=1
0033 UCXI=UX(M,1)
0034 UCYI=UY(M,1)
0035 VWX1 = VWX(1)
0036 VWY1 = VWY(1)
0037 IF(J.EQ.1) THEN
0038 VWX1=VW*COS(THETA1)
0039 UCXI=UC
0040 ELSE
0041 ENDIF
0042 IF(I.EQ.4) GO TO 103
0043 GO TO 200
0044 103 IF(J.NE.1) GO TO 2
0045 IF(IC.GT.1.OR.IW.GT.1) GO TO 3
0046 GO TO 100
0047 2 IF(IC.GT.2.OR.IW.GT.1) GO TO 3
0048 GO TO 100
0049 3 CONTINUE

NEXT 7 STATEMENTS CALCULATE THE VELOCITY USED IN THE SPREADING
MODELS -- UTBAR -- WHEN THE CURRENT OR WIND IS A FUNCTION OF TIME

CALL SUBROUTINE UTPEAK TO COMPUTE MAXIMUM
TRANSPORT VELOCITY WHEN THE CURRENT OR
WIND IS A FUNCTION OF TIME
0050 CALL UTPEAK

CALL SUBROUTINE CURRENT TO CALCULATE
AVERAGE TRANSPORT VELOCITY OVER ENTIRE
SPILL DURATION
0051 CALL CURRT
0052 CONTINUE

0053 IF(J.GE.2) M=ISP
0054 IF(J.EQ.1) M=1
0055 IF(UBAR(M).LT.(0.3*UPEAK(M))) GO TO 50
0056 UTBAR = UBAR(M)
0057 GO TO 200

---

UTBAR LT. (0.3*UPEAK)
SET UT = 0 AND CHANGE SPREAD MODEL TO MODEL
C

WITHOUT CURRENT

C

0058  50  DO 55 KK=1, ID
0059        UBAR(KK) = 0.0
0060  55  CONTINUE
0061
0062  IF( STP.EQ.4.1 ) STP=2.1
0063  IF( STP.EQ.4.2 ) STP=2.2
0064  PRINT *, 'CHANGE TO MODEL ', STP
0065  QQ TO 200
0066  100  UBAR = SQRT((UCX1+0.035*VWX1)**2 +
0067                          (UCY1+0.035*VWY1)**2)
0068     200 CONTINUE

C

---- CALL SUBROUTINE INIT TO CALCULATE
C INITIAL CONDITIONS ----

C

0068  WRITE (1,299)
0069  299 FORMAT(lHI/10X,
0070                      2/10X, IH*,
0071                      16X,22HSPREADING MODEL OUTPUT,18X,1H*/10X.
0072  CALL INIT
0073  IF(KKK. EG. 3) GOTO 351

C

'KKK' IS A CODE THAT DETERMINES IF AN INSTANTANEOUS SPILL HAS
EVAPORATED OR, FOR A CONTINUOUS SPILL, IF THE EVAPORATION RATIO
DISCHARGE RATE, DURING THE INITIAL CONDITION TIME PERIOD. IT
IS COMPUTED IN "INT12A" AND "INIT4A".

C

0072  TIME=TII
0073  YY(1)=ATK
0074  YY(2)=ATN
0075  YY(3)=HTK
0076  YY(4) = 0.0
0077  YY(5) = 0.0
0078  ISTP=STP
0079  IF(ISTP.EQ.1) GO TO 350
0080  ---- WHEN ISTP=1 SPILL IS INSTANTANEOUS ----
0081  310 IF (TIME.LT. TSPILL) GO TO 350

C

FROM HERE TO 350 IS EXECUTED ONLY IF SPILL IS CONTINUOUS
AND DISCHARGE HAS JUST STOPPED

C

---- SPILL WAS CONTINUOUS. HOWEVER IT HAS STOPPED... ----
---- CALL 'SWITCH' AND CHANGE TO APPROPRIATE
INSTANTANEOUS SPILL MODEL ----

C-59
CALL SWITCH CONTINUE

CALL SUBROUTINE TRANSP TO CALCULATE SURFACE TRANSPORT VELOC.
CALL TRANSP

----- CALL 'INTE' TO SOLVE SIMULTANEOUS DIFFERENTIAL EQUATIONS -----

CALL INTE(XEND)

IF (TIME .GE. TSTOP) GO TO 353

IF (SHAPE .LT. 1.9) GO TO 351

***********************************************************************
SKIP THE SLICK HITTING THE COAST LINE ROUTINE "GROUND" WHEN SPILL IS IN RIVER.
***********************************************************************

CALL GROUND(IH)

***********************************************************************
IF IH > 0, THE SLICK HAS HIT THE COAST LINE.
***********************************************************************

IF (IH .GT. 0) GO TO 998

***********************************************************************
FROM HERE TO 353 IS A ROUTINE THAT TRIES OUT THAT AN INSTANTANEOUS SLICK HAS EVAPORATED (355) OR THE EVAPORATION RATE HAS INCREASED TO EQUAL THE DISCHARGE RATE FOR A CONTINUOUS SPILL. THE CRITERION IS TCHECK > TIME
AND IS DETERMINED IN SUBROUTINE "CHEAMS".
***********************************************************************

IF (TCHECK .GT. TIME) GO TO 353

TEMP = T.ME/60.

IF (ISTP .EQ. 1) GO TO 352

TMPT=TSPILL/60.

WRITE (1,354) TEMP, TMPT

WRITE (6,354) TEMP, TMPT

SPILLM = SPILMR * TIME

TIME = TSPILL

TCHECK = TSTOP

GO TO 310

CONTINUE

DELTIM = (SPILLM - TOTALE - TOTALD) / (EVAPM*YY(1) + DISSOM * YY(1))

TOTALE=TOTALE + DELTIM * EVAPM * YY(1)

TOTALD=TOTALD + DELTIM * DISSOM * YY(1)

TMASS = 0.

TOTALM = 0.

YY(1) = 0.

YY(2) = 0.

YY(3) = 0.

RAD1 = 0.
0110  RAD2 = 0.
0111  TIME = TIME + DELTIM
0112  TEMP = TIME / 60.
0113  WRITE (1,355) TEMP
0114  WRITE (6,355) TEMP
0115  GO TO 999
0116  353  CONTINUE
0117  354  FORMAT (////X,
0118     1  60H---------------------------------------------------------------,
0119     2 /1X,1H*,2X,
0120     3 48HTHE RATE OF MASS LOSS HAS INCREASED UNTIL IT IS .8X,1H*/1X,
0121     4 1H*,2X,34HAPPROXIMATELY EQUAL TO THE RATE OF ,22X,1H*/1X,1H*,2)
0122     5 25HSPILLING AT TIME EQUAL TO,E12.5,2X,7HMINUTES.,10X,1H*/1X,1H*,
0123     6 2X,55HTHE SLICK SIZE REMAINS CONSTANT FROM NOW UNTIL SPILLING,
0124     7 1X,1H*/1X,1H*,2X,14HSTOPS AT TIME=E12.5,
0125     8 25H MINUTES AND THE PRINTOUT,5X,1H*/1X,1H*,2X,
0126     9 49HTHRESURES WHEN THE SLICK SIZE BEGINS TO VARY AGAIN.,7X,1H*/1X,
0127    1  60H---------------------------------------------------------------
0128  355  FORMAT (////X,
0129     1  60H---------------------------------------------------------------,
0130     2 /1X,1H*,
0131     3 58HALL THE SPILLED MASS HAS BEEN EVAPORATED AND(OR) DISSOLVED,
0132     4 1H*/1X,1H*,
0133     5 30HAT TIME APPROXIMATELY EQUAL TO,E12.5,2X,7HMINUTES,
0134     6 7X,1H*/1X,
0135     7 60H---------------------------------------------------------------
0136  IF (TIME .LT. TPT) GO TO 400
0137  357  FORMAT (////X,
0138     1  60H---------------------------------------------------------------,
0139     2 /1X,1H*,
0140     3 60HIF (TIME.LT.TPT) GO TO 400
0141  359  FORMAT (////X,
0142     1  60H---------------------------------------------------------------,
0143     2 /1X,1H*,
0144     3 70HNEXT 6 STATEMENTS DETERMINE IF PRINTOUT IS REQUIRED AND BREAK
0145     4 TIME INTO MINUTES AND SECONDS FOR PRINTOUT
0146     5 60H---------------------------------------------------------------
0147  IJ = TIME
0148  IK = TPT
0149  DIC = ABS(TIME - FLOAT(IJ))
0150  IF (DIC .GT. DELT) GO TO 400
0151  MD =MOD(IJ,IK)
0152  IF (MD .NE. 0) GO TO 400
0153  350  CALL PRINTO
0154  DETERMINE IF THICKNESS OF THICK SLICK IS LESS THAN HMINT.
0155  IF SO, STOP.
0156  60H---------------------------------------------------------------
0128  A00  IF(ISTP, EQ, 4, AND, TIME, LT, TSPILL) GOTO 510
0129  IF (YY(3), LT, HMIN, TIME)
0130     WRITE(1, 500) HMIN, TIME
0131     WRITE(6, 500) HMIN, TIME
0132  500  FORMAT(///5X,
1         29HTHE THICK SLICK IS LESS THAN, E12.5, 11H M AT TIME=, E13.6,
2         8H SECONDS)
0133     GO TO 999
0134     ELSE
0135     ENDIF
0136
0137  510  IF (TIME, GT, TSTOP) GO TO 999
0138     GO TO 300
0139     CONTINUE
0140
0141  998  CONTINUE
0142
0143  999  RETURN
0144  END
SUBROUTINE SPTYPE

THIS SUBROUTINE SPECIFIES SPILL TYPE

THIS SUBROUTINE IS CALLED BY "DMODEL". IT INPUTS THE CHEMICAL PROPERTY DATA AND THE TYPE OF SPILL (INSTANTANEOUS OR CONTINUOUS). IT SETS UP THE FOLLOWING CODE:

STP = 1.1. INSTANTANEOUS IN RIVER
STP = 1.2. INSTANTANEOUS IN OPEN WATER
STP = 2.1. CONTINUOUS IN RIVER WITH NO CURRENT
STP = 2.2. CONTINUOUS IN OPEN WATER WITH NO CURRENT
STP = 4.1. CONTINUOUS IN RIVER WITH CURRENT
STP = 4.2. CONTINUOUS IN OPEN WATER WITH CURRENT

SUBROUTINE SPTYPE (PB)
COMMON/STYPE/SPILLM. SPILMR. TSPILL. WS. STP. SPM
COMMON/CONTOUR/SHAPE,X(10),Y(10),XC,YC,IC,1W,ISP,XO,YO
COMMON/WATER/DENW.VISW.QR
COMMON/CHEMI/DENO. DCA. DCW. CS. CMW
COMMON/ENVOR/PY, VISA. DENA. TDC
COMMON/INTER/COEF, SIOWA, SICOA. SIQOW. SIO
COMMON/MOVE/UPEAK( 10).XLE. XTE. YLE. YTE. DELT. TIME. TSTOP. TCHECK
COMMON/ID/IDI, 102,1103
COMMON/NAME! NC(2, 20)
CHARACTER*10 NA1ME(2).NC

ID1=0
ID2=0
ID3=0
WRITE (6,10)
WRITE (1,10)

10 FORMAT (1H1//5X.2OH******************************/
1 5X,1H4.4X,1OHSPILL TYPE,4X.1H4/ 2
5X,2OH******************************/

--- CHEMICAL NAME AND PROPERTIES ----

** STATEMENTS FROM THIS POINT TO ABOUT STATEMENT 849 **
** CAN BE REPLACED BY "CHRIS" DATA FILES IN MERGED **
** HACS PROGRAMS **

THE INPUT CHEMICAL PARAMETERS ARE

DENO = DENSITY, KG/CU M
CMW = MOLECULAR WEIGHT
DCA = DIFFUSION COEFFICIENT IN AIR, SQ M/SEC
DCW = DIFFUSION COEFFICIENT IN WATER, SQ M/SEC
PV = VAPOR PRESSURE, N/SQ M
CS = SOLUBILITY LIMIT, KG/CU M
SIGOA = CHEMICAL-AIR INTERFACIAL TENSION, N/M
C80OMW - CHEMICAL - WATER INTERFACIAL TENSION, N/M

CALCULATED CHEMICAL PARAMETERS ARE:

SIG = SPREADING COEFFICIENT

SIG = SIGMA - SIGOA - SIGOW, N/M

COEF = 1 - DENO/DENW

NOTE: COEF IS CALLED DELTA IN THE REPORT.

SIGOW = CHEMICAL - WATER INTERFACIAL TENSION, N/M

CALCULATED CHEMICAL PARAMETERS ARE:

SIG = SPREADING COEFFICIENT

SIG = SIGMA - SIGOA - SIGOW, N/M

COEF = 1 - DENO/DENW

NOTE: COEF IS CALLED DELTA IN THE REPORT.

                                                                                      0018  WRITE (1.19)
                                                                                      0019  15 FORMATT (/5X,12HPROPERTIES :)
                                                                                      0020  1109 WRITE(6,1110) (J, NC(1,J), NC(2,J), J+1, NC(1,J+1), NC(2,J+1)
                                                                                      1     J+1.20.2)
                                                                                      0021  1110 FORMATT(1X,90HWE HAVE STANDARD PROPERTIES FOR THE FOLLOWING CH
                                                                                      1     EMICALS,./10(1X,12.2H, .2A10.2X,12.2H, .2A10,//))
                                                                                      0022  WRITE(6,8)
                                                                                      0023  8 FORMATT(5X,25HENTER THE NO. YOU WANT OR, /, 5X,14HNEGATIVE VALUE
                                                                                      1     3BH - IF YOU WANT TO INPUT THE PROPERTIES, /, 5X,
                                                                                      2     14H 99 .25H - IF THE CHEMICAL IS NOT,
                                                                                      3     12H ON THE LIST)
                                                                                      READ(5,*,ERR-1109) ICS
                                                                                      IF (ICS .LT. 0) GO TO 17
                                                                                      IF (ICS GT. 90) GO TO 12
                                                                                      CALL CHEMCL(ICS, NAME, P9, PHI, DENO, CS, CMW, DCA,
                                                                                      1     DCW, SIGOA, SIGOW)
                                                                                      GO TO 1036
                                                                                      0028  12 WRITE (6,13)
                                                                                      0029  13 FORMAT (/5X,32HWHAT IS THE NAME OF THE CHEMICAL?)
                                                                                      0030  14 READ (5,14,ERR=12) NAME
                                                                                      0031  15 FORMAT (2A10)
                                                                                      0032  17 WRITE (6,18)
                                                                                      0033  18 FORMATT (1X,25HENTER ITS DENSITY IN KG/CU M. )
                                                                                      0034  19 READ (5,*,ERR=17) DENO
                                                                                      0035  20 WRITE (6,701)
                                                                                      0036  700 FORMATT (1X,41HENTER ITS MOLECULAR WEIGHT IN KG/KG-MOLE. )
                                                                                      0037  701 READ (5,*,ERR=700) CMW
                                                                                      0038  22 WRITE (6,23)
                                                                                      0039  23 FORMATT(//1X,36HENTER DIFFUSION COEFFICIENT OF VAPOR IN AIR IN
                                                                                      S/M/SEC.)
                                                                                      0040  26 READ (5,*,ERR=22) DCA
                                                                                      0041  c
                                                                                      0042  30 WRITE (6,31)
                                                                                      0043  31 FORMAT(//1X,
                                                                                      0044  35 HENTER DIFFUSION COEFFICIENT OF LIQUID IN WATER IN SG M/SEC.)
                                                                                      0045  36 READ (5,*,ERR=30) DCW
                                                                                      0046  c
                                                                                      0047  34 WRITE (6,35)
                                                                                      0048  35 FORMATT(//1X,45HIS PV (VAPOR) 1. A NUMBER OR 2. A FORMULA?)
                                                                                      0049  36 READ (5,*,ERR=34) I
                                                                                      0050  GO TO (36,38) I
                                                                                      0051  36 WRITE (6,37)
                                                                                      0052  37 FORMATT(//1X,17HENTER CONSTANT PV)
                                                                                      0053  38 READ (5,*,ERR=36) PV
                                                                                      0054  GO TO 39
                                                                                      0055  39 WRITE(6,138)

C-64
FORMAT(/IX, 138. HPV IS A FUNCTION OF TEMPERATURE/ 1 10.0**(A1-B1/(C1+TDC)) 2

0055 READ (5.*, ERR=39) A1, B1, C1
0056 PV = 10.0**(A1-B1/(C1+TDC))
0057 CONTINUE
0058 WRITE (6,40)

0059 FORMAT(/IX, 47. INPUT THE SOLUBILITY LIMIT OF CHEMICAL IN WATER/ 1 11H (KG/CU. M.))
0060 READ (5., ERR-38) CS
0061 WRITE (6,61)

0062 FORMAT(/IX, 44. CHEMICAL/AIR INTERFACE TENSION AND, 1 /6X, 36H(2) WATER/CHEMICAL INTERFACE TENSION, 2 /1X, 16HUNIT : NEWTON/M)
0063 READ (5.*, ERR=60) SIGOA, SIGOW
0064 CONTINUE
0065 WRITE (1,19) PB
0066 WRITE (1,19) PB
0067 9 FORMAT(/IX, 23. BAROMETRIC PRESSURE : ,F12.3X, 8HMILLIBAR.//)
0068 WRITE (1,11) TDC
0069 WRITE (6,61) TDC
0070 11 FORMAT(/IX, 14. TEMPERATURE : ,F12.3X, 9HDEGREES C.//)
0071 WRITE (1,16) NAME
0072 WRITE (6,16) NAME
0073 16 FORMAT(/IX, 18. CHEMICAL NAME IS: ,2A10)
0074 WRITE (1,41) DENO
0075 WRITE (6,41) DENO
0076 WRITE (1,1013) CMW
0077 WRITE (6,1013) CMW
0078 1013 FORMAT(/IX, 18. MOLECULAR WEIGHT =, F10.3X, 10HKG/KG-MOLE)
0079 WRITE (1,42) DCA
0080 WRITE (6,42) DCA
0081 WRITE (1,44) DCW
0082 WRITE (6,44) DCW
0083 WRITE (1,46) PV
0084 WRITE (6,46) PV
0085 WRITE (1,48) CS
0086 WRITE (6,48) CS
0087 41 FORMAT(/IX, 25. CHEMICAL DENSITY = ,F12.2X, 8HMKG/CU M
0088 42 FORMAT(/IX, 25. DIFFUSION COEFF (AIR) =,E12.5X, 9HSMG M/SEC
0089 44 FORMAT(/IX, 25. DIFFUSION COEFF (WATER) =,E12.5X, 9HSMG M/SEC
0090 46 FORMAT(/IX, 25. VAPOR PRESSURE =,F12.2X,

1 12HNEWTON/SQ M)
0091 48 FORMAT(/IX, 25. SOLUBILITY IN WATER =,F12.2X, 8HMKG/CU M)
0092 WRITE (1,1035) SIGOA, SIGOW
0093 WRITE (6,1035) SIGOA, SIGOW
0094 1035 FORMAT(/IX, 33. THE INTERFACE TENSION WRT AIR IS ,E10.5,

1 2X, 9HNEWTON/M, /5X.
2 35H THE INTERFACE TENSION WRT WATER IS ,E10 5.2X,
3 9HNEWTON/M)
0095 SIG = SIGWA-SIGOW-SIGOA
0096 WRITE (1,49) S1Q
0097 WRITE (6,49) S1Q
0098 49 FORMAT(/IX, 29. THE SPREADING COEFFICIENT IS ,E10. 5.2X, 9HNEWTON
THE SPILL PARAMETERS ARE.

SPILLM = TOTAL MASS OF INSTANTANEOUS SPILL, KG
SPILLMR = DISCHARGE RATE OF CONTINUOUS SPILL, KG/SEC
TSPILL = TOTAL DISCHARGE TIME, SEC

---

WRITE (6,51)
FORMAT (/X,47L1SPLP)
READ (5,.*,ERR=50) ITYPE
GO TO (100,200) ITYPE

---

INSTANTANEOUS SPILL

---

WRITE (1,101)
FORMAT (/3X,27H1. THE SPILL IS INSTANTANEOUS.)
WRITE (6,103)
FORMAT (/3X,44HINPVT THE TOTAL SPILLED VOLUME (CUBIC METER))
READ (5,.*,ERR=102) TEM
SPILLM = DENO * TEM
WRITE (1,104) SPILLM
FORMAT (/5X,29H2. TOTAL MASS OF SPILL = E12. 5, 2X, 3HKG.)

---

CONTINUOUS SPILL

---

WRITE (1,201)
FORMAT (/3X,27HM1. THE SPILL IS CONTINUOUS.)
WRITE (6,203)
FORMAT (/3X,39HINPT THE RATE OF DISCHARGE (CU M./SEC))
READ (5,.*,ERR=204) TEM
SPILMR = DENO * TEM
WRITE (1,206) SPILMR
FORMAT (/3X,29H2. THE MASS DISCHARGE RATE = ,F8. 3, 2X, 7HKG/SEC.)
WRITE (6, 208)

0131 WRITE (1, 210) TSPILL
0132 READ (5, *, ERR=207) TSPILL
0133 WRITE (1, 210) TSPILL
0134 WRITE (1, 210)
0135 FORMAT (/2X, 11H TOTAL DURATION OF SPILL = ,E12.5, 4HMIN.)

0136 CONTINUE
0137 I=SHAPE
0138 IF (I.EQ.1) GO TO 250

0139 IF (IC .NE. 0 OR IW .NE. 0) GO TO 240

0140 CONTINUE
0141 IF (IC = 2) GO TO 299

0142 CONTINUE
0143 IF (IC .NE. 4) GO TO 299

0144 CONTINUE
0145 IF (IC .NE. 2) GO TO 299

0146 CONTINUE
0147 IF (IC .NE. 0 OR IW .NE. 0) GO TO 260

0148 CONTINUE
0149 IF (IC .NE. 4) GO TO 299

0150 CONTINUE
0151 RETURN

0152 END
SUBROUTINE SWITCH

THIS SUBROUTINE IS USED TO SWITCH THE CONTINUOUS MODEL TO THE PROPER INSTANTANEOUS MODEL AFTER THE SPILL STOPS.

THIS SUBROUTINE IS CALLED BY "SPREAD". IT CHANGES A CONTINUOUS SPILL TO AN INSTANTANEOUS SPILL AFTER THE DISCHARGE STOPS, AND COMPUTES THE CENTER OF THE NEW INSTANTANEOUS SPILL SLICK.

ISTP = STP

ISTP = 2: CONTINUOUS SPILL WITH NO CURRENT;
ISTP = 4: CONTINUOUS SPILL WITH CURRENT

IF (ISTP.EQ.4) GO TO 100

SPILLM = SPILMR * TSPILL

IF (STP.EQ.2.1) STP = 1.1
IF (STP.EQ.2.2) STP = 1.2
GO TO 999

CONTINUE

IF (STP.EQ.4.2) GO TO 150

SPILLM = SPILMR * TSPILL

XC = YY(1)/(2.*WW)

CENTER OF INSTANTANEOUS SLICK = CENTER OF CONTINUOUS SPILL SLICK IF SLICK IS IN RIVER

STP = 1.1
GO TO 999

CONTINUE

IF (SPM.< 0.0) GO TO 200

STP = 1.2

C-68
GO TO 999
CONTINUE

TEMP1 = UTBAR * TSPILL
TEMP2 = 3.0 * SQRT(YY(1))
XC=(2./3.)*(XLE-XO)
YC=(2./3.)*(YLE-YO)

CENTER OF INSTANTANEOUS SLICK = CENTROID OF TRIANGULAR
CONTINUOUS SLICK SLICK IN OPEN WATER.

IF (TEMP1.LE_TEMP2) GO TO 250
SPILLM = SPILMR * TSPILL
STP = 1.2
GO TO 999

CONTINUE

NEED TO LET SPILL SPREAD LIKE AN INSTANTANEOUS SPILL IN A
RIVER UNTIL IT SPREADS ENOUGH SO THAT 3*SQRT(THICK SLICK AREA)
IS GREATER THAN LENGTH OF SLICK.

SPILLM = SPILMR * TSPILL
STP = 1.1
CALL TRANSP
CALL INTE(XEND)
CALL MOVE
IJ = TIME
IK = TPT
MD = MOD(IJ, IK)
DIC=ABS(TIME-FLOAT(IJ))
IF(DIC.GT.DELT) QOTO 300
IF (MD.NE.0) GO TO 300
CALL PRINTO

TEMP1 = UTBAR * TSPILL
TEMP2 = 3.0 * SQRT(YY(1))
IF(TIME.GT.TSTOP) QOTO 999
IF (TEMP1.LE_TEMP2) GO TO 275
STP = 1.2
IF (TIME.GT.TSTOP) GO TO 999
IF (YY(3).LT.HMIN) GO TO 999

CONTINUE
RETURN
END
SUBROUTINE TRANSP
COMPUTING THE SURFACE TRANSPORT VELOCITY

THIS SUBROUTINE IS CALLED BY "SPREAD" AND INITIAL CONDITION
SUBROUTINES "INT12A" AND "INIT4A". IT COMPUTES THE SURFACE
TRANSPORT VELOCITY OF THE SLICK AND THE RELATIVE WIND OVER
THE SLICK AT THE DESIRED TIME.

** UTX, UTY = COMPONENTS OF TRANSPORT VELOCITY, M/SEC
** UTOT = TOTAL TRANSPORT VELOCITY, M/SEC
** UREL = RELATIVE WIND, M/SEC

SUBROUTINE TRANSP
COMMON/MOVE/PEAK(10), XLE, XTE, YLE, YTE, DELT, TIME, TSTOP, TCHECK
COMMON/CONTOUR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON/TRANSITION/UX(10,10), UY(10,10), VWX(10),
VWY(10), THETA(10), TI(10), ID, IT, IV,
UX(10), UY(10), TI(10)
COMMON/CONSTANT/UX, UY, UBAR, Ui, Wi, ALPH, THETA
COMMON/CURRENT/UBAR(10), DMOVE, UTOT, UTX, UTY, UREL
COMMON/STYLE/SPILL, SPILLR, TBSPILL, WS, STP, SPM

J = SHAPE
ISTP = STP
LT = 0
LL = 0
IC1 = IC + 1
IF (J.EQ.1) GO TO 100

------ IN OPEN WATER ------

GO TO (9, 9, 10, 20, 30) IC1
CONSTANT CURRENT OR NO CURRENT

UU1 = UX(1,1)
UU2 = UY(1,1)
GO TO 55

CURRENT IS FUNCTION OF LOCATION ONLY

LT = 1
GO TO 30

CURRENT IS FUNCTION OF TIME ONLY

LL = 1
GO TO 40

CONTINUE

STATEMENTS FROM HERE TO 38 DETERMINE BOX OR SLICE IN WHICH
LEADING EDGE OF A CONTINUOUS SPILL SLICK LIES OR IN WHICH
THE CENTER OF AN INSTANTANEOUS SPILL SLICK LIES.
** LL = BOX OR SLICE NO. (AT END OF STATEMENTS)

C-70
IF \( J \geq 3 \) THEN

IF \( I_{STP} = 2 \) OR \( I_{STP} = 4 \) THEN

\[ \begin{align*}
XL & \leq XLE \\
YL & \leq YLE
\end{align*} \]

ELSE

\[ \begin{align*}
XL & \leq XC \\
YL & \leq YC
\end{align*} \]

ENDIF

IF \( XL \geq XU(LL) \) AND \( XL \leq XU(LL+I) \) THEN

IF \( J \geq 3 \) THEN

\[ \begin{align*}
LL & \leftarrow LL \\
35 & \text{CONTINUE}
\end{align*} \]

ENDIF

IF \( YL \geq YU(LL) \) AND \( YL \leq YU(LL+I) \) THEN

\[ \begin{align*}
LL2 & \leftarrow LL \\
35 & \text{CONTINUE}
\end{align*} \]

ENDIF

IF \( LL2 = 1 \) THEN

\[ \begin{align*}
LL & \leftarrow LL \\
35 & \text{CONTINUE}
\end{align*} \]

ELSE

\[ \begin{align*}
LL & \leftarrow LL + 3 \\
35 & \text{CONTINUE}
\end{align*} \]

ENDIF

IF \( LT \leq 1 \) THEN

\[ \begin{align*}
30 & \text{CONTINUE}
\end{align*} \]

ELSE

\[ \begin{align*}
UU1 & \leftarrow UX(LL,LT-1) + (UX(LL,LT) - UX(LL,LT-1)) \times \\
& \left(\frac{\text{TIME} - \text{TI}(LT)}{\text{TI}(LT) - \text{TI}(LT-1)}\right)
\end{align*} \]

\[ \begin{align*}
UU2 & \leftarrow UY(LL,LT-1) + (UY(LL,LT) - UY(LL,LT-1)) \times \\
& \left(\frac{\text{TIME} - \text{TI}(LT)}{\text{TI}(LT) - \text{TI}(LT-1)}\right)
\end{align*} \]

\[ \begin{align*}
35 & \text{CONTINUE}
\end{align*} \]

ENDIF

IF \( W = f(TIME) \) THEN

\[ \begin{align*}
W1 & \leftarrow VX(I-1) + (VX(I) - VX(I-1)) \times \\
& \left(\frac{\text{TIME} - \text{TT}(I-1)}{\text{TT}(I-1) - \text{TT}(I)}\right)
\end{align*} \]

\[ \begin{align*}
W2 & \leftarrow VY(I-1)
\end{align*} \]

\[ \begin{align*}
35 & \text{CONTINUE}
\end{align*} \]

ENDIF

ENDIF

C

** \( UU1, UU2 \) = CURRENTS IN BOX OR SLICE AT DESIRED TIME **

C

U1 = UX(LL,LT)

U2 = UY(LL,LT)

IF \( I_{WT} = 1 \) THEN

\[ \begin{align*}
W1 & \leftarrow VX(I) \\
W2 & \leftarrow VY(I)
\end{align*} \]

DO 75 I = 1, 10

IF \( \text{TIME} \geq \text{TT}(I) \) THEN

75 CONTINUE

79 CONTINUE

C

** IF WIND = f(TIME), INTERPOLATE TO FIND WIND AT DESIRED TIME **

C

W1 = VX(I-1) + (VX(I) - VX(I-1)) \times
1 \[(TT(I) - TT(I-1))\]

\[W2 = VWY(I-1) + (VWY(I) - VWY(I-1)) \times (TIME - TT(I-1)) / (TT(I) - TT(I-1))\]

1 \[(TT(I) - TT(I-1))\]

CONTINUE

\[
\begin{align*}
UTX &= UU1 + 0.035 \times W1 \\
UTY &= UU2 + 0.035 \times W2 \\
UREL &= \text{SQRT}((UTX - W1)^2 + (UTY - W2)^2) \\
UTOT &= \text{SQRT}(UTX^2 + UTY^2) \\
\end{align*}
\]

GO TO 999

IN RIVER OR CHANNEL

100 CONTINUE

IF (IC.LE.1) GO TO 120

UC = UO + UI \times \text{SIN}(6.28318/WT*(TITWE+ALPH))

IF (IW.LE.1) THEN

VWXX = VW*COS(THETA1)

QOTO 140

ELSE

ENDIF

DO 130 I-1, 10

IF (TIME.LT.TT(I)) GO TO 135

CONTINUE

** IF WIND = F(TIME), INTERPOLATE TO FIND WIND AT DESIRED TIM **

135 VWXX = VWX(I-1) + (VWX(I) - VWX(I-1)) \times (TIME - TT(I-1)) / (TT(I) - TT(I-1))

1 \[(TT(I) - TT(I-1))\]

VWYY = VWY(I-1) + (VWY(I) - VWY(I-1)) \times (TIME - TT(I-1)) / (TT(I) - TT(I-1))

\[
\begin{align*}
UTX &= UC + 0.035 \times VWXX \\
UREL &= \text{SQRT}((UTX - VWXX)^2 + (VWYY)^2) \\
UTOT &= UTX \\
\end{align*}
\]

RETURN

999 END
SUBROUTINE UERTST
PRINTS A MESSAGE TO INDICATE AN ERROR CONDITION IN
THE RUNGE-KUTTA ROUTINE "RUNKUT".

THIS SUBROUTINE IS PART OF THE RUNGE-KUTTA INTEGRATION
ROUTINE "RUNKUT".

SUBROUTINE UERTST(IER, NAME)

SPECIFICATIONS FOR ARGUMENTS

INTEGER IER
DOUBLE PRECISION NAME
DOUBLE PRECISION NAMSET, NAMEQ
DATA NAMSET/6HUERSET/ DATA NAMEQ/6H/
DATA LEVEL/4/, IEQDF/0/, IEQ/1H/
IF(IER. GT. 999) QOTO 25
IF(IER. LT. -32) QOTO 55
IF(IER. LE. 128) QOTO 5
IF(LEVEL. LT. 1) QOTO 30
CALL UCETIO(1, NINIOUNIT)
IF(IEQDF. EQ. 1) WRITE(IOUNIT, 35) IER, NAMEQ, IEQ, NAME
IF(IEQDF. EQ. 0) WRITE(IOUNIT, 35) IER, NAME
IF (IER. LE. 64) QOTO 10
IF(LEVEL. LT. 2) QOTO 30
CALL UCETIO(1, NINIOUNIT)
IF(IEQDF. EQ. 1) WRITE(IOUNIT, 45) IER, NAMEQ, IEQ, NAME
IF(IEQDF. EQ. 0) WRITE(IOUNIT, 45) IER, NAME
IF (IER. LE. 64) QOTO 10
IF(LEVEL. LT. 3) QOTO 30
CALL UCETIO(1, NINIOUNIT)
IF(IEQDF. EQ. 1) WRITE(IOUNIT, 45) IER, NAMEQ, IEQ, NAME
IF(IEQDF. EQ. 0) WRITE(IOUNIT, 45) IER, NAME
CONTINUE
CHECK FOR UERSET CALL
IF (NAME. NE. NAMSET) QOTO 25
LEVOLD=LEVEL
IER=IER
LEVEL=IER
IF(LEVEL. LT. 0) LEVEL=4
IF(LEVEL. GT. 4) LEVEL=4
0035   GOTO 30
0036   CONTINUE
0037   IF(LEVEL.LT.4) GOTO 30

PRINT MESSAGE FOR UNDEFINED

CALL UGETIO(1, NIN, IUNIT)
0038   IF(IEQDF.EQ.1) WRITE(IUNIT, 50) IER, NAMEQ, IEG, NAME
0040   IF(IEQDF.EQ.0) WRITE(IUNIT, 50) IER, NAME
0041   IEQDF=0
0042   RETURN
0043   IEQDF=1
0044   NAMEQ=NAME
0045   RETURN
0047   IEQDF=1
0048   NAMEQ=NAME
0049   RETURN
0050   END
SUBROUTINE UGETIO

RETRACTS CURRENT VALUES AND SETS NEW VALUES FOR INPUT
AND OUTPUT UNIT IDENTIFIERS.

THIS SUBROUTINE IS PART OF THE RUNGE-KUTTA NUMERICAL INTEGRATION
ROUTINE "RUNKUT".

SUBROUTINE UGETIO(IOPT, NIN, NOUT)
INTEGER IOPT, NIN, NOUT
DATA NIND/1/, NOUTD/2/
IF(IOPT.EQ.3) GOTO 10
IF(IOPT.EQ.2) GOTO 5
IF(IOPT.EQ.1) GOTO 9005
NIN=NIND
NOUT=NOUTD
GOTO 9005
5 NIND=NIN
GOTO 9005
10 NOUTD=NOUT
9005 RETURN
END
SUBROUTINE UTPEAK

THIS SUBROUTINE IS DESIGNED TO DETERMINE THE MAXIMUM TRANSPORT VELOCITY (WHEN IT IS A FUNCTION OF TIME).

THIS SUBROUTINE IS CALLED BY "SPREAD". IT CALCULATES THE VELOCITY USED IN THE SPREADING MODELS, UC + 0.035 * VW (COMPONENT IN EACH OF THE 9 SLICES OR BOXES. FOR A RIVER, I = 1.

** VARIABLE NAME: **

UTPEAK(I) = MAXIMUM VALUE OVER TIME OF UC + 0.035 * VW (COMPONENT IN EACH OF THE 9 SLICES OR BOXES. FOR A RIVER, I = 1.

SUBROUTINE UTPEAK

COMMON/STYP/SLPILM, SPLILR, SPLILW, STP, SPM
COMMON/CONTUR/SHAP, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
COMMON/CONST/UC, VW, UTBAR, UO, UI, WT, ALPH, THETAl
COMMON/TRANSIT/UX(10, 10), UY(10, 10), VW(10, 10), VV(10, 10), THETA(10, 10), TI(10), ID, IT, IV,
XU(10, 10), YU(10, 10), TT(10)

COMMON/MOVE/UTPEAK(10), XLE, XTE, YLE, VTE, DELT, TIME, TSTOP, TCHECK
COMMON/SPREAD/STP, THA, HTN, HMIN, INDEX, IFLAG
I = STP
J = SHAPE

IF (J.NE.1) GO TO 100

*-----------------------------------*
* IN RIVER OR CHANNEL              *
*-----------------------------------*

UTPEAK(1) = 0.0
IF (IC.EQ.2. AND. IW.LE.1) GO TO 20
GO TO 30

*---------------------------------------------------------------*
* CALCULATE UTPEAK(1) = PEAK VALUE OF UC + 0.035 * VW FOR A TIDAL RIVER  *
*---------------------------------------------------------------*

UTPEAK(1) = (UO+UI)+0.035*VW*COS(THETA1)
GO TO 999

CONTINUE
DO 50 I=1,10
IF (IC.EQ.1) GO TO 45

*---------------------------------------------------------------*
* CALCULATE AVERAGE VALUE OF VALUE OF TIDAL CURRENT FROM T = 0 TO T = TT(1) AND ADD WIND COMPONENT TO COMPUTE DUMMY VARIABLE UTOTAL. THEN SET UTPEAK(I) EQUAL TO MAXIMUM UTOTAL.  *
*---------------------------------------------------------------*

UC=UO+UI*WT/(2.0*3.14159)*(-COS(6.28318/WT*(TT(I)+ALPH))+

C-76
10 COS(6.28318*ALPH/WT))

0020  45  UTOTAL=UC+0.035*VWX(I)+THETA(I)
0021  50  IF(UTOTAL.GT. UPEAK(I)) UPEAK(I)=UTOTAL
0022  50  CONTINUE
0023  50  GO TO 999

------------------------------------------------------------------------

IN OPEN WATER
------------------------------------------------------------------------

0024  100  CONTINUE
0025  105  DO 105 I=1,9
0026  105  UPEAK(I) = 0.0
0027  105  CONTINUE
0028  105  DO 200 J=1,10
0029  120  DO 125 K=1,10
0030  130  IF (TI(J).EQ. TT(K)) GO TO 135
0031  130  IF (TI(J).LE TT(K)) GO TO 130
0032  135  CONTINUE

***********************************************************************

************ INTERPOLATE TO FIND WIND SPEED AT TIME TI(I) CORRESPONDING TO
************ CURRENT INPUT (TT(I) MAY NOT BE SAME AS TI(I))
************

0035  135  W1 = VWX(K-1)+(VWX(K)-VWX(K-1))*(TI(J)-TT(K-1))/
1 (TT(K)-TT(K-1))
0036  135  W2 = VWY(K-1)+(VWY(K)-VWY(K-1))*(TI(J)-TT(K-1))/
1 (TT(K)-TT(K-1))
0037  140  GO TO 140
0038  140  W1 = VWX(K)
0039  140  W2 = VWY(K)
0040  140  UU1 = UX(I,J)+0.035*W1
0041  140  UU2 = UY(I,J)+0.035*W2
0042  140  UTOT = SQRT(UU1**2+UU2**2)

***********************************************************************

************ CALCULATE MAXIMUM VALUE OF UPEAK FOR EACH OF THE NINE BOXES
************ OR SLICES FOR THE WHOLE TIME DURATION
************

0043  140  IF (UTOT.GT. UPEAK(I)) UPEAK(I)=UTOT
0044  180  CONTINUE
0045  200  CONTINUE
0046  200  RETURN
0047  999  END

C-77
SUBROUTINE WATER (TA, RHO, VMU)

THIS SUBROUTINE IS USED TO CALCULATE WATER PROPERTIES.
IT IS CALLED BY PROGRAM "DMODEL".

REF: ROBERT L. LOWELL JR. AND ELI RESHOTKO, "NUMERICAL
STUDY OF THE STABILITY OF A HEATED WATER BOUNDARY
LAYER", CASE WESTERN RESERVE UNIVERSITY,
FTAS TA 73-93 (1974)

T = ABSOLUTE WATER TEMPERATURE (DEG K) SAME AS AIR
CP = SPECIFIC HEAT OF WATER, JOULE/GM-DEG V
RHO = DENSITY OF WATER, GM/CU M
VMU = KINEMATIC VISCOSITY OF WATER, SQ. M/SEC

CALCULATE SPECIFIC HEAT OF WATER

T = TA + 273.15
CP = 2.13974E-9 +8137E-2*T+2.68536E-6*T**2-2.42139E-8*T**3

CALCULATE DENSITY OF WATER

RHO = 1.-(TA-3.962)*2*(TA+288.941)/(506929.2*(TA+6812963)
IF (TA .EQ. 0 ) GO TO 5
RHO = RHO + 0.011445 * EXP(-374.3/TA)
RHO = RHO * 0.999975

CONVERT FROM UNIT OF GM/CU. CM TO KG / CU. M.
RHO = RHO * 1000.0

CALCULATE VISCOSITY OF WATER

TD = TA - 20.
IF (TA .LT. 20 ) GO TO 10
RLOGMU = -1.37023*TD+8.36E-4*TD**2)/(109.*TA)
VMU = 0.01002 * (10. ** RLOGMU)
GO TO 20
RLOGMU = 1301. / (998.333 + 8.1855+TD+0.00585*TD**2)-3.30233
VMU = 10. ** RLOGMU
CONTINUE

CALCULATE KINEMATIC VISCOSITY

VMU = (VMU / 10.0) / RHO
RETURN
** 1.0 < SHAPE < 2.0 = RIVER **
SHAPE = 1.0 IC = 0: NO CURRENT
SHAPE = 1.1 IC = 1: CONSTANT CURRENT
SHAPE = 1.2 IC = 2: TIDAL RIVER
** 2.0 < SHAPE < 3.0 = LAKE **
SHAPE = 2.1: CIRCULAR LAKE
SHAPE = 2.2: RECTANGULAR LAKE
SHAPE = 2.3: ARBITRARY LAKE
** 3.0 < SHAPE = COAST
SHAPE = 3.1: STRAIGHT COAST
SHAPE = 3.2: ARBITRARY COAST

FOR LAKES AND COASTS, THE CURRENT CODE IS:
IC = 0: NO CURRENT
IC = 1: CONSTANT CURRENT
IC = 2: CURRENT = F(SPACE)
IC = 3: CURRENT = F(TIME)
IC = 4: CURRENT = F(SPACE AND TIME)

--- IN THE CURRENT PROGRAM, THE UNIT NUMBER FOR THE
INPUT AND OUTPUT DEVICES ARE:
1 = WRITE ON DISK FILE
5, 6 = READ OR WRITE FROM CONSOLE
FOR A RIVER OR CHANNEL:

- \( \text{WW} = \text{WIDTH}, \text{M} \)
- \( \text{D} = \text{DEPTH}, \text{M} \)
- \( \text{RO} = \text{BOTTOM ROUGHNESS}, \text{M} \)
- \( \text{UC} = \text{CURRENT, M/SEC} \)

*IF THE CURRENT IS TIDAL,

\[
\text{UC} = \text{UCO} + \text{UCI} \cdot \sin(2. \cdot \pi \cdot (T + \text{ALPHA})/\text{WT})
\]

WHERE \( \text{T} = \text{TIME, SEC} \)
- \( \text{WT} = \text{PERIOD, SEC} \)

CONTINUE

WRITE (1,22)

22 FORMAT (/5X,29H2. THE SPILL IS IN A CHANNEL.)

WRITE (6,25)

25 FORMAT (/1X,51H GIVE THE WIDTH AND DEPTH OF THE CHANNEL (IN METERS))

READ (5,*.ERR=24) WW,D

WRITE (1,26)

26 FORMAT (/5X,30H2. THE GEOMETRY OF THE CHANNEL/.)

12HW = WIDTH = \(12.5/1000\)METERS/, 8X.

12HD = DEPTH = \(12.5/1000\)METERS

WRITE (6,127)

127 FORMAT (/1X,36H INPUT THE BOTTOM ROUGHNESS(METERS) OF THE CHANNEL) WHERE ZERO IF YOU WANT TO USE THE DEFAULT VALUE.

READ (5,*.ERR=28) RO

IF (RO.EQ.0) RO=0.0584*0

WRITE (6,45)

45 FORMAT (/1X,36H NON-TIDAL CURRENT ------)

IC = 0

SHAPE = 1.0

UC=0.

H=0.

WRITE (1,32)

32 FORMAT (/5X,30H THE CHANNEL HAS NO CURRENT.)

GO TO 600

CONTINUE

WRITE (6,42)

42 FORMAT (/1X,24H IS IT TIDAL CURRENT? Y/N)

READ (5,12,ERR=41) ICH

IF (ICH.EQ. 'Y') GO TO 50

--- NON-TIDAL CURRENT ------

SHAPE = 1.1

IC = 1

WRITE (6,43)
CURRENT SPEED MUST BE CONSTANT.

INPUT CURRENT SPEED METER/SEC)

READ (5,*) UC
WRITE (1,4) UC

THE CURRENT SPEED IS CONSTANT AND EQUAL TO 1.0 METER/SEC.

GO TO 600

----- TIDAL RIVER ----- 

READ (5,*) UC
WRITE (1,5) UC

IT IS NOT A TIDAL RIVER. THE CURRENT SPEED IS CONSTANT AND EQUAL TO 1.0 METER/SEC.

IT IS A TIDAL RIVER. THE CURRENT VELOCITY CAN BE WRITTEN AS

WHERE

IT IS A TIDAL RIVER.

SPILL IS IN OPEN WATER

CONTINUE

IC=0
WRITE (6,104)
FORMAT (/1X,17HIS IT A LAKE? Y/N)
READ (5,*) ICH
IF (ICH.EQ. 'N') GO TO 200

FOR A LAKE:
D = DEPTH, M
R = RADIUS OF CIRCULAR LAKE, M
L1,L2 = LENGTH AND WIDTH OF RECTANGULAR LAKE, M
X(I),Y(I) = COORDINATES OF BOUNDARY OF IRREGULAR LAKE, M

WRITE (6,112)
FORMAT (/1X,26HIS IT A CIRCULAR LAKE? Y/N)
READ (5,12,ERR=100) ICH
IF (ICH.EQ. 'N') GO TO 140
CIRCULAR LAKE

SHAPE = 2.1
WRITE (6,122)

FORMAT (/1X,46H GIVE THE RADIUS AND DEPTH OF THE CIRCULAR LAKE, / 1 /1X,14H(UNIT : METER))
READ (5, *, ERR=120) R, D
WRITE (1,124) R, D

FORMAT (/5X,35H1. THE SPILL IS IN A CIRCULAR LAKE. / 1 /5X,29H2. THE GEOMETRY OF THE LAKE: / 2 8X,12HR = RADIUS = E12.5, 2X, 6HMETERS/ 3 8X,11HD = DEPTH = E12.5, 2X, 6HMETERS)

**********************************************************************
TRANSFER TO STATEMENTS DESCRIBING CURRENT
**********************************************************************

GO TO 500

WRITE (6, 142)
FORMAT (/1X,29H IS IT A RECTANGULAR LAKE? Y/N)
READ (5, 12, ERR=140) ICH
IF (ICH. EQ. 'N') GO TO 160

RECTANGULAR LAKE

SHAPE = 2.2
WRITE (6,152)

FORMAT (/1X,45H GIVE THE LENGTH (L1), WIDTH (L2) AND DEPTH OF, 1 19H THE LAKE. (METERS)/ 2 55H THE POINT X=0, Y=0 IS THE LOWER LEFT CORNER OF THE LAKE.)
READ (5, *, ERR=150) L1, L2, D
WRITE (1,154)


**********************************************************************
TRANSFER TO STATEMENTS DESCRIBING CURRENT
**********************************************************************

GO TO 500

LAKE W/ ARBITRARY SHAPE

SHAPE = 2.3
WRITE (6,162)

FORMAT (/1X,43H THE SPILL IS IN A LAKE WITH ARBITRARY SHAPE. / 1X,98H DESCRIBE THE SHAPE WITH 10 PAIRS OF X, Y COORDINATES (METERS). (0,0) SHOULD BE NEAR THE SPILL SITE.)
SHAPE = 2.3
WRITE (1,164)

FORMAT (/5X,46H1. THE SPILL IS IN AN IRREGULARLY SHAPED LAKE)
THE FOLLOWING POINTS SPECIFY THE BOUNDARY OF THE LAKE.

TRANSFER TO STATEMENTS DESCRIBING IRREGULAR SHAPE

GO TO 300

---- SPILL MUST BE IN COASTAL WATER ----

FOR A COAST:

\[ D = \text{DEPTH}, \quad M \]
\[ X(1), Y(1), X(2), Y(2) = \text{TWO COORDINATES DESCRIBING A STRAIGHT COAST LINE}, \quad M \]
\[ X(I), Y(I) = \text{COORDINATES DESCRIBING AN IRREGULAR COAST LINE}. \]

CONTINUE

WRITE (6,202)
FORMAT (/1X,31HSPILL MUST BE IN COASTAL WATER.)

WRITE (6,204)
FORMAT (/1X,23HIS COAST STRAIGHT ? Y/N)

READ (5,12,ERR=203) ICH
IF (ICH.EQ.'N') GO TO 220

---- STRAIGHT COAST LINE -----

 SHAPE = 3.1
 WRITE (1,210)
 FORMAT (/5X,42H1. THE SPILL OCCURS IN COASTAL WATER WITH .
  1 20MSTRAIGHT COAST LINE.)

 WRITE (6,212)
 FORMAT (/1X,36HGIVE THE DEPTH OF THE COASTAL WATER.)

 READ (5,*,ERR=211) D

 WRITE (6,215)
 FORMAT (/1X,62HGIVE 2 (X,Y) COORDINATES OF THE STRAIGHT COAST L
  E IN METERS.)

 READ (5,*,ERR=214) X(1), Y(1), X(2), Y(2)

 WRITE (1,218)
 D, X(1), Y(1), X(2), Y(2)

 FORMAT (/5X,36H2. THE DEPTH OF THE COASTAL WATER IS,
  1 19FOLLOWING 2 POINTS /
  2 20X,1HX, 17X,1HY/10X,1H1,3X,E12. 5,5X,E12. 5/
  3 10X,1HX, 3X,E12.5,5X,E12. 5)

TRANSFER TO STATEMENTS DESCRIBING CURRENT

GO TO 300

---- IRREGULAR COAST LINE -----

CONTINUE

SHAPE = 3.2
OILS

WRITE (1,222)
FORMAT ('//5X,42H1. THE SPILL OCCURS IN COASTAL WATER WITH /
1 20IRREGULAR COAST LINE//5X,
2 48H2. THE FOLLOWING POINTS SPECIFY THE BOUNDARY OF ,
3 11HCOAST LINE. )
WRITE (6,224)
FORMAT ('//1X,48H1. THE SPILL OCCURS IN COASTAL WATER WITH IRREGULAR 
1 11H COAST LINE/
* 1X,107HDESCRIBE THE COAST LINE WITH 10 PAIRS OF (X,Y) 
*ORDINATES (METERS). (0,0) SHOULD BE NEAR THE SPILL ORIGIN. )

STATEMENTS 300-324 INPUT IRREGULAR LAKE AND COAST SHAPES

STATEMENTS 500-600 INPUT CURRENTS
C
C ---- CONSTANT CURRENT IN OPEN WATER (STATEMENTS 513-516) ----
C FOR A CONSTANT CURRENT, UX(1,1) = X-COMPONENT,
UY(1,1) = Y-COMPONENT, M/SEC
C
0153 513 WRITE (6,514)
0154 514 FORMAT (/1X,40HINPUT CONSTANT CURRENT SPEED UCX AND UCY, 
1 /1X,18H(UNIT : METER/SEC))
0156 515 READ (5,*), ERR=513) UX(1,1),UY(1,1)
0157 516 WRITE (1.516) UX(1,1),UY(1.1)
0158 514 FORMAT (/1X,41H3. THE CURRENT IS CONSTANT WITH MAGNITUDE, 
1 8X,5HUCX =. F12.2X, 9METER/SEC, 
2 8X,5HUCY =. F12.2X, 9METER/SEC)
0159 515 GO TO 600
0160 517 WRITE (6.518)
0161 518 FORMAT(/1X,35HIS CURRENT A FUNCTION OF TIME ? Y/N)
0162 519 READ (5,12,ERR=517) ICH
0163 520 IF (ICH.EQ. 'Y') GO TO 520
C ---- CURRENT IS A FUNCTION OF LOCATION ONLY ----
C (TRANSFERS TO 532 FOR INPUT AFTER PRINTING OUT LEGEND)
C
0164 IC=2
0165 WRITE(1.519)
0166 519 FORMAT(/1X,35HIS CURRENT A FUNCTION OF TIME ? Y/N)
0167 520 GO TO 520
0168 520 WRITE(1.1001)
0169 1001 FORMAT(/1X,41H3. THE CURRENT IS NOT A FUNCTION OF TIME/ 
1 8X.44HHOWEVER IT DOES CHANGE WITH SURFACE POSITION)
0170 1002 READ(5.12,ERR=520) ICH
0171 1020 IF (ICH.EQ. 'Y') GO TO 1020
C GO TO 1020 WHEN CURRENT = F(TIME AND SPACE)
C*************************************************************************
C
0172 IC=4
0173 WRITE(1.1003)
0174 1003 FORMAT(/1X,41H3. THE CURRENT IS A FUNCTION OF BOTH TIME, 
1 /8X,13H AND LOCATION)
0175 1004 GO TO 532
0176 1020 IC=3
0177 1025 WRITE(1.1025)
0178 1025 FORMAT(/5X,39H THE CURRENT IS A FUNCTION OF TIME ONLY.)
C ---- CURRENT SPEED VARIED WITH TIME AND/OR LOCATION ----
C*************************************************************************
C
0179 WHEN CURRENT = F(TIME) ONLY, THE CURRENTS ARE:
UX(1,1) = X-COMPONENT AT TIME T(I), M/SEC
UY(1,1) = Y-COMPONENT AT TIME T(I), M/SEC
T(I) = SPECIFIED TIMES (10), SEC
WRITE(6,522)
FORMAT(//5X,41H GIVE TIME AND X,Y CURRENT AT 10 INSTANTS./,5X,
* 50HTH MAXIMUM TIME MUST BE AT LEAST AS GREAT AS LAST/5X,
* 25H PRINT-OUT TIME REQUESTED. 26HTIME SHOULD BE IN MINUTE:
0181 DO 525 I=1,10
0182 READ(5,*,ERR=520) TI(I),UX(1,I),UY(1,I)
0183 DO 524 J=2,10
0184 UX(J,I)=UX(1,I)
0185 UY(J,I)=UY(1,I)
0186 CONTINUE
0187 CONTINUE
0188 WRITE(1,526)
0189 FORMAT(/,10X,9HTIME(MIN),11X,9HUX(M/SEC),6X,9HUY(M/SEC))
0180 DO 530 I=1,10
0190 TI(1)*60.
0191 WRITE(6,533) IF(SHAPE.GE.3.0) GOTO 547
0192 FORMAT(/5X,46H GIVE THE 4 X-COORDINATES (METERS) THAT SPECIFY/
* 44HTHE HORIZONTAL GRID. THE FIRST AND LAST MUST/5X,
* 37H COINCIDE WITH THE LENGTH OF THE LAKE.)
0193 CONTINUE
0194 CONTINUE
0195 GOTO 600

**********************************************************************
STATEMENTS 532-600 GIVE INPUT WHEN CURRENT = F(SPACE). IF
CURRENT IS ALSO A FUNCTION OF TIME, A DO-LOOP IS SET UP TO
GIVE INPUT AT 10 TIME INSTANTS.
**********************************************************************

WRITE(6,533)
FORMAT(//5X,50HIF A LAKE, THE X,Y CURRENT MUST BE GIVEN AT CE-
5R/SX,50HOF 9 RECTANGULAR BOXES (3X3 GRID) THAT COVER LAKE./5X,
*49HIF A COAST, THE X,Y CURRENT MUST BE GIVEN FOR THE/5X,71H9 Y-
*CES THAT EXTEND OUT FROM THE 10 X,Y POINTS DESCRIBING THE COAST
IF(SHAPE.GE.3.0) GOTO 547

WRITE(6,533)
FORMAT(//5X,46H GIVE THE 4 X-COORDINATES (METERS) THAT SPECIFY/
* 44HTHE HORIZONTAL GRID. THE FIRST AND LAST MUST/5X,
* 37H COINCIDE WITH THE LENGTH OF THE LAKE.)

**********************************************************************
STATEMENTS FROM HERE TO 555 ARE DO-LOOPS TO SPECIFY THE GRID
FOR THE CURRENTS. XU(1) AND YU(1) ARE THE GRID FOR A LAKE BE
YU(4) 0 0 0 0 0 7 8 9 0 0 0 0 4 5 6 0 0 0 1 2 3
YU(1) 0 0 0 0
XU(1) XU(4)

FOR A COAST THE GRID IS:
* * *
* 1 * 2 * 3 * AND SO ON
* * * * 0
* * 0**XU(4)
* O** YU(4)
0**

XU(1)
YU(1)

******************************************************************************

DO 537 I=1,4
DO 537 I=1,4
READ(5,*,ERR=534) XU(I)
CONTINUE
WRITE(6,536)
WRITE(6,538)
FORMAT('/5X,38HNOW GIVE THE 4 Y-COORDINATES (METERS). /5X, 60HTHE FIRST AND LAST MUST COINCIDE WITH THE WIDTH OF THE LAKE.
DO 540 I=1,4
DO 540 I=1,4
READ(5,*,ERR=534) YU(I)
CONTINUE
WRITE(1,542)(XU(I),I=1,4)
WRITE(1,542)(XU(I),I=1,4)
1)
1)
4(E12. 5,2X))
4(E12. 5,2X))
GOTO 551
GOTO 551
WRITE(6, 547)
WRITE(6, 547)
FORMAT('/5X,47H GIVE THE 10 X-COORDINATES (METERS) THAT SPECIFY/ THE LENGTH OF THE COAST.)
DO 550 I=1,10
DO 550 I=1,10
READ(5,*,ERR=547) XU(I)
CONTINUE
WRITE(1,552)(XU(I),I=1,10)
WRITE(1,552)(XU(I),I=1,10)
1)
1)
47H-COORDINATES THAT FORM THE 9 SLICES IN METERS://1X, 5(E12. 5,2X))
2)
2)
5(E12. 5,2X)/1X, 5(E12. 5,2X))
WRITE(6, 555)
WRITE(6, 555)
IF(IC.EQ.2) GOTO 563
I=1
IF(IC.EQ.2) GOTO 563
IF(IC.EQ.2) GOTO 563
WRITE(6,561)I
WRITE(6,561)I
WRITE(6,561)I
FORMAT('/5X,21HCURRENTS FOR NUMBER ,I3, 1X, 5H TIME.)
******************************************************************************

THIS IS THE DO-LOOP WHEN CURRENT IS ALSO A FUNCTION OF TIME.
TIME INSTANTS (10). CURRENTS ARE:
UX(J,I) = X-COMPONENT, M/SEC
UY(J,I) = Y-COMPONENT, M/SEC

C-87
J = BOX OR SLICE NO.
I = TIME NO.

DO 564 J=1,9
READ(5.*,ERR=551) UX(J,I),UY(J,I)
CONTINUE
IF(IC.EQ.2) GOTO 580
I=I+1
IF(I.EQ.11) GOTO 570
GOTO 560
WRITE(6,571)
FORMAT(/5X,42HNOW GIVE THE TEN TIME INSTANTS IN MINUTES.)
DO 575 I=1,10
READ(5.*,ERR=570) TI(I)
CONTINUE
IF(IC.EQ.2) GOTO 800
I=1
IF(IC.EQ.2) GOTO 590
WRITE(6,585) TI(I)
WRITE(1,585) TI(I)
FORMAT(/20X,5HTIME=.E12.5,7HMINUTES)
TI(I)=TI(I)*60.
WRITE(6,593)
WRITE(1,593)
FORMAT(/20X.52HUX(M/SEC) AND UY(M/SEC) IN THE NINE BOXES OR SL.
*ES.)
WRITE(6,594)
WRITE(1,594)
FORMAT(/10X,1H1,7X,1H2,7X,1H3,7X,1H4,7X,1H5,7X,1H6,7X,1H7,7X,1H8
7X,1H9)
WRITE(6,595)(UX(J,I),J=1,9)
WRITE(1,595)(UX(J,I),J=1,9)
WRITE(6,596)(UY(J,I),J=1,9)
WRITE(1,596)(UY(J,I),J=1,9)
FORMAT(/1X,2HUX,2X,9(3X,F3.2))
FORMAT(/1X,2HUY,2X,9(3X,F3.2))
IF(IC.EQ.2) GOTO 600
I=I+1
IF(I.EQ.11) GOTO 600
GOTO 560
CONTINUE
WRITE(6,605)
WRITE(1,605)
FORMAT(/1X,21HIS THERE WIND IN THE AREA? Y/N)
READ(5,12,ERR=602) ICH
IF (ICH.EQ.'Y') GOTO 700
WRITE (1,610)
FORMAT(/5X,32H4. THERE IS NO WIND IN THE AREA.)
CONTINUE
CALL WIND
CONTINUE
CALL SUBROUTINE TO CALCULATE TRANSPORT
VELOCITY DUE TO WIND
GOTO 999
GOTO 999
SUBROUTINE WIND

THIS SUBROUTINE INPUTS THE WIND VELOCITY AND WAVE HEIGHT. IT IS CALLED BY SUBROUTINE "WBS". IT SETS UP THE FOLLOWING CODE:

IW = 0 : NO WIND
IW = 1 : CONSTANT WIND
IW = 2 : WIND = F(TIME)

0002 COMMON/CONTOR/SHAPE, X(10), Y(10), XC, YC, IC, IW, ISP, XO, YO
0003 COMMON/ENVOR/PV, VISA, DENA, TDC
0004 COMMON/TRANSIT/UX(10,10), UV(10,10), WVX(10),
     WVY(10), THETA(10), TI(10), ID, IT, IV,
     XV(10), YU(10), TT(10)
0005 COMMON/CONSTAT/UC, VW, UTHAR, UC, Ul, WT,
     ALPH, THETAl
0006 COMMON/SIZE/R, D, WW, L1, L2, H, RO

0007 PI=ACOS(-1.)
0008 I = SHAPE
0010 FORMAT (/1X, 27H THIS WIND SPEED CONSTANT? Y/N)
0011 READ (5, 12, ERR=1) ICH
0012 FORMAT(A1)
0013 IF (ICH.EQ. 'N') GO TO 40
0014 IW = 1
0015 WRITE (6, 15)

************** CONSTANT WIND ******

VW = WIND SPEED, M/SEC
THETA1 = WIND ANGLE WITH RESPECT TO X-AXIS OR
         CHANNEL AXIS, RADIANS
VWX(1) = X-COMPONENT OF VW
VWY(1) = Y-COMPONENT OF VW

**************

0016 FORMAT (/1X, 42H INPUT WIND SPEED (METER/SEC) AND DIRECTION,
          /1X, 15H ANGLE (DEGREES))
0017 READ (5, *, ERR=14) VW, THETA1
0018 WRITE (1, 21) VW, THETA1
0019 FORMAT (/5X, 3H4. THE WIND IS STEADY WITH SPEED OF, F12.2X,
          1 9HMETER/SEC./8X, 13H AND ANGLE OF, F12.2X, 7HDEGREES)
0020 THETA1=THETAl*PI/180.
0021 IF (I.EQ. 1) GO TO 150
0022 VXW(1) = VW * COS(THETA1)
0023 VWY(1) = VW * SIN(THETA1)
0024 TWIND = VW
0025 GO TO 150

C-89
---- WIND SPEED VARIES WITH TIME ----

**************

0026 CONTINUE
0027 I W = 2
0028 I = SHAPE
0029 GO TO ( 50, 60, 60 ) I

**************

I = 1 : RIVER
I = 2 OR 3 : LAKE OR COAST

**************

CONTINUE

---- IN RIVER OR CHANNEL ----

0030 WRITE ( 6, 52 )
0031 FORMAT ( 1X, 45H WIND SPEED OVER CHANNEL DEPENDS ON TIME. / 1X, $ 60H INPUT TIME (MIN), WIND SPEED (M/SEC), AND DIRECTION ANGLE (DEGREES). / 1X, 52H USE 10 TIME INSTANTS, AND LAST TIME MUST BE AT LEAST $/ 1X, 35H AS MAXIMUM PRINT-OUT TIME. )

0032 DO 54 I = 1, 10
0033 READ ( 5, * , ERR = 51 ) TT ( I ), VWX ( I ), THETA ( I )
0034 THETA ( I ) = THETA ( I ) * PI / 180.
0035 VWX = VWX ( I )
0036 THETA = THETA ( I )
0037 VWY = VWX ( I ) * SIN ( THETA ( I ) )
0038 VWX = VWX ( I ) * COS ( THETA ( I ) )
0039 54 CONTINUE
0040 WRITE ( 6, 62 )
0041 FORMAT ( 1X, 45H WIND SPEED OVER LAKE OR COAST DEPENDS ON TIME. / 1X, $ 60H INPUT TIME (MIN), WIND SPEED (M/SEC), AND DIRECTION ANGLE (DEGREES). / 1X, 52H USE 10 TIME INSTANTS, AND LAST TIME MUST BE AT LEAST $/ 1X, 35H AS MAXIMUM PRINT-OUT TIME. )

0042 DO 64 I = 1, 10
0043 READ ( 5, * , ERR = 51 ) TT ( I ), VWX ( I ), THETA ( I )
0044 FORMAT ( 1X, 45H WIND SPEED OVER LAKE OR COAST DEPENDS ON TIME. / 1X, $ 60H INPUT TIME (MIN), WIND SPEED (M/SEC), AND DIRECTION ANGLE (DEGREES). / 1X, 52H USE 10 TIME INSTANTS, AND LAST TIME MUST BE AT LEAST $/ 1X, 35H AS MAXIMUM PRINT-OUT TIME. )

0045 CONTINUE

--- IN OPEN WATER ---

0046 WRITE ( 6, 62 )
0047 FORMAT ( 1X, 45H WIND SPEED OVER LAKE OR COAST DEPENDS ON TIME. / 1X, $ 60H INPUT TIME (MIN), WIND SPEED (M/SEC), AND DIRECTION ANGLE (DEGREES). / 1X, 52H USE 10 TIME INSTANTS, AND LAST TIME MUST BE AT LEAST $/ 1X, 35H AS MAXIMUM PRINT-OUT TIME. )

0048 CONTINUE

C-90
READ(5,*,ERR=60) TT(I), VWX(I), THETA(I)
THETA(I)=THETA(I)*PI/180.
VW=VWX(I)
THETA1=THETA(I)
VWy(I)=VWX(I)*SIN(THETA(I))
VWX(I)=VWX(I)*COS(THETA(I))
CONTINUE
C
WRITE (1,102)
DO 101 I=1,10
THETA(I)=THETA(I)*180./PI
TWN=SQRT(VWX(I)**2.+VWy(I)**2.)
WRITE(1,105)TT(I),TWIND,THETA(I)
105 FORMAT (5XF10.2,7X.F10.5,9X,F10.5)
WRITE(1,106)TT(I)*60.
106 FORMAT (5XF10.2,7X.F10.5)
THETA(I)=THETA(I)*PI/180.
TT(I)=TT(I)*60.
CONTINUE
C
GOTO(299,199,199),I
WRITE(6,200)
FORMAT (/IX,3OHINPUT MEAN WAVE HEIGHT (METER)/
$1X,45HDEFAULT VALUE (EQ. (111.32) OF REPORT) IS USED/IX,
$16HBY INPUTTING -1.)
READ (5,*,ERR=199) H
IF(H.LT.0.) H=0.01364*TWIND
WRITE(1,210) H
210 FORMAT (/IX,19HMEAN WAVE HEIGHT IS, F6.2, 2X, 6HMETERS)
RETURN
END