WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Analytical Fate and Mass Transport Modeling of Harbor Island Tank Farms:

ARCO OIL, GATX (Former SHELL OIL) and TEXACO OIL

“A Decision Making Tool in the Cleanup Action Plan”

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CONTAMINANT FATE AND TRANSPORT MODELING

1.0 INTRODUCTION

This document decribes analytical modeling which was conducted by the Washington State Department of Ecology (Ecology) to predict the fate and transport of petroleum hydrocarbons in the groundwater discharging to surface water bodies adjacent to Harbor Island. The modeling focused on the ARCO, TEXACO, and GATX (formerly Shell Oil) terminals which are all in the final stages of the Model Toxics Control Act (MTCA) remedial investigation/feasibility study (RI/FS) process.

The Interim TPH Policy guideline issued by Ecology on January 16, 1997, may be used to calculate the vadose zone soil concentrations that are protective of groundwater unless the release of hydrocarbons in soil has already reached groundwater. Hydrocarbons in soils at Arco, GATX, and Texaco have already reached the groundwater because of the shallow groundwater table on the island. Since hydrocarbons have reached groundwater, fate and transport modeling was used to predict the travel times and exit concentrations of the hydrocarbons that have already reached groundwater; and to evaluate if the exit concentrations will exceed cleanup levels at the points of compliance. For this fate and transport, the assumed points of compliance are, the shoreline of the Duwamish River West Waterway, the shoreline of the Elliott Bay, and the shoreline of the Duwamish River East Waterway for the ARCO, TEXACO and GATX sites respectively.

In addition to Ecology's modeling efforts, Geraghty Miller developed a similar model for the ARCO site on behalf of ARCO. Since these efforts were initiated at the same time, Ecology (Nnamdi Madakor, Site Manager) and Geraghty & Miller (Terry Wadsworth) established a cooperative relationship to support the evaluation of the conceptual model, determine model input parameters, compare model results and evaluate flow and transport beneath the ARCO site. Ecology used the Prince model 5 software code, an infinite analytical model developed by Princeton Waterloo Hydrogeologic Software, and Geraghty & Miller used WinTran™, a analytical flow/numerical transport modeling Software. The Prince code estimates the fate and transport of dissolved contaminants through the use of an infinite analytical solution technique where as WinTran™, estimates fate and transport using a finite-element solution technique. The comparison of the two models provides confirmation on model outputs and insight on the effects of a solution technique on the fate and transport estimates.

1.1 Model Objectives

The objectives of the fate and transport model are 1) to estimate the travel times and exit concentrations of the hydrocarbons that have already reached groundwater; and 2) to evaluate if the exit concentrations at the points of compliance will exceed applicable surface water standards. For this fate and transport, the points of compliance are, the shoreline of the Duwamish River West Waterway, the shoreline of the Elliott Bay, and the shoreline of the Duwamish River East Waterway for the ARCO, TEXACO, and GATX, sites respectively.

1.2 Model Approach

The approach taken in this modeling study consisted of defining the study objectives, establishing a conceptual model, selecting a computer code, constructing a flow and transport model, performing sensitivity analysis, making predictive simulations, post model audit, and documenting the study. These steps are designed to ascertain and document an understanding of a system, the transition from conceptual model to mathematical model, and the degree of uncertainty in the model predictions. Although these steps are generally followed in the presented order, there is however substantial overlap between steps and there is often iteration among steps.

Definition of the study objectives is an important step in applying a mathematical model. The objectives aid in determining the level of detail and accuracy required in the model simulation. The objectives of this modeling study are provided in Section 1.1 of this document.

A conceptual model of a hydrologic system is an interpretation of the characteristics and dynamics of the physical hydrogeologic system. The purpose of the conceptual model is to consolidate site and regional hydrogeologic and hydrologic data into concepts that can be evaluated quantitatively. The conceptual model of Harbor Island can be found in EPA's modeling report (Weston, 1993) and is depicted in Figure F-1, Appendix F.

Computer code selection is the process of choosing the appropriate software capable of simulating the characteristics of the physical hydrogeologic system, as identified in the conceptual model and the processes necessary to achieve the objective. The Prince model 5 software code, an infinite analytical model developed by Princeton Waterloo Hydrogeologic Software, was selected because it has been widely used by others addressing similar conditions. This computer code has been tested and well documented in literature and publications.

Model construction is the process of transforming the conceptual model into a mathematical form. The model typically consists of two parts, the data set and the computer code. The model construction process includes building the data set utilized by the computer code. Fundamental components of the model are discussed in Section 3.0.

Sensitivity analysis is a quantitative method of determining the effect of parameter variation on the model results. The purpose of a sensitivity analysis is to quantify the uncertainty in the model caused by uncertainty in the estimates of the model parameters. The sensitivity analyses performed for this study are discussed in Section 5.0.

Predictive simulations are the analyses of scenarios defined as part of the study objectives. The simulations are used to forecast the response of the flow and/or transport system to different site conditions. Results of the Predictive simulations are presented in Section 6.0.

To achieve the objective, benzene (the most mobile of the petroleum hydrocarbon indicator parameters) was modeled. The source area of contamination used in the model for each site is the groundwater monitoring well with the highest benzene concentration located downgradient from known soil hot spots. Empirical analytical results from these groundwater monitoring wells represent the initial input concentrations representing the modeled source area. The source is simulated as a discontinuous source allowed to discharge for a period of a given time in days. A simulation time of 2000 to 4000 days was evaluated for the model. Source duration of 150 days was evaluated to reflect the spill of December 6, 1996 through May 6, 1997, for the GATX site only.

Review of the USEPA's regional groundwater model (Weston 1993) was conducted to help establish the flow parameters for the analytical model and to examine hydraulic gradients, groundwater velocities, groundwater flow directions, and groundwater recharge and discharge locations. This review was accomplished through the reconstruction of a preliminary Island Wide Modflow model. The flow parameters, conceptual hydrogeologic relationships and the flow regime depicted by the island-wide flow model was used in the development of the input parameters for the Prince and WinTran™ codes. Subsequently, Ecology applied the input parameters developed through the cooperative effort for the Arco Site, to the Texaco and GATX Sites located on Harbor Island.

1.3 Report Organization

This report summarizes the information collected and analyzed during the construction, development, iteration, and simulation of the analytical fate and transport modeling of the contaminants of concern on Harbor Island. The report discusses some island-wide partinent information, but primarily focuses on the tank farms, ARCO, GATX, and TEXACO which are the areas of interest for this case study. In sections that discuss the mathematical model, emphasis is placed on the methodology for the mathematical code and the input parameters used to develope the Prince analytical fate and transport; other supporting information like the output graphics and the input parameter calculations are presented in appendices.

The report is organized as follows:

- **Section 1.0** presents the objectives and data needs addressed in the mathematical fate and transport model. The approach and organization of the analytical model are also presented.
- **Section 2.0** presents a summary of the island-wide site characterization and hydrogeology; historical site conditioins for the tank farms; chemical of concerns and their potential pathways and final receptors.
- **Section 3.0** presents the mathematical code, assumptions, and input parameters for the model iteration.
- **Section 4.0** presents the model development, methodology, and modeled source areas for the tank farms.
- **Section 5.0** presents discussions on the model sensitivity analysis and impacts to variation in input parameters.
- **Section 6.0** presents the analytical results for the various model simulations.
- **Section 7.0** presents discussions on the Post Audit for the model results compared to empirical field data.
- **Section 8.0** presents conclusions regarding the fate and transport of the contaminant of concern with respect to the nearby surface water bodies.

2.0 SITE CHARACTERIZATION

Harbor Island was built (man made) on tidelands on the river mouth delta of the Duwamish River. Major drainage modifications of the lower Duwamish River occured in the early 1900s to improve the seaport and to provide an area for industry and shipping. Former shallow tidal areas of the Duwamish River delta were filled with material largely derived from dredging of the Duwamish channel and adjacent waterways. The sinuous course of the lower Duwamish River was straightened and deepened, and now is the Duwamish Waterway.

Historically, Harbor Island has been used for industrial development. Currently the island is zoned exclusively as General Industrial, with the exception of a 200-foot shoreline zone that is designated Urban Industrial (City of Seattle 1987). The Island is occupied by several large industrial plants, including petroleum companies, metal fabricators, ship-building facilities, and port facilities.

2.1 Island-Wide Hydrogeology

Harbor Island and the Duwamish-Green River Valley occupy a north-south tending elongate, glacially scoured trough bounded by drift uplands. The trough is occupied by post-glacial alluvium which attains a thickness of up to 200 feet (EPA RI 1993). The adjacent ridges consists of Vashon and pre-Vashon drift.

The geology beneath the site consists of fill resting on alluvium. Alluvium is composed of unconsolidated fine- to coarse-grained, silty-to-clean, fine-to-medium sand with thin interbeds of silt. This sediment was deposited in fluvial/deltaic environment of the Duwamish River delta. These deposits are overlain by a veneer of mechanically and hydraulically placed anthropogenic fill exhibiting similar textural characteristics.

Shallow unconfined groundwater occurs within the fill and deltaic sediment on Harbor Island. The depth to groundwater ranges from 2.5 to 11 feet bgs. The elevation of the groundwater table surface ranges from 0.50 to 4.50 feet North American Vertical Datum (NAVD). No local confined or semi confined water-bearing zones were identified during the groundwater investigations on the island (EPA RI 1994, ECOLOGY RI, 1996).

The groundwater on the island is in communication with the adjacent marine estuary including the Elliott Bay and the adjacent waterways. Groundwater throughout the island shows varying degrees of tidal response. Groundwater recharge occurs through infiltration of precipitation. Recharge is likely greatest in the northern portions of the island (see Fig.1, page 10) where the coverage of asphalt is the lowest. The higher water table elevations in the northern half of the island supports this notion. The groundwater is discharged to the adjacent waterways as freshwater and becomes brackish at depths of 45 feet, toward the shore and deeper inland (groundwater flow dynamic, Harbor Island, EPA, 1993, Figure F-1, Appendix F).

2.2 Site Conditions

2.2.1 ARCO

Current on-site source areas of concern used for modeling fate and transport in the groundwater beneath the ARCO site are areas in the vicinity of Tank No's 1, 9, and 11, located inland and within Plant No. 1 (ARCO site map, page 10). These potential source areas were selected based on the results of the remedial investigation which indicated historical spills in these areas prior to 1988. The result of these spills are hot spots in soil and groundwater at upland locations which have concentrations of highly weathered total petroleum hydrocarbons (TPHs), gasoline, diesel, and oil and grease, and carcinogenic polynuclear aromatic hydrocarbon, (cPAHs). Other site concerns, like the floating product under the warehouse next to the shoreline, are addressed through the remedial action alternatives in the cleanup action plan (CAP). Chemicals of concern detected in either soil or groundwater attributed to the ARCO operations are predominantly highly weathered TPHs and cPAHs.

Surface runoff and marine sediment considerations are under review by EPA. Recent sediment studies conducted along ARCO's shoreline of the West Waterway show that sediment impact from the petroleum and polynuclear aromatic hydrocarbons do not exceed levels that pose threat to human health and the sediment environment and will not require active sediment remediation. This sediment study does not address surface water media, quality and standards.

2.2.2 GATX

Current on-site source areas of concern used for in modeling the GATX site (GATX Revised RI, 1997) are the results of historical operations and a recent spill of December 1996 around Tanks No. 42 and 43, and product lines in the "C Yard" located inland at the middle of the Island (see GATX site map, page 10). The distance between GATX and the East Waterway is approximately 2300 feet, and the Port of Seattle, Terminal 18 lies in between GATX and the Shorelines. The result of these spills are TPH and cPAH hot spots in soil and groundwater at the site. In summary, chemicals of concerns detected in either soil or groundwater attributed to the GATX operations are predominantly TPH and cPAHs.

EPA is planning cleanup at the East Waterways, but it will mostly be accomplished through the Port's dredging project at Terminal 18 for navigation reasons.

2.2.3 TEXACO

Current on-site source areas of concern used for modeling of the TEXACO site (TEXACO RI, 1994) are the result of inland historical operations/spills prior to 1992 around the Main Tank Farm, next to the Truck Loading Rack, and Tank No. 80001 (Texaco site map, page 10). Other site concerns that include recent spills and free product at the Shoreline Manifold Area are addressed under the remedial action alternatives in the CAP. Chemical of concerns detected in either soil or groundwater attributed to the TEXACO operations are predominantly TPH and cPAHs.

Also, EPA determined that the sediment impact in Elliott Bay, next to the Texaco Shoreline Manifold Area does not pose a threat to human health and the sediment environment and will not require active sediment remediation. Although sediment concentraions exceed chemical criteria, results of bioassays showed the sediment were not toxic. This sediment study does not address surface water media, quality and standards.

2.3 Chemicals of Concern

Chemicals of concern at the ARCO, GATX and TEXACO sites include total TPH and PAHs. These chemicals have been identified (ARCO RI, 1994, TEXACO RI, 1994, & GATX RI Revised 1997) and refined based on the most recent groundwater quality data.

Chemicals of concern are considered relative to applicable state and federal laws that are relevant and appropriate requirements (ARARs), health based comparison levels and the beneficial use of the site groundwater which is to protect the surface waters of the Duwamish River waterways, Elliott Bay, aquatic organisms and human health from the consumption of contaminated aquatic organisms. Ecology and the EPA determined that the site groundwater is not a potential future source of drinking water due to insufficient potable groundwater available for use and salinity.

2.4 Potential Transport Pathways and Environmental Receptors

The transport of the chemicals of concern (total TPHs, and cPAHs) is a dynamic process that can potentially occur across several different media. Based on the review of the site analytical data and the site physical properties, the flow chart, page 9, depicts potential sources and transport mechanisms identified for the site and they include;

- soil re-entrainment to air (primary source and mechanism):

This includes re-entrainment of contaminants detected in soil to air. Surface soil source areas have the potential to release chemicals to air by volatilization and via airborne particulates.

- soil leaching and infiltration (secondary source and mechanism):

This includes leaching of chemicals from the soil and infiltration to groundwater and ultimate discharge to the nearby surface water. Chemical concentrations of concern have been identified in groundwater and there is some potential that these occurances have resulted from, or been enhanced by the leaching of chemicals from the vadose zone soils beneath the facilities to the groundwater table where they are further discharged where marine organisms could be exposed.

- surface runoff and storm drain discharges (tertiary source and mechanism):

This includes transport by surface runoff to storm drains where discharge is direct to the nearby surface water body. Runoff may occur directly overland or through storm drain discharges. Additionally, contaminants in storm drain catch basin sediment may desorb and be carried to the waterway through storm drain discharges where marine organisms could be exposed.

Final receptors are marine organisms in the waterways, humans that consume marine organisms, day workers that inhale air entrained particulates, and terrestial biota alike (see flow chart, page 9).

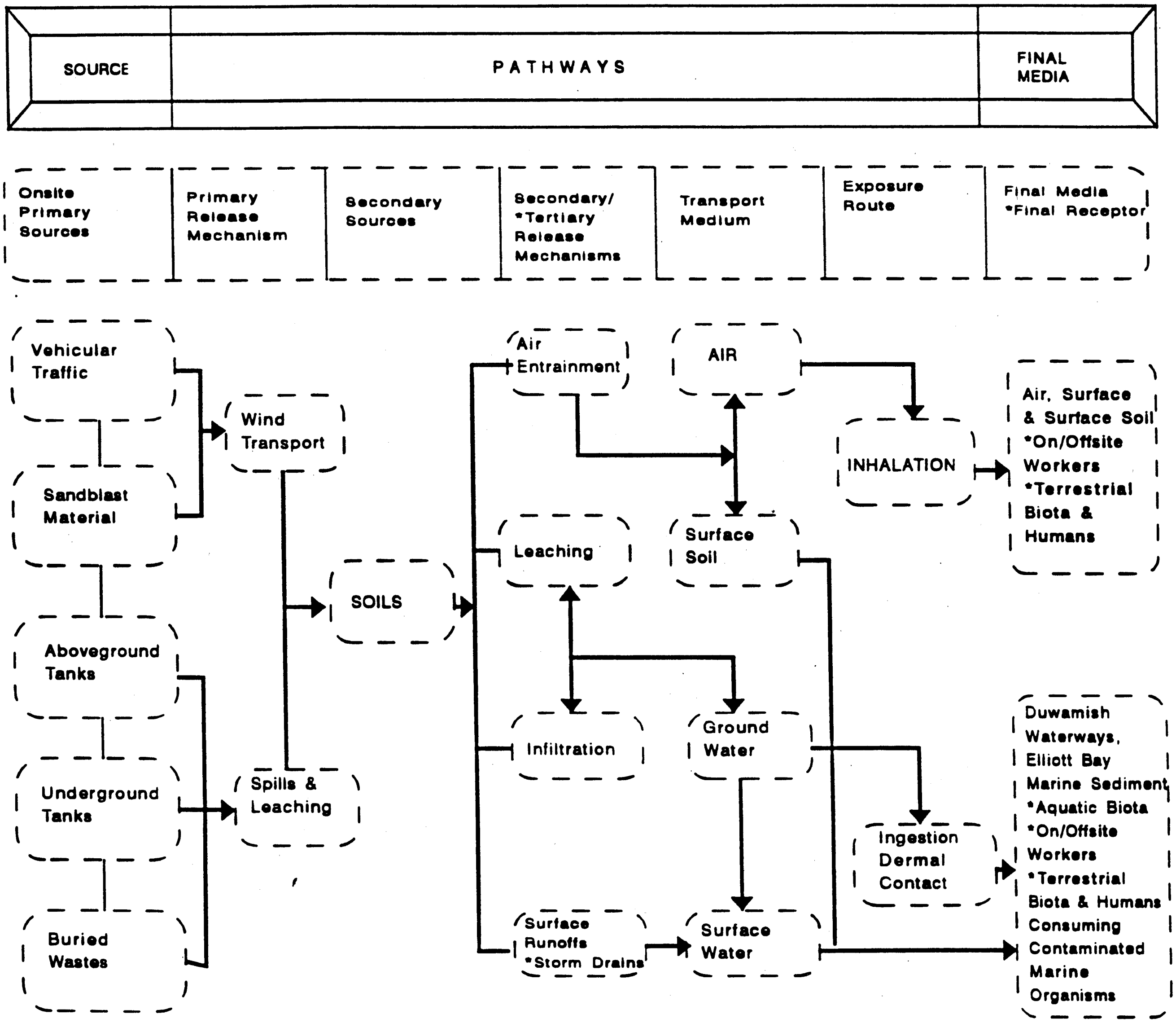
However, Ecology issued the Interim TPH Policy guideline on January 16, 1997, which allows the use of Methods B and C for determining TPH cleanup levels (chemical of concern), for the following potential exposure pathways: (1) direct human contact, and (2) soil-to-groundwater.

The soil-to-groundwater pathway is the recommended and appropriate method to develop the soil TPH cleanup levels for Harbor Island to ensure continued protection of the surface water next to the sites.

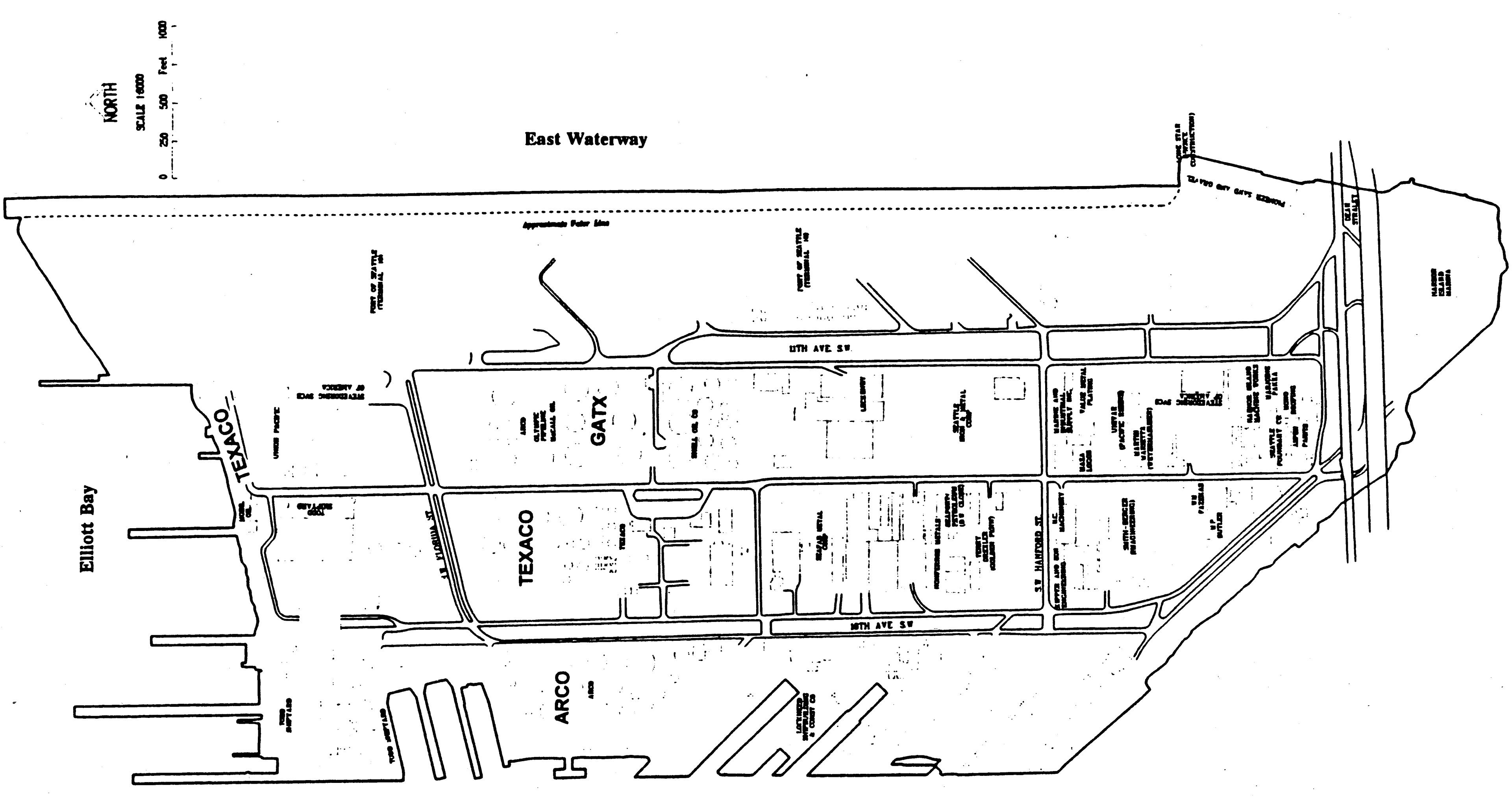
The potential exposure pathway of concern for the tank farms, is soil-to-groundwater-to-surface-waters. Therefore, the final environmental receptors associated with the West and East Waterways of the Duwamish River, and Elliott Bay to the north, are marine organisms that could be exposed and humans who may consume contaminated marine organisms.

Harbor Island Flow Chart

Potential Pathways of Contamination



SITE VICINITY MAPS FOR ARCO, GATX, & TEXACO

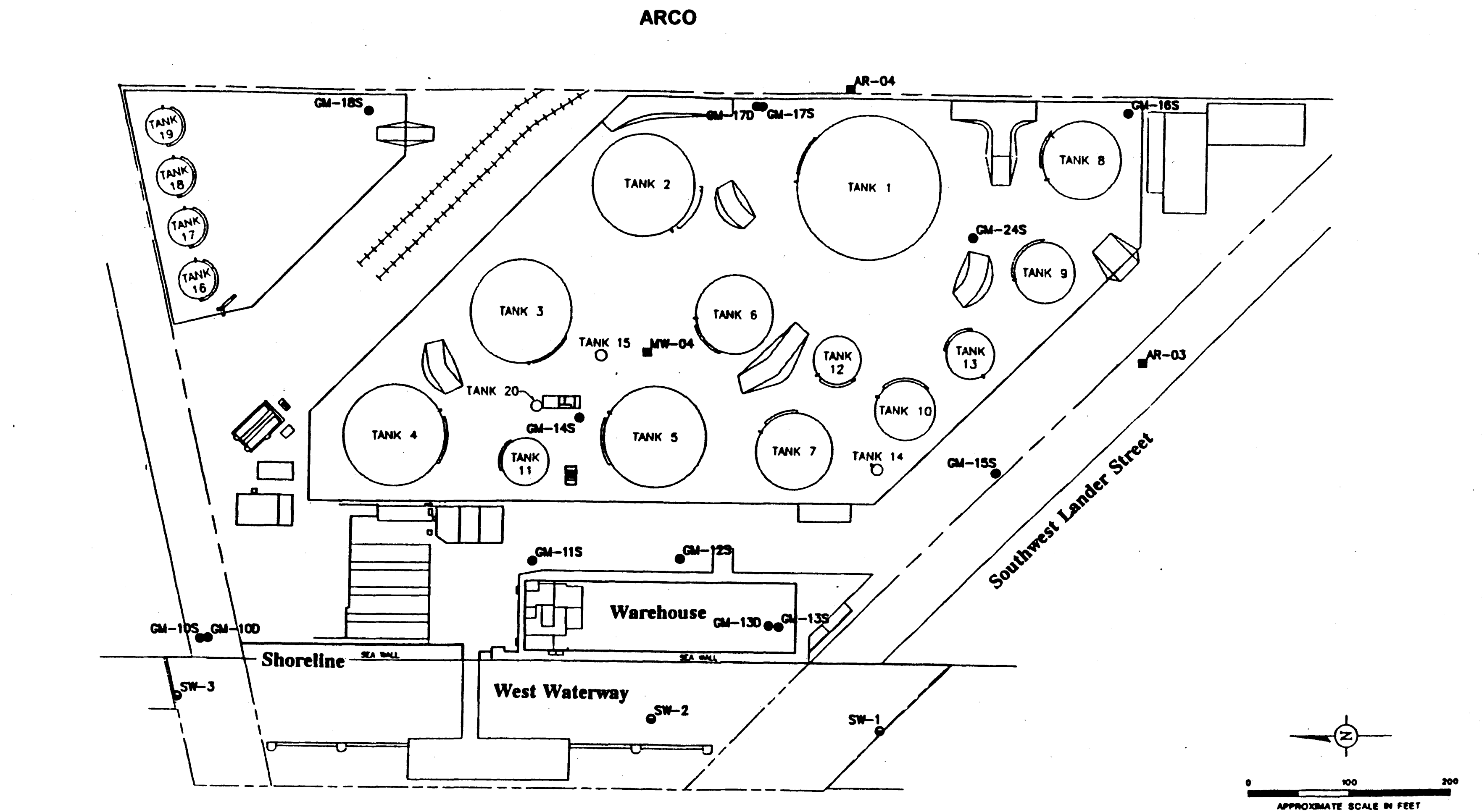


HARBOR ISLAND

Significant Facilities Map

Fig. 1

WESTON JOB NUMBER: 4000-02-21-0014 DATE: January, 1991



LEGEND

● GM-10S	MONITORING WELL (S=SHALLOW, D=DEEP)
■ AR-03	MONITORING WELL INSTALLED BY USEPA
⊙ SW-1	SURFACE WATER SAMPLING LOCATION

GERAGHTY & MILLER, INC.
Environmental Services

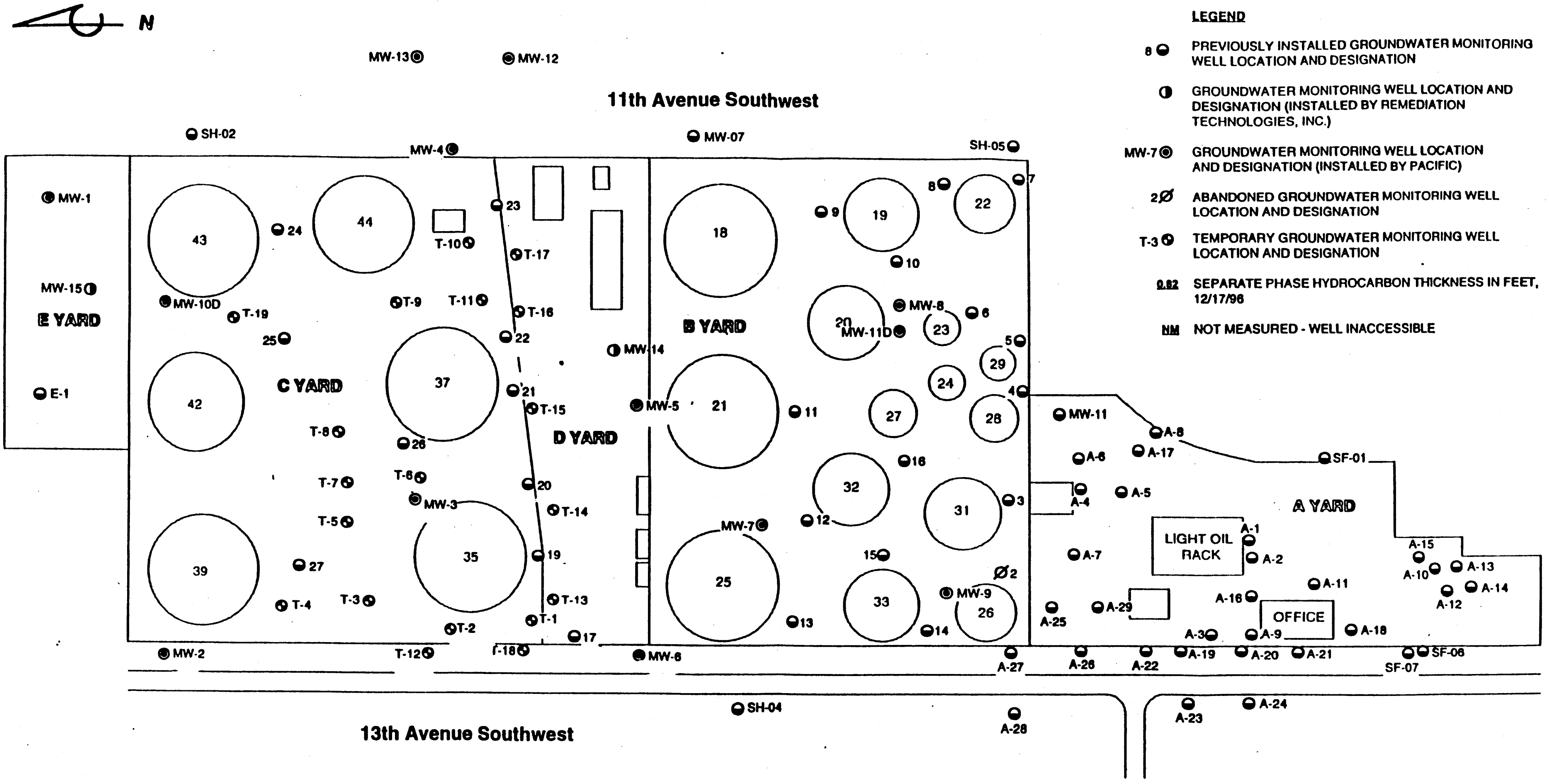
DRAWING NO. 400-125

ARCO HARBOR ISLAND TERMINAL 21T – PLANT 1

MONITORING WELL & SURFACE WATER SAMPLING LOCATION MAP

Fig. 1.1

FILENAME: S11433\11450.DWG CREATED: JUL 23 1993 08:39:08 UPDATED: APR 01 1994 14:10:32 PLOTTED: APR 01 1994 14:14:11 (VS824)



LEGEND

8 ◒ PREVIOUSLY INSTALLED GROUNDWATER MONITORING WELL LOCATION AND DESIGNATION

◐ GROUNDWATER MONITORING WELL LOCATION AND DESIGNATION (INSTALLED BY REMEDIATION TECHNOLOGIES, INC.)

MW-7 ◉ GROUNDWATER MONITORING WELL LOCATION AND DESIGNATION (INSTALLED BY PACIFIC)

2 Ø ABANDONED GROUNDWATER MONITORING WELL LOCATION AND DESIGNATION

T-3 ⊗ TEMPORARY GROUNDWATER MONITORING WELL LOCATION AND DESIGNATION

0.82 SEPARATE PHASE HYDROCARBON THICKNESS IN FEET, 12/17/96

NM NOT MEASURED - WELL INACCESSIBLE

PACIFIC
ENVIRONMENTAL
GROUP, INC.

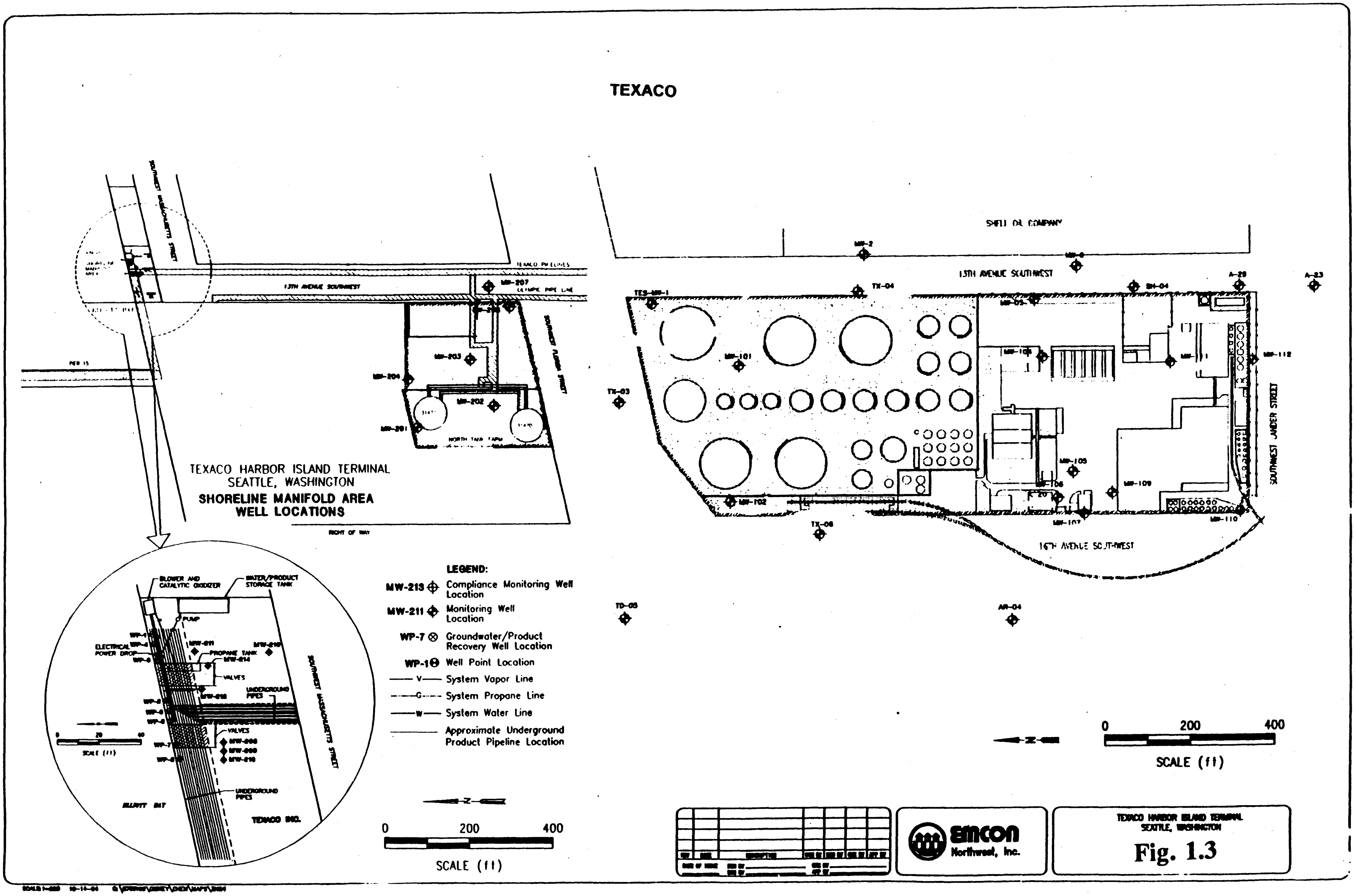
SCALE IN FEET

0 100 200

GATX TERMINALS CORPORATION - HARBOR ISLAND TERMINAL
2720 13th Avenue Southwest
Seattle, Washington

GATX

Fig. 1.2



TEXACO HARBOR ISLAND TERMINAL
SEATTLE, WASHINGTON

Fig. 1.3

3.0 MATHEMATICAL MODEL

A mathematical flow and transport model was developed using the Prince code to evaluate contaminant fate and transport which include the effects of dispersion, sorption, and decay. The mathematical model requires several types of data or input parameters for the flow and the transport model. These input parameters include the following:

- groundwater velocity (V),
- initial concentration (C),
- first order decay constant (K),
- first order source decay constant (gamma) ,
- dispersion coefficient in the X direction (D_x),
- dispersion coefficient in the Y direction (D_y),
- retardation factor (R_f),
- time that the source is initiated (T_{on}),
- time that the source is to be removed relative to the initiated source time (T_{off}),
- angle of regional flow along the X axis (Theta),
- coordinate of source location along the X axis (X_o),
- coordinate of source location along the Y axis (Y_o).

Model input parameters for the ARCO, GATX and TEXACO sites are presented in Tables 1, 2, and 3, pages, 16, 17, and 18 respectively. The calculations and modeled processes are described in detail in Appendix E.

Mathematical assumptions inherent in the Prince code used by ECOLOGY are that 1) the aquifer is of infinite width and 2) that the down-gradient regional flow distances are much larger than the length of the modeled area. These assumptions are violated in this case study since Harbor Island is not infinite in length and the down-gradient distance does not extend past the shoreline. Since the distances being analyzed (from the potential source area to the shoreline) are short relative to the width of the aquifer, the model will provide a reasonable approximation to the fate and transport of constituents in the groundwater beneath the Island. In addition, results from the model using the WinTran™ code were used to confirm travel times and exit concentrations.

The Prince code simulated a point source which developed a source area from a continous source duration of a given interval (T_{off} - T_{on}). In addition, Ecology's model considered site-specific retardation values calculated from the average bulk density of soil (ARCO RI), the average total organic carbon (TOC) from 12 soil samples (GATX RI), and the average effective porosity derived from the RI for the tank farms. (in contrast, the mathematical fate and transport model developed using the WinTran™ code by Geraghty and Miller, simulated an initialized source area and no retardation). (Appendix. E. presents detail input calculations, and Appendices A, through D, contain graphical and report outputs). The following are brief description of some of the input parameters in the mathematical model code.

3.1 Groundwater Velocity (V)

In most groundwater systems, advection is the principle mechanism by which contaminants are transported. In an advection dominated system, the direction and rate of contaminant transport coincides with that of groundwater flow. Also, advection describes chemical transport via entrainment with groundwater flow.

Advection and dispersion are used to describe mass transport in groundwater flow. Dispersion typically combines the effects of diffusion and mechnical dispersion to describe mixing zone about a chemical front. Diffusion is mixing caused by chemical gradients. In groundwater flow systems with a significant advective flow component, diffusion has very little impact on mass transport.

Groundwater velocity can be empirically determined through the following mathematical equation from the Darcy's law as:

$$V_x = \frac{K}{n_e}\frac{dh}{dl}$$

where:

V_x = average linear velocity
K = hydraulic conductivity
n_e = effective porosity
$\frac{dh}{dl}$ = hydraulic gradient

Please see Appendix E, Tables B1-3, for detail calculations of the site groundwater velocities.

3.2 Initial Concentration (C)

Initial concentrations are empirical field data collected at monitoring wells located downgradient from known soil hot spots. Initial concentrations are considered source areas and are modeled to predict fate and exit concentration to a receptor downgradient from the source.

3.3 First Order Decay Constant (k)

k is first order decay constant in units of (1/T) and it is contaminant specific based on the half life of the contaminant considered over time. Examples of k are abiotic reactions that include hydrolyzation of chlorinated hydrocarbon known as reductive dechlorination and radioactive decay. Another example, is a natural decay of hydrocarbons known as natural biodegradation. k can be empirically determined through the First Order Decay Constant:

k = 0.693/T per day
T = half life of the contaminant/day

3.4 First Order Source Decay Constant (gamma)

gamma is the first order constant for the Gaussian distribution boudary condition source. Also, it has units of (1/T). This boundary condition is expressed mathematically as

$$C = C_{max} \exp [- \text{gamma} \times t] \text{ [Gaussian distribution]}$$

When gamma is set to zero, one has only a Gaussian distribution boundary condition. When gamma is greater than zero, the Gaussian distribution bounday condition decays exponentially with time. Gamma is used when the source strength dilutes (for example, by rainfall infiltration) or decays (for example, by biodegradation or reductive chlorination) exponentially with time.

3.5 Dispersion Coefficient in the X Direction (D_x)

Mechanical dispersion is caused by both micro-differences in groundwter flow velocity at the pore level and differences in the rate at which groundwater travels through the aquifer.

The mixing that occurs along the streamline of groundwater flow is called longitudinal dispersion or along the X axis (direction)

Factors contributing to dispersion include:

- friction- as fluid moves through the pores, it will move faster through the center of the pore than along the edges
- path tortuosity- some of the fluid will travel in longer pathways than other fluids
- pore size- fluid that travels through larger pores (gravels) will travel faster than fluids moving in smaller pores (silt and clays)

3.6 Dispersion Coefficient in the Y Direction (D_y)

Dispersion that occurs perpendicular to the pathway of groundwater flow is lateral dispersion, transverse or along the Y axis (direction).

3.7 Retardation Factor (R_f)

R_f results when a solute sorbs to soil particles or organic matter sorbs in soil. It is also defined as the water velocity divided by the solute velocity. When the solute travels at a velocity less than the groundwater velocity, R_f is > 1.0. However, if the solute travels faster than the groundwater velocity (very rare, but can occur for viruses), R_f is < 1.0. When the solute travels at the same velocity with the groundwater velocity, $R_f = 1.0$ (no retardation)

Solutes are considered in two broad classes: *conservative and reactive*.

Conservative solutes do not react with the soil and/or native groundwater or undergo biological or radioactive decay. The chloride ion is a good example of a conservative solute. These substances will have a retardation factor close to 1, and they are the early arrivals in a detection monitoring program.

Reactive substances can undergo chemical, biological, or radioactive change that will tend to reduce the concentration of the solute or slow their movement through soil. Chemical reaction include cation exchange, precipitation-dissolution, and oxidation-reduction. Many of the heavy metals are readily adsorbed onto solid surfaces or trapped by clays through ion exchange. Biological reactions may be either aerobic, in the presence of oxygen or anaerobic, in the absence of oxygen.

The retardation factor is also expressed by the following equation:

$$R_f = 1 + \frac{\rho_b K_d}{\eta} = \frac{V_w}{V_c} = \frac{X}{X^*}$$

where:

R_f = retardation factor, dimensionless
K_d = distribution (adsorption) coefficient, gram/mL
ρ_b = bulk density of soil, gram/cm^3
V_w = velocity of ground water (L/T)
V_c = velocity of solute or contaminant
η = effective porosity, dimensionless
X = distance traveled by uncontaminated ground water
X^* = distance traveled by contaminant (solute) for a given time

3.8 Time that Source is Initiated (T_{on})

T_{on} is 'Time on' and it represents the initial time of source release. It is the initial starting time (in any consistent time units) when the concentrations along the Gaussian distribution are activated.

3.9 Time that Source is Turned Off Relative to T_{on} (T_{off})

T_{off} is 'Time off' and it is the ending time (in any consistent time units) when the concentrations along the Gaussian distribution source are turned off or set to zero.

3.10 Angle of Regional Groundwater Flow Along X axis (Theta)

Theta is the direction of the uniform groundwater velocity measured positive counterclockwise from the X-axis in degrees from 0 to 360.

3.11 Coordinate of Source Location Along the X axis (X_0)

X_0 is the X-location of the center of the Gaussian distribution boundary condition source (pollutant source is located at the origin at X = 0, i.e. zero distance from the source)

3.12 Coordinate of Source Location Along the Y axis (Y_0)

Y_0 is the Y-location of the center of the Gaussian distribution boundary condition source (pollutant source is located at the origin at Y = 0, i.e. zero distance from the source)

TABLE 1
ARCO Model Input for Analytical Flow and Mass Transport

Parameter	**Benzene**		
Source	Units	GM-14s	AR-03
K		0.001733	0.001733
Gamma		0	0
Dx		1.5	1.5
Dy		0.15	0.15
R_f		1.3	1.3
T_{on}	days	0	0
T_{off}	days	2000	2000
Theta		270	270
Xo	feet	369	938
Yo	feet	240	297
V (average)	ft/day	0.1	0.1
C	ug/l	200	1100

TABLE 2
GATX Model Input for Analytical Flow and Mass Transport

Parameter	**Benzene**		
Source	Units	T-17	MW-24
K		0.001733	0.001733
Gamma		0	0
Dx		1.5	1.5
Dy		0.15	0.15
R_d		1.3	1.3
T_{on}	days	0	0
T_{off}	days	2000 (2) 150	2000
Theta		270	270
Xo	feet	5100	5000
Yo	feet	2500	2500
V (average)	ft/day	0.1	0.1
Conc.	ug/l	11800	4630

See Appendix. E. for input calculations, and Appendices C and D, for the graphical and report outputs.
(2) December 6, 1996 through May 6, 1997, 150 days since the spill

TABLE 3
TEXACO Model Input for Analytical Flow and Mass Transport

Parameter	**Benzene**		
Source	Units	TX-03	SH-04
K		0.001733	0.001733
Gamma		0	0
Dx		1.5	1.5
Dy		0.15	0.15
R_d		1.3	1.3
T_{on}	days	0	0
T_{off}	days	2000	2000
Theta		180	180
Xo	feet	2900	6100
Yo	feet	3200	3400
V (average)	ft/day	0.1	0.1
Conc.	ug/l	360	8100

See Appendix. E. for input calculations, and Appendices C and D, for the graphical and report outputs.

4.0 MODEL DEVELOPMENT

The process of transforming the conceptual model into the mathematical form required by the Prince code began with a review of the USEPA's regional groundwater model (Weston 1993). This review included the construction and limited calibration of an island-wide numerical flow model (numerical, Geraghty & Miller) that preceded this fate and transport case study. This numerical model helped establish the flow parameters for the analytical model and to examine hydraulic gradients, groundwater velocities, groundwater flow directions, and groundwater recharge and discharge locations. The flow parameters, conceptual hydrogeologic relationships and the flow regime depicted by the island-wide flow model was used in the development of the input parameters for the Prince and WinTran™ codes. Subsequently, Ecology applied the input parameters developed through the cooperative effort for the ARCO Site, to the TEXACO and GATX Sites located on Harbor Island.

Limited calibration of the island-wide baseline flow model was accomplished by comparing predicted groundwater head values to empirical field values of June 1994 measured by the three tank farms (ARCO, TEXACO, AND SHELL). June is a period of average tide observed at Harbor Island (EPA-RI, 1993). The calibrated variables for the baseline flow are recharge or infiltration, hydraulic conductivity, aquifer thickness or bottom elevation, and groundwater velocities (Please see Appendix E, Table B-3). These variables are within the ranges for the Harbor Island hydrogeologic system.

The calibrated variables used to predict groundwater head values that represents the best fit of the empirical field measurements of June 1994, are: infiltration, 15 in/yr (0.04in/day), hydraulic conductivity, 7.5 ft/day, bottom elevations or aquifer thickness, ~~35 feet for areas near the island edges~~, ~~and~~ 80 ~~feet for the center of the island~~ (see Appendix F, HI groundwater conceptual flow dynamic depiction).

To achieve the objectives of the modeling study, benzene (the most mobile of the petroleum hydrocarbon indicator parameters) was modeled as a conservative indicator of petroleum hydrocarbons in groundwater. The source area of contamination used in the model for each site was selected as the groundwater monitoring well with the highest benzene concentration located downgradient from known soil hot spots. Empirical analytical results from these groundwater monitoring wells represent the initial input concentrations representing the modeled source area. The source is simulated as a timed injection allowed to introduce Benzene into the groundwater flow system for a period of 150 days. Source duration of 150 days was evaluated to reflect the spill of December 6, 1996 through May 6, 1997 for the GATX site only. Total simulation times for the model study ranged between 2000 to

4000 days.

4.1 ARCO

Source areas for the ARCO fate and transport simulation are monitoring wells GM-14S, and AR-03, located inland of Plant No. 1 next to the West Waterway. These wells had the highest benzene concentrations and are located downgradient of known historical spill areas considered hot spots. The last documented spill at the Arco Site was in 1988, and the petroleum hydrocarbons on this site are considered aged. Specific model parameters used in simulating transport of Benzene in the groundwater beneath the ARCO site are provided in Table 1, page 16.

4.2 GATX

Source areas for the GATX fate and transport simulation are monitoring wells T-17 and MW-24, located in the middle of the island in Yard C. These wells have the highest benzene concentrations and are located downgradient of the recent spill areas considered hot spots. The last documented spill at the GATX site was in December 1996, and the petroleum hydrocarbons on this site are considered fresh. Specific model parameters used in simulating transport of Benzene in the groundwater beneath the GATX site are provided in Table 2, page 17. See Appendix. E. for input calculations, and Appendices C and D, for the graphical and report outputs.

4.3 TEXACO

Source areas for the TEXACO fate and transport simulation are monitoring wells TX-03 and SH-04, located inland within the Main Tank facility at the middle of the island. These wells have the highest benzene concentrations and are located downgradient of known historical spill areas considered hot spots. The last documented spill at the inland tank area of the Texaco site was in 1992, and the petroleum hydrocarbons on the inland part of the site are considered fairly aged. Other recent spills that occurred in 1996 happened next to the Shoreline Manifold Area, and are not part of this model consideration. Specific model parameters used in simulating transport of Benzene in the groundwater beneath the TEXACO site are provided in Table 3, page 18.

5.0 MODEL SENSITIVITY

The predictions made by a groundwater flow and transport model are the end product of many individual decisions on input parameters (Tables 1, 2, & 3, pages 16, 17, & 18 respectively). Some of these parameters may be poorly known. This section identifies the degree of uncertainty associated with some of the major parameters and evaluates how the model predictions might change with a different choice of input value. Model 1, (see Table 4, page 26) represents a worst case baseline condition. Nine different models (for ARCO site) were attempted to evaluate the model sensitivity analysis presented for this case study.

This section concentrates on the impact of variations in input parameters on the fate and transport presented in this article, but briefly discusses relevant input parameters for the flow model (ARCO HI. FS, Geraghty & Miller, 1996) that preceded this fate and transport.

5.1 Model Sensitivity to Variations in Hydraulic Conductivity (K)

Evaluating the impact of changes in K on water balance and travel times for the sensitivity analysis done for the flow model, is dependent of aquifer thickness, rate of recharge, and effective porosity. Since the heads in the flow model are not fixed during the sensitivity analysis, the discharge rate, travel times, and average velocities does not depend linearly on the choice of K. A reduction by a factor of 2 in K does not necessarily result in a decrease in discharge or average velocity along pathline of the same amount. See Appendix E, Table B-3, for the various K values measured on the island from various studies.

The impact of changes in K on transport is less quantifiable. The critical input value to the transport model is the average velocity along pathline, v, which does depend linearly on K. However, the transport equations are not linear in v, indicating that a simple scaling of time-to-the-exit-point would not be strictly correct.

5.2 Model Sensitivity to Variations in Aquifer Thickness (b)

The shallow groundwater on Harbor Island are part of an aquifer system which may extend to bedrock, a thickness of nearly 3000 feet (EPA RI, Weston, 1993). The critical aquifer thickness used in the flow modeling that preceded this fate and transport (Geraghty & Miller) is for that part of the aquifer which participates in the shallow flow pattern.

The assumed values for aquifer thickness (or bottom elevations) in the flow model is 35 feet for the east and west waterways of the island edge, and 80 feet for the center of the island. (see Appendix F, EPA RI, after R. Weston, 1993, Conceptual Groundwater

Flow Dynamic for Harbor Island)

Choice of aquifer thickness for the flow model impacts discharge recharge rates and the estuarine loading rates. An increase in aquifer thickness causes a corresponding linear increase in recharge/discharge, loading and change predicted groundwater head compared to the observed.

The impact of changes in aquifer thickness on transport is less quantifiable, but the expectation is no impact on contaminant travel times or on the shapes of pathlines.

5.3 Model Sensitivity to Variations in Areal Recharge (q)

For the fate and transport, as noted in Appendix E, under the discussion of gamma, the possible dilution of contaminant solute concentration at the source by recharge of clean water infiltration is not accounted for. Gamma was set to zero, thereby, simulating a conservative or worst case condition. The average predicted exit concentrations compared to the empirical data without considering areal recharge shows a difference in the magnititude order of 2 to 10. This is within a comfortable threshold based on a range of 0-100.

Average rate of precipitation for the Seattle area is in the range of 30 in/yr (RI Arco, 1994, See Appendix E, Table B-3, for other values evaluated). Sensitivity analysis for the flow model using the 30 in/yr average infiltration, predicted groundwater head elevations twice the empirical data observed in the field. Most of Harbor Island is paved, except for the above ground storage tank areas where the oil companies are located.

Average precipitation rate of 0.04 in/day or 15 in/yr, with an effective porosity of 0.35, and a K value of 7.5 ft/day, and a corresponding aquifer thickness of 35ft. for the island edges and 80 feet at the center, predicted groundwater head elevations comparable to the empirical data observed in the field.

5.4 Model Sensitivity to Variations in Dispersivity (x)

The aquifer dispersivity, x, does appear to have some influence on the maximum exit concentration, however, little or no influence was observed in the travel time-to-the-exit-point. Model sensitivity (Table 4, page 26) shows that the magnitude of effect in variations to dispersivity is in the order of 1 to 2 for the maximum exit concentration.

As noted in Appendix E, Model Descriptions, the number of measured dispersivity values in the scientific literature is fairly small. In the two studies referenced in Appendix E, which were conducted in carefully controlled field experiments in sandy aquifers using tracers, values of ∝x, range from 1.476 to 3.15 feet (0.45 to 0.95 m), and 9.843 to 98.43 feet (3 to 30 m) have been published in nemerical modelling studies where the dispersivity was determined by calibrating the numerical model to field data.

5.5 Model Sensitivity to Variations in Retardation (Rf)

The retardation factor Rf also has a major effect on the maximum exit concentration and the travel time-to-the-exit-point. Rf values are contaminant-specific and are also a function of the type of aquifer material and the amount of contaminant in the soil and groundwater. Appendix E, Model Description, discusses the site specific calculation of the Rf values used for the Princeton Model. Geraghty & Miller's Model set Rf value to 1, indicating no retardation.

Figures 1, and 2 of the Ecolgoy Model, and Geraghty & Miller's Model in Appendix A, shows that increasing retardation has two identifiable effects. One effect is to delay the breakthrough time curve (Ecology's model with retardation, predicts time of arrival to be 2400 days (6.7 yrs), the latter with no retardation predicts time of arrival to be 2300 days, (6.3 yrs). The other effect is the spread of the width of the solute front.

Other variations of Rf presented in Table 4, page 26, models 2 and 3, shows effect on the maximum exit concentration in the magnitude order of 2.6 to 7, and 1.2 magnitude order for the travel time-to-the-exit-point.

5.6 Model Sensitivity to Variations in Velocity (v)

The velocity factor v, also has a major effect on the exit maximum concentration and the travel time-to-the-exit-point. V values are contaminant-specific and are also a function of the type of aquifer material and the amount of contaminant in the soil and groundwater. Appendix E, Model Description, Tables B-1 through B-3, discusses various velocity evaluated and the calculations derived from the RI for the tank farms.

The sensitivity analysis on velocity variations between a maximum of 0.14 ft/day and a minimum 0.04 ft/day (Table 4, page 26, models 2 and 5), shows effect on the contaminant solute travel time-to-the-exit-point in the magnitude order of 1.4 to 2, and 37 to 438 magnitude order effect for the maximum exit concentration.

5.7 Model Sensitivity to Variations in Decay (k)

The decay factor k, also has a major effect on exit maximum concentration, and relatively minimal effect was observed in the travel time-to-the-exit-point. k is first order decay constant in units of 1/T, and it is difficult to determine in the field due to the multitude of factors affecting it. k values are contaminant-specific based on the half life of the contaminant considered over time.

As noted in Appendix E, Model Descriptions and site specific calculations used for this fate and transport, the number of measured k values for benzene, toulene, ethylbenzene, and xylene (BTEX) in the scientific literature is fairly small. In the one study referenced in Appendix E, typical values for BTEX compounds have been reported in the range of 0.0002/day to 0.025/day.

The model sensitivity (Table 4, page 26, model 2: k = 0.001733/day, model 7: k = 0.0002/day, and model 8: k = 0.025/day) shows that the magnitude of effect in variations to k, on exit maximum concentration is in the magnitude order of 3 to 7, for model 2 compared to model 8, and greater than a magnitude order of 720,000 for model 2 compared to model 7. Effect in variations to k, on the travel time-of-the-exit-point is in the magnitude order of less than 1 to 1.

5.8 Model Sensitivity to Variations in Source Duration (T_{off})

Source duration or Time off (T_{off}) is when the concentration along the gaussian distribution source are turned off or set to zero (see Appendix E). For example, the T_{off} of 150 days for the GATX site, modeled for the recent spill at that location (December 6, 1996), represents the assumed time the source was removed (May 6, 1997), thereby, the maximum concentration of 11,800 ug/l benzene detected at the source is simulated as the residual concentration in the groundwater after source removal.

The model sensitivity to variations in source duration (2000 and 3000 days), shows (Table 4, page 26, models 2 and 9) relative little effect on the contaminant solute travel time-to-the-exit-point and the maximum exit concentration in the magnitude order of less than 1 to 1.

Another variation in source duration presented in Appendix C, figures 2 and 3 (2000 days), and figures 2b and 3b (150 days), for GATX shows that the effect in variation to source duartion (Table 6, page 31) is in the magnitude order of 1 to 2 for the travel time-of-the-exit-point and in the magnitude of 8 to 10 for the maximum exit concentration.

5.9 Summary Model Sensitivity

In summary, the sensitivity analysis of the solute fate and transport shows that the following are critical input parameters and will significantly affect the model outcome; velocity, dispersion along the x, and y, directions, retardation and the decay constant.

Velocity effects the maximum concentration as well as the estimated exit travel times. Dispersion was found to effect travel times but little effect on the exit concentration. Retardation delays the breakthrough time curve and reduces the exit concentrations. Introducing decay into the model, reduces the maximum exit concentration with minimal effect on travel time.

TABLE 4

Sensitivity Analysis

Harbor Island Transport Summary (Arco Site Used)

Parameter		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
K =		0	0.0017	0.0017	0.0017	0.0017	0.0017	0.0002	0.025	0.0017
Gamma =		0	0	0	0	0	0	0	0	0
Rd =		1	1.3	2	1.3	1.3	1.3	1.3	1.3	1.3
Dx =		1.5	1.5	1.5	0.5	1.5	1.5	1.5	1.5	1.5
Dy =		0.15	0.15	0.15	0.05	0.15	0.15	0.15	0.15	0.15
Velocity =	ft/day	0.14	0.14	0.14	0.14	0.04	0.1	0.14	0.14	0.14
Theta =		270	270	270	270	270	270	270	270	270
Csource =	ug/l	200	200	200	200	200	200	200	200	200
Tsource =	Days	3000	3000	3000	3000	3000	3000	3000	3000	2000

		Max. Conc. ug/l								
Dist. (feet)	Threshold	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
Source = 0	71	200	200	200	200	200	200	200	200	200
Whouse = 96	71	194	26	10	22	0.7	15	0.000036	74	27
Shorel. = 240	71	185	7	1	5	0.016	3	1.2 E-9	47	7

	Max. Travel Time (days)								
Distance	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
Source = 0	0	0	0	0	0	0	0	0	0
Warehouse = 96	2280	2400	2600	2400	3400	2400	2400	2160	2280
Shoreline = 240	2760	2800	3400	3200	4667	3200	3120	2280	2880

TABLE 4 Cont.

	CHANGE IN SOURCE DURATION							CHANGE IN Rf		
		Max. Conc. ug/l						Max. Conc. ug/l		
Distance	Threshold	Model 1	Model 2	Model 9			Threshold	Model 1	Model 2	Model 3
Source = 0	71	200	200	200			71	200	200	200
Whouse = 96	71	194	26	27			71	194	26	10
Shorel. = 240	71	185	7	7			71	185	7	1
		Travel Time (days)						Travel Time (days)		
Source = 0		0	0	0				0	0	0
Whouse = 96		2280	2400	2280				2280	2400	2600
Shorel. = 240		2760	2800	2880				2760	2800	3400
	CHANGE IN VELOCITY							CHANGE IN Dx, Dy		
		Max. Conc. ug/l						Max. Conc. ug/l *		
Distance	Threshold	Model 1	Model 2	Model 5	Model 6		Threshold	Model 1	Model 4	Model 6
Source = 0	71	200	200	200	200		71	200	200	200
Whouse = 96	71	194	26	0.7	15		71	194	22	15
Shorel. = 240	71	185	7	0.016	3		71	185	5	3
		Travel Time (days)						Travel Time (days)		
Source = 0		0	0	0	0			0	0	0
Whouse = 96		2280	2400	3400	2400			2280	2400	2400
Shorel. = 240		2760	2800	4667	3200			2760	3200	3200
	CHANGE IN DECAY CONSTANT: k									
		Max. Conc. ug/l								
Distance	Threshold	Model 1	Model 2	Model 7	Model 8					
Source = 0	71	200	200	200	200					
Whouse = 96	71	194	26	0.000036	74					
Shorel. = 240	71	185	7	1.2 E-9	47					
		Travel Time (days)								
Source = 0		0	0	0	0					
Whouse = 96		2280	2400	2400	2160					
Shorel. = 240		2760	2800	3120	2280					

6.0 RESULTS

If contamination already exits downgradient from the "source" wells, arrival times will be shorter than those predicted with the model. Each fate and transport pathline starts at the "source" monitoring well and travel times are estimated from that well. The model predictions are best used to predict timeframes in which exceedance will occur, rather than specific dates.

Tables 5, 6, and 7, summarizes the groundwater transport results obtained using values presented in Tables 1, 2, & 3. Tables 5, 6, and 7, shows that groundwater discharge from the tank farms located inland on Harbor Island will not exceed surface water referenced standards at the shoreline. The predicted model results are considered conservative within a threshold magnitude order of 2 to 10 compared to the empirical field data downgradient to the source.

Petroleum products under the warehouse of the ARCO site, Plant No. 1, and at Texaco, by the Shoreline Manifold Area, next to the shorelines are not part of this model consideration. These areas are addressed separately under the remedial action alternatives presented in the cleanup action plan.

6.1 ARCO

The model predicts that benzene molecules (see Appendix B) originating in the groundwater near Tank 11, or specifically from shallow monitoring well GM-14 (MW GM-14s), located approximately 240 feet from the shorelines, with initial concentrations of 200 ug/l, will reach the east side of the warehouse (see site vicinity map, page 10, also see Appendices A & D) in 2400 days or 6.7 years at a maximum concentration of 14.8 ug/l.

The model of Geraghty & Miller that simulated the worst case condition (without retardation) for the site predicted that the same benzene molecule will reach the eastside of the warehouse in 2300 days or 6.3 years at similar concentration.

Ecology's model used site specific retardation factor while Geraghty & Miller did not. Geraghty & Miller's model is limited to the Arco site only (see Appendix E for calculations). Further, it will take 3000 days or 8.22 years according to Ecology's model for the same benzene molecule to reach the shoreline of the Duwamish River West Waterway at a maximum concentration of 2.5 ug/l. The surface water criterion at the point of compliance is 71 ug/l.

The ARCO RI report and the EPA RI shows that the tidal influence from the shoreline extend from 180 to 200 feet inland at the West Waterway of the Duwamish River. This tidally influenced area (see site vicinity map) is confirmed to exhibit groundwater elevation changes. The changes in groundwater elevations near the shoreline create a complex hydrological systems. The changes in groundwater elevation result in changes to the local groundwater velocity. The changes in local groundwater velocity may result in lengthening or shortening travel times for contaminants to reach the shoreline. The changes in local groundwater velocity may also result in the desorbing of cPAHs and other metals absorbed on the soils. The elevation changes may also have localized effects on the geometry of the free product plume beneath the warehouse. Some of the inland wells (180 feet from the shoreline) at the tidally influenced areas, have shown anomalous increases of cPAHs and floating products intermittently.

TABLE 5

ARCO Model Results for Analytical Flow and Mass Transport

PARAMETER	Benzene		
Source	**Units**	**GM-14s**	**AR-03**
Receptors		West Waterway	West Waterway
Source distance to receptor	feet	240	297
Initial concentration	ug/l	200	1100
Criterion at point of compliance: Shoreline	ug/l	71	71
Predicted travel time1	days	2400	2200
Predicted travel time2	days	3400	3480
Modelled distance to receptor	feet	96: E.Warehouse 0.5: Shoreline	200: GM-15 0.5: Shoreline
Maximum predicted exit concentration	ug/l	14.8 at E.Wareh. 2.5 at Shoreline	193 at GM-15 4.4 at Shoreline

1: distance modelled from the source is 144 ft.
2: distance modelled from the source is 239.5 ft.

6.2 GATX

The model predicts that benzene molecules originating in the groundwater near Tanks 42 and 43, or specifically from monitoring well T-17, located approximately 2500 feet from the shoreline of the East Waterway, with initial concentrations of 11,800 ug/l, will reach the 11th. Avenue Southwest street, near MW-12 (see site vicinity map, page 10.), in 2800 days or 7.7 years at a maximum concentration of 312.2 ug/l.

Further, the model also predicts that the same benzene molecule will reach the upland western edge of the Port of Seattle, Terminal 18, property in approximately 4,400 days or 12.1 years at a maximum concentration of 7.6 ug/l. The surface water criterion at the point of compliance is 71 ug/l and the shoreline is approximately 2100 feet from the Terminal 18 upland western property boundary. Please see Appendices C through E, for input calculations and graphical and result outputs. *A depiction of the autocad base map for the GATX site was not available for this case study, due to technical imitations of the software's child memory to accommodate the large size of the base map.*

The model that simulated site conditions for the 150 days since the spill of December 6, 1996 predicts that benzene molecule originating from well T-17, located approximately 2500 feet from the shoreline of the East Waterway, with initial concentrations of 11,800 ug/l, will reach the 11th. Avenue Southwest street, 200 feet away from the source, near MW-12, in 1600 days or 4.4 years at a maximum concentration of 40.8 ug/l. Further, the model predicted that the same benzene molecule will reach the shoreline of the East Waterway, in 21,000 days (57.5 years) at a maximum concentration of 1.4×10^{-17} ug/l.

This is a conservative estimate because the model set gamma to zero, thereby assumed that infiltration was zero at the contaminant solute source. Seattle had a severe winter storm during the time of this spill in December, 1996 and thereafter, January, 1997. The contaminant solute source area is unpaved and subject to dilution from infiltration and futher attenuation at the source and downgradient from the source.

Groundwater samples collected on February 24, 1997, at monitoring well, MW-4, located 100 feet away from the source had a concentration of 0.531 ug/l for benzene, while monitoring well, MW-12, located 200 feet away from the source, was non detect for benzene.

Further, the model also predicts that the same benzene molecule will reach the upland western edge of the Port of Seattle, Terminal 18, property, 400 feet away from the source in approximately 3,200 days or 8.8 years at a maximum concentration of 0.77 ug/l. The surface water criterion at the point of compliance is 71 ug/l and the shoreline is approximately 2100 feet from the Terminal 18 upland western property boundary.

Please see Appendices C through E, for input calculations and graphical and result outputs.

TABLE 6
GATX Model Results for Analytical Flow and Mass Transport

PARAMETER	**Benzene**		
Source	**Units**	T-17	MW-24
Receptors		East Waterway	East Waterway
Source distance to receptor	feet	2500	2550
Initial concentration	ug/l	11,800	4630
Criterion at point of compliance: Shoreline	ug/l	71	71
Predicted travel timel	days	2800	2800
Predicted travel time	days	4400	4400
Predicted T. (2)	days days	1600 3200	
Predicted T. (3)	days	21,000	
Modelled distance to receptor	feet	2300:11th Ave SW 2100:Terminal 18 0.5: Shoreline	2350:11 Ave SW 2150:Termial 18
Maximum predicted exit concentration (1)	ug/l	312.2 at 11 Ave. 7.6 at Terml. 18	122.5 at 11 Ave. 3.0 at Terml. 18
Maximum predicted exit concentration (2)		40.8 at 11 Ave. 0.77 at T. 18	
Maximum predicted exit concentration (3)		1.4 X 10^{-17} at the Shoreline	

(1) model simulated for 2000 days
(2) model simulated for 150 days since the spill of Dec. 6, 1996 - May 6, 1997.
(3) modeled to the shoreline of East Waterway of the Duwamish River

6.3 TEXACO

The model predicts that benzene molecules originating in the groundwater near Tank 80001, or specifically from monitoring well TX-03, located approximately 2900 feet from the shoreline of the Elliott Bay to the north of the island, with initial concentrations of 360 ug/l, will reach Southwest Florida Street (see site vicinity map, page 10.) in 2240 days or 6.1 years at a maximum concentration of 59.5 ug/l.

Further, the model also predicts that the same benzene molecule will reach the edge of the Texaco's North Tank Farm in approximately 2880 days or 7.9 years at a maximum concentration of 9.5 ug/l. The surface water criterion at the point of compliance is 71 ug/l and the shoreline is approximately 2700 feet from the edge of the Texaco's North Tank Farm. Please see Appendices C through E, for input calculations and graphical and result outputs. *A depiction of the autocad base map for the Texaco site was not available for this case study, due to technical imitations of the software's child memory to accommodate the large size of the base map.*

TABLE 7

TEXACO Model Results for Analytical Flow and Mass Transport

PARAMETER	Benzene		
Source	**Units**	TX-03	SH-04
Receptors		Elliott Bay	Elliott Bay
Source distance to receptor	feet	2900	6100
Initial concentration	ug/l	360	8400
Criterion at point of compliance: Shoreline	ug/l	71	71
Predicted travel time1	days	2240	2800
Predicted travel time2	days	2880	5200
Modelled distance to receptor	feet	2800:SW Florida 2700:North Tank	5900:T.Load rack 5600:Beyond rack
Maximum predicted exit concentration	ug/l	60 at SW Florida 10 at North Tank	222 at Load rack 3.0 Beyond rack

1: distance modeled from the source is 200 ft.
2: distance modeled from the source is 500 ft.

7.0 POST AUDIT

As a reality check, predicted exit concentrations are compared with onsite empirical data collected at groundwater monitoring wells located downgradient of the source. Some of these monitoring wells include newly constructed conditional compliance monitoring wells near the shoreline (TEXACO).

Upland areas of the Tank Farms, ARCO, GATX, and TEXACO, presented in this fate and transport simulation are not paved, hence subject to infiltration, dilution, and further degradation. By setting gamma to zero, (assuming no infiltration, dilution, nor further degradation at the solute source, except for the calculated first order decay constant which is a function of the half life of the contaminant solute with time), a conservative or worst case condition is presented in this fate and transport exercise.

High concentrations of cPAH and floating product are observed occasionally in the monitoring wells along the shorelines of the ARCO site on Harbor Island. This area of the Harbor Island Waterway is considered tidally influenced, with high flux, due to groundwater reversals. It is possible that desorbing of CPAH from the soil to groundwater is taking place at this location evidenced by the occasional high concentrations in the groundwater monitoring wells. Floating product are also present in some wells at the Shoreline Manifold Area of the TEXACO site.

7.1 ARCO

The surface water criterion for Benzene at the Shoreline, point of compliance is 71 ug/l. Table 8, page 34, presents the maximum exit concentrations for benzene and the empirical analytical results at downgradient monitoring wells from the source.

The two modeled sources are GM-14s and AR-03. Monitoring wells GM-11s, and GM-15s are respectively downgradient from the sources.

The first model source predicted that a benzene molecule originating from GM-14s will reach the approximate location of GM-11s at a maximum concentration of 14.8 ug/l. Empirical data of November 1996, at GM-11s, detected benzene at a concentration of 165 ug/l.

GM-11s is located in a tidally influenced area and is affected by the floating product under the warehouse. The floating product under the warehouse is not considered in this case study, but is addressed in the remedial action alternative presented in the cleanup action plan (CAP) for this site. GM-11s is approximately 100 feet from the shoreline, Arco remedial investigation report shows that the tidal influence extends 180 feet inland measured from the shoreline at this location of the West Waterway of the Duwamish River.

The observed differences in the benzene concentration, between the predicted exit concentration and the empirical field data, at this location, is anomalous, and is attributed to tidal influences and effects of the tide on the floating product under the warehouse.

The second model source predicted that a benzene molecule originating from AR-03 will reach the approximate location of GM-15s at a maximum concentration of 193 ug/l. GM-11s is located 200 feet from the shoreline and considered to be loacted outside the tidally influenced area. Empirical data of November 1996, at GM-15s, detected benzene at a concentration of 10.9 ug/l.

The model's prediction is conservative because, gamma, was set to zero, indicating no infiltration at the solute source. However, the above ground tank storage areas are unpaved, therefore, are subject to infiltration and further attenuation.

TABLE 8
ARCO Post Model Audit for Analytical Flow and Mass Transport

PREDICTED	**MAX. CONC.**	**EMPIRICAL**	**SITE DATA -**	**AGED SPILL**	**SINCE 1988**
Source	Conc. ug/l Benzene	**Nearest Wells Down Gradient**	Conc. ug/l: Analytical Results/date	**Shoreline Compliance Wells.**	Conc. ug/l: Analytical Results/date
GM-14s (1)	14.8	*GM-11s	*165: Nov.1996	None at this time	Not applicable
GM-14s (2)	9.5	-	-	"	"
AR-03 (1)	193	GM-15s	10.9: Nov.1996	"	"
AR-03 (2)	4.4	-	-	"	"

* located at tidally influenced area and affected by floating product under the warehouse (see site vicinity map, page 10)

7.2 GATX

The surface water criterion for Benzene at the Shoreline, the assumed point of compliance for this fate and transport is 71 ug/l. Table 9, page 36, presents the maximum exit concentrations for benzene and the empirical analytical results at downgradient monitoring wells from the source. This model did not consider the sever winter storm of December 1996, and January 1997, that effected the contaminant solute source, in terms of infiltration from precipitation, dilution, and attenuation at the unpaved modleled domain. Therefore, the predictions presented in this model are considered conservative or worst case condition.

The two modeled sources are T-17 and MW-24. Monitoring wells MW-4, MW-12, and MW-13 are downgradient from the sources.

The first (1) model (2000 days for 200 feet) predicted that a benzene molecule originating from T-17 will reach the 11th Avenue Southwest, next to MW-12, 200 feet away from the source, at a maximum concentration of 312.2 ug/l. Empirical data of February 24, 1997, at the property boundary, next to MW-4, located 100 feet away from the source, detected benzene at a concentration of 0.531 ug/l. Benzene was not detected at MW-12.

The second (2) model (150 days for 200 feet) presents a different source duration that reflects the spill at the source location of December 6, 1996, through an assumed remediation time of May 6, 1997.

The model predicted that a benzene molecule originating from T-17 will reach the approximate location of the 11th Avenue Southwest, next to MW-12, 200 feet away from the source, at a maximum concentration of 40.8 ug/l in 4 years. Empirical data of February 24, 1997, at the property boundary, next to MW-4, located 100 feet away from the source, detected benzene at a concentration of 0.531 ug/l. Benzene was not detected at MW-12. Further, the model predicted that the same benzene molecule will reach the shoreline of the East Waterway in 57.5 years, at a maximum concentration of 1.4×10^{-17} ug/l.

The magnitude of effect in variations to the source duration (150 - 2000 days) is in the order of 1 to 2 on the travel time-of-the-exit-point, and 8 to 10 order on maximum exit concentration. However, the magnitude of effect in variations to the source duration (2000 - 3000 days) is in the order of less than 1 to 1 on both maximum exit concentration and travel time-to-the-exit-point.

TABLE 9
GATX Post Model Audit for Analytical Flow and Mass Transport

PREDICTED MAX. CONC.		**EMPIRICAL SITE DATA - (Dec. 1996 FRESH SPILL)**			
Source	Conc. ug/l Benzene	**Nearest Wells Down Gradient**	Conc. ug/l: Analytical Results/date	**Shoreline Compliance Wells.**	Conc. ug/l: Analytical Results/date
TX-17 (1) TX-17 (2)	312.2 40.8	MW-4	0.531: 2/24/97	None at this time	Not Applicable
TX-17 (3) TX-17 (4)	7.6 0.77	MW-12	ND: 2/24/97	"	"
TX-17 (5)	1.4×10^{-17}	Shoreline	-	"	"
MW-24 (6)	122.5	MW-4	0.531: 2/24/97	"	"
MW-24 (7)	3.0	MW-13	ND: 2/24/97	"	"

ND = None Detected

(1) modeled for 2000 days and 200ft from the source, MW-4 is 100ft from source

(2) modeled for 150 days and 200ft. from the source, "

(3) modeled for 2000 days and 400ft from the source, MW-12 is 200ft from source

(4) modeled for 150 days and 400ft. from the source, "

(5) modeled for 150 days and 2499.5 feet from the source.

(6 & 7) modeled for 2000 day at 200 & 400ft from the source, MW-4 & 13 are 100 and 200 feet respectively, from the sources.

7.3 TEXACO

The surface water criterion for Benzene at the Shoreline, the assumed point of compliance for this fate and transport is 71 ug/l. Table 10, below, presents the maximum exit concentrations for benzene and the empirical analytical results at downgradient monitoring wells from the source. TEXACO is located at the center of the island, and (TEXACO RI,) is least affected by tidal influences at the upland Main Office area.

The two modeled sources are TX-03 and SH-04. Monitoring wells MW-202, 203, MW-05, and MW-11 are downgradient from the sources. Conditional Compliance monitoring wells at the shoreline are MW-213, and MW-214.

The first (1) model (2000 days for 100 feet) predicted that a benzene molecule originating from TX-03 will reach the Southwest Florida Street at a maximum concentration of 59.9 ug/l. The nearest well to Florida Street, is MW-202, located in the North Tank Farm, 300 feet away from the source. Empirical data of December 1993, from MW-202 detected benzene at a concentration of 30.0 ug/l. Benzene was not detected at MW-213 and MW-214 conditional compliance monitoring wells near the shoreline.

The magnitude order of difference between the predicted and empirical maximum concentration is in the order of 2.

A second monitoring well located in the vicinity is MW-203, about 400 feet away from the source, have benzene concentrations of 5.4 ug/l (December 1993).

TABLE 10
TEXACO Post Model Audit for Analytical Flow and Mass Transport

PREDICTED	**MAX. CONC.**	**EMPIRICAL**	**SITE DATA -**	**AGED SPILL**	**SINCE 1992**
Source	Conc. ug/l Benzene	**Nearest Wells Down Gradient**	Conc. ug/l: Analytical Results/date	**Shoreline Compliance Wells.**	Conc. ug/l: Analytical Results/date
TX-03 (1)	59.5	MW-202	30 : Dec. 1993	MW-213	ND: April 8, 1997
TX-03 (2)	9.5	MW-203	5.4: Dec. 1993	MW-214	ND:April '97
SH-04 (1)	222	MW-11	111: Sept.1993	MW-213	ND:April '97
SH-04 (2)	0.84	MW-05	0.5: Sept.1993	MW-214	ND:April '97

Criteria for Benzene at the Shoreline, point of compliance = 71 ug/l.
ND = None Detected

8.0 CONCLUSION

The model predictions presented in this case study, indicate that discharge of benzene, the most mobile of the petroleum hydrocarobon indicator parameters from the upland or inland locations of the tank farms on Harbor Island (ARCO, GATX, & TEXACO), will not impact the surface water surrounding the island at concentrations exceeding standards and are not likely within 57 years and about 6 years for the near shore location (ARCO Plant 1).

The magnitude order of difference between the predicted exit concentration and the empirical data measured in the field are within a comfort level range of 2 to 10, based on a range of 0-100. The model predictions presented in this article are considered conservative.

9.0 REFERENCES

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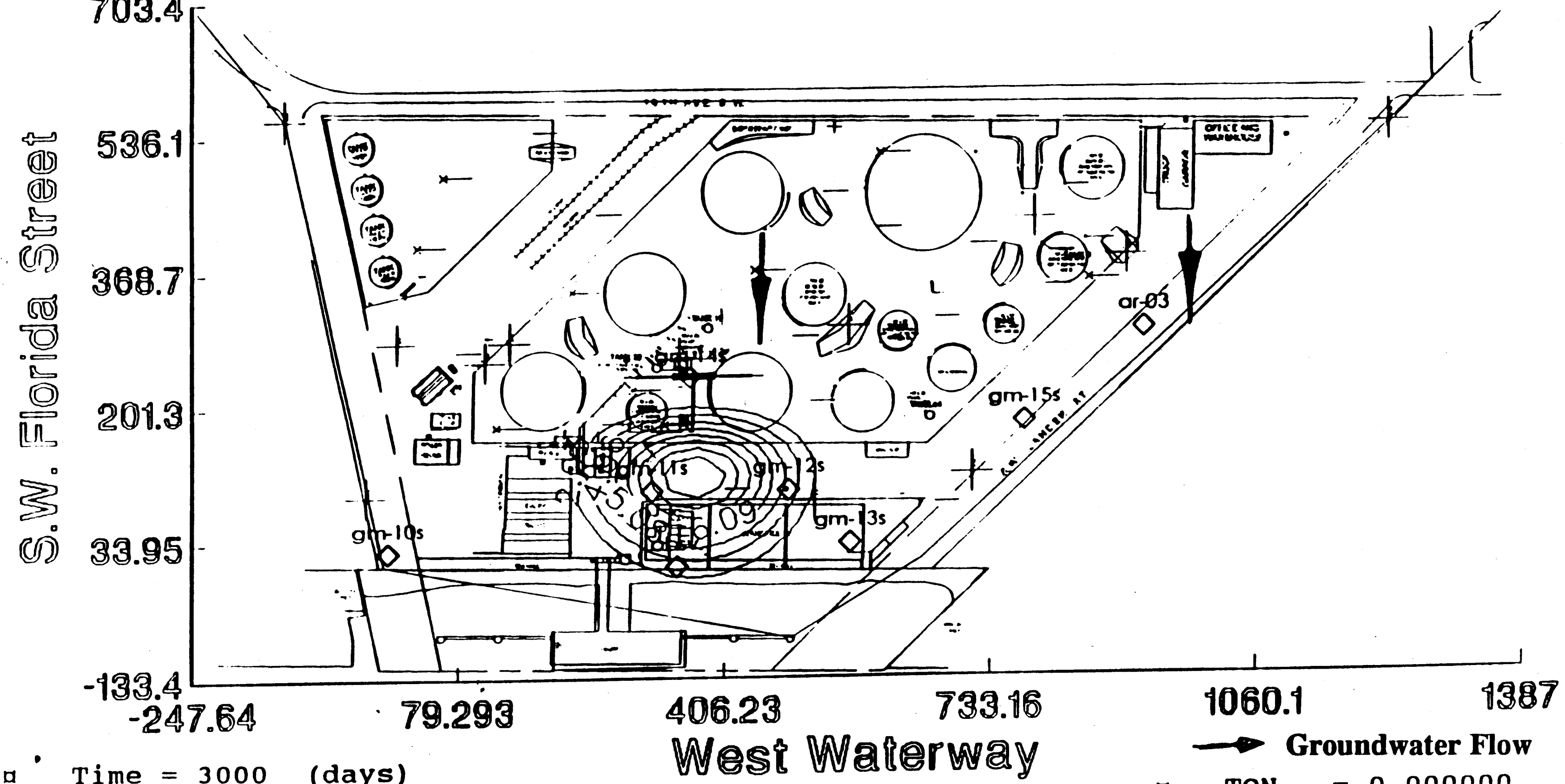
APPENDIX. A

ARCO FATE & TRANSPORT
BASE MAP GRAPH OUTPUT-PRINCETON ANALYTICAL MODEL

Princeton Analytical Models of Flow and Mass Transport

ARCO FATE & TRANSPORT

Fig. 1: Arco GM-14s Benzene Transpt



¤ Time = 3000 (days)

¤ K = 0.001733
¤ GAMMA = 0.000000
¤ RD = 1.300000
¤ X0 = 369.000000
¤ Y0 = 240.000000

¤ DX = 1.500000
¤ DY = 0.150000
¤ V = 0.100000
¤ THETA = 270.000000

¤ TON = 0.000000
¤
¤ TOFF = 2000.000000
¤ S = 80.000000
¤ CP = 200.000000

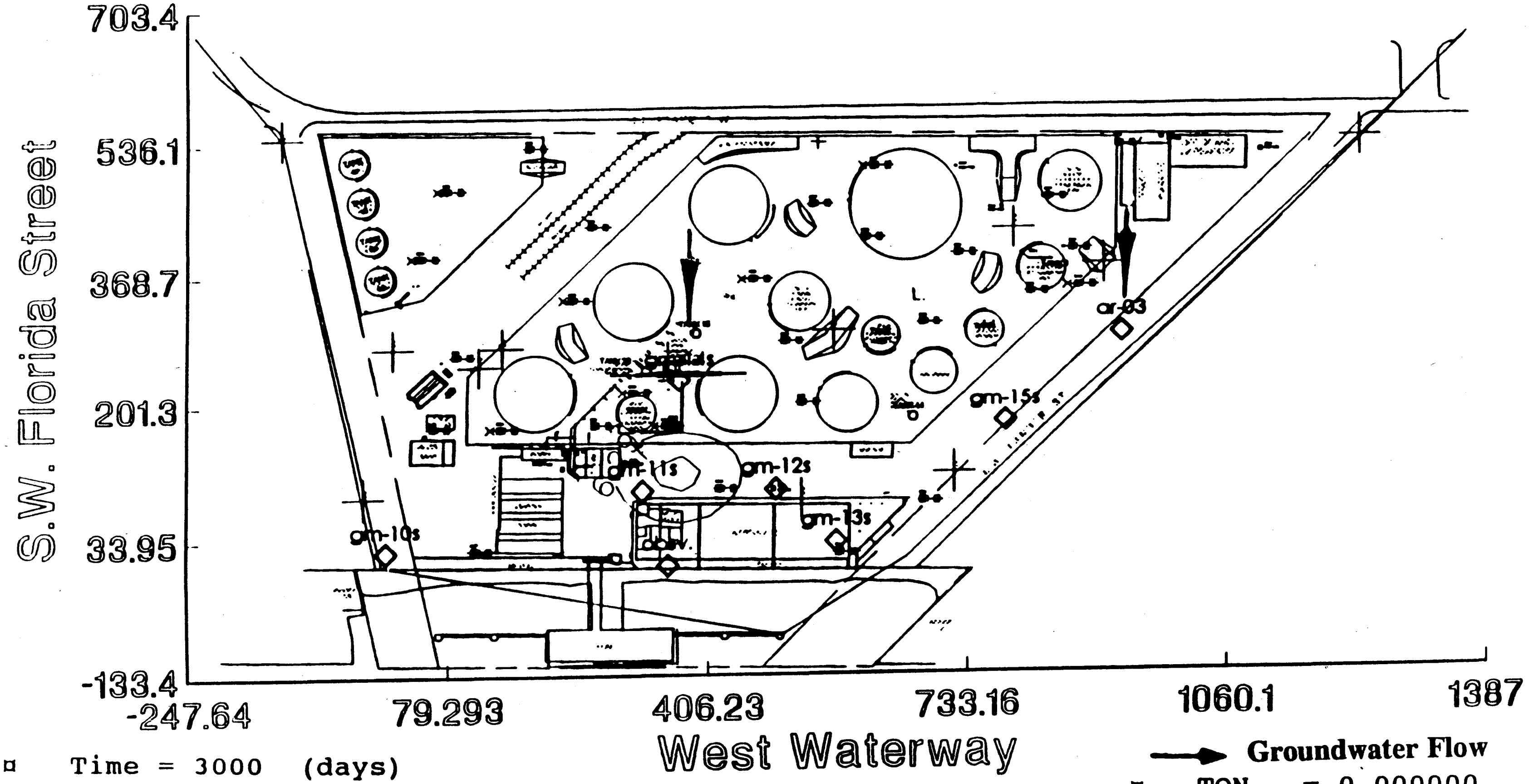
MODELLER: Nnamdi Madakor

Dept. Ecology, Toxics Cleanup Program, NWRO
Date: April 28, 1997

Princeton Analytical Models of Flow and Mass Transport

ARCO FATE & TRANSPORT

Model 1: ARCO GM-14s Benzene F/Tras



→ Groundwater Flow

¤ Time = 3000 (days)

¤ K = 0.001733
¤ GAMMA = 0.000000
¤ RD = 1.300000
¤ XO = 369.000000
¤ YO = 240.000000

¤ DX = 1.500000
¤ DY = 0.150000
¤ V = 0.100000
¤ THETA = 270.000000

¤ TON = 0.000000
¤
¤ TOFF = 2000.000000
¤ S = 80.000000
¤ CP = 200.000000

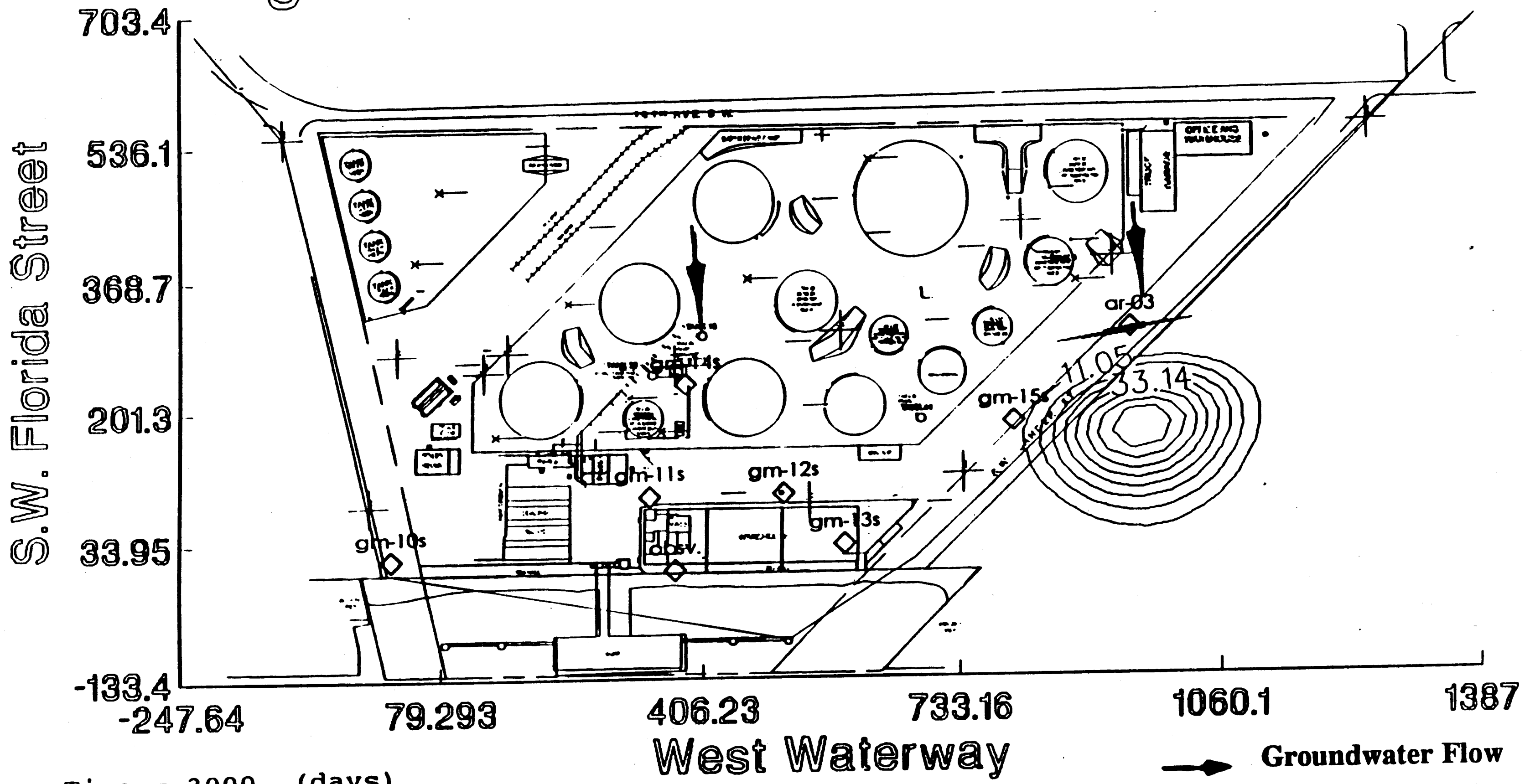
MODELLER: Nnamdi Madakor

Dept. Ecology, Toxics Cleanup Program, NWRO
Date: April 28, 1997

Princeton Analytical Models of Flow and Mass Transport

ARCO FATE & TRANSPORT

Fig. 2: Arco AR-03 Benzene Transpt.



¤ Time = 3000 (days)
¤ K = 0.001733
¤ GAMMA = 0.000000
¤ RD = 1.300000
¤ X0 = 938.000000
¤ Y0 = 297.000000

¤ DX = 1.500000
¤ DY = 0.150000
¤ V = 0.100000
¤ THETA = 280.000000

¤ TON = 0.000000
¤
¤ TOFF = 2000.000000
¤ S = 80.000000
¤ CP = 1100.000000

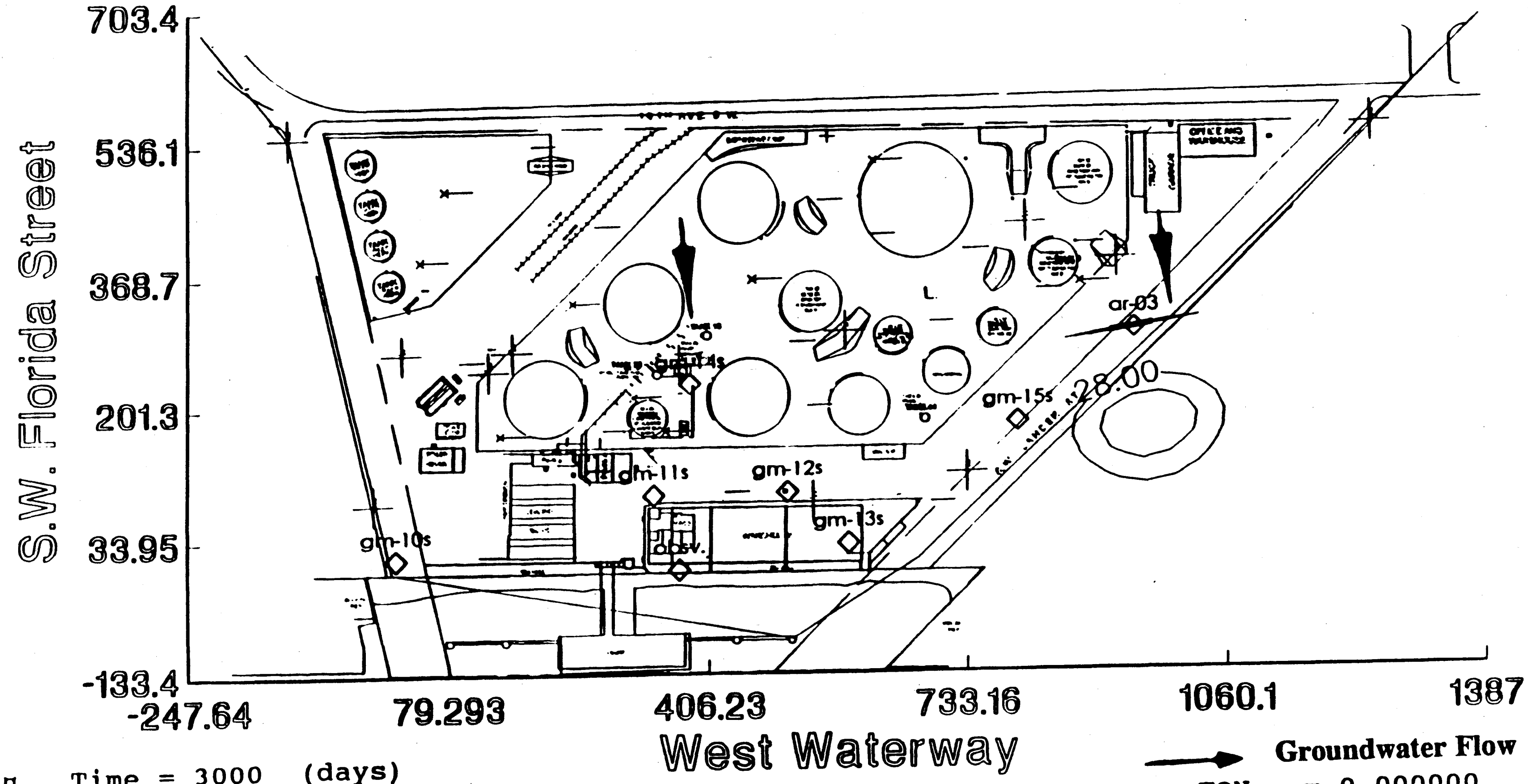
MODELLER: Nnamdi Madakor

Dept. Ecology, Toxics Cleanup Program, NWRO
Date: April 28, 1997

Princeton Analytical Models of Flow and Mass Transport

ARCO FATE & TRANSPORT

Model 2: ARCO AR-03 Benzene F/Trans



¤ Time = 3000 (days)
¤ K = 0.001733
¤ GAMMA = 0.000000
¤ RD = 1.300000
¤ X0 = 938.000000
¤ Y0 = 297.000000

¤ DX = 1.500000
¤ DY = 0.150000
¤ V = 0.100000
¤ THETA = 280.000000

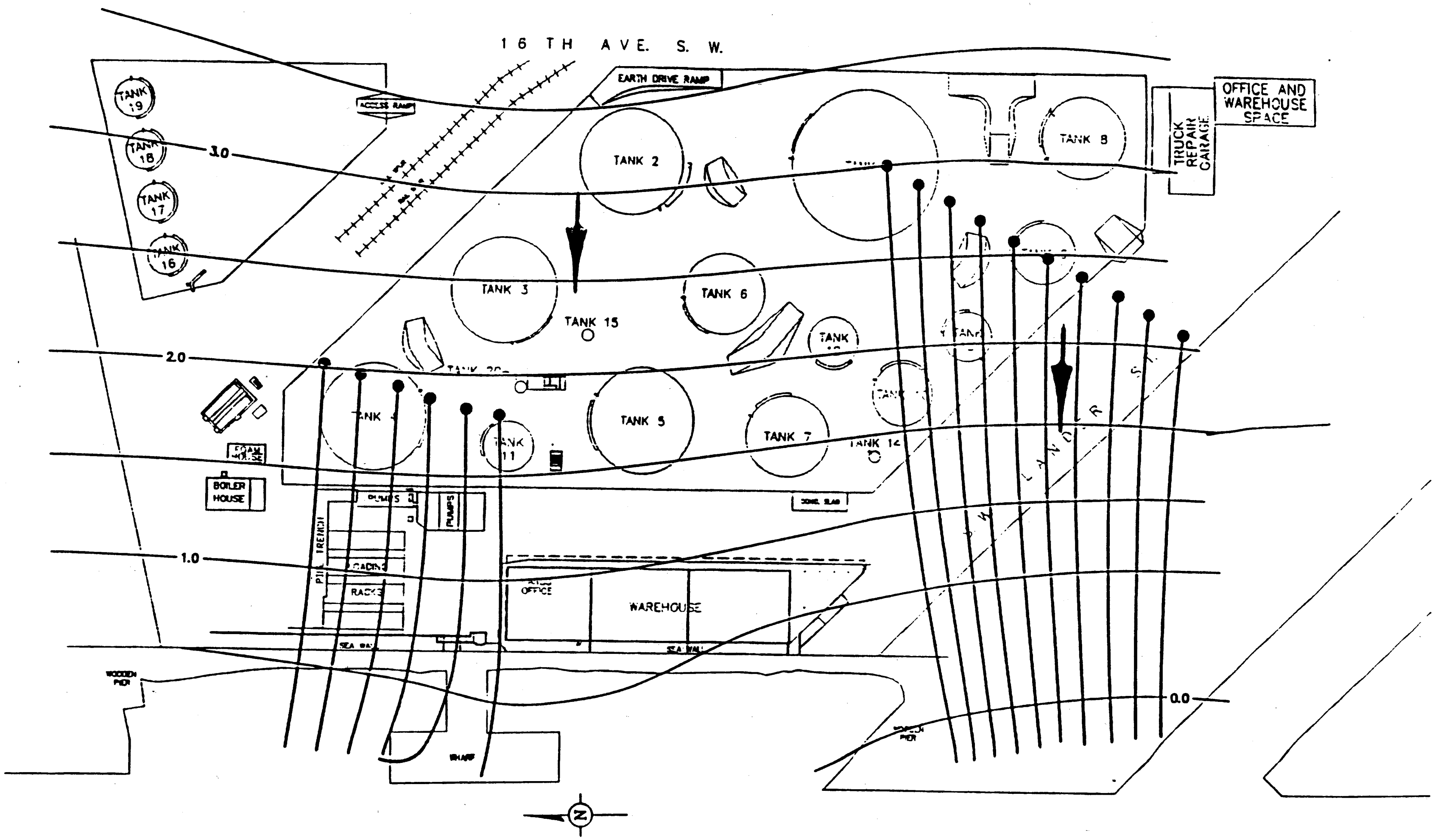
¤ TON = 0.000000
¤
¤ TOFF = 2000.000000
¤ S = 80.000000
¤ CP = 1100.000000

MODELLER: Nnamdi Madakor

Dept. Ecology, Toxics Cleanup Program, NWRO
Date: April 28, 1997

APPENDIX. B

ARCO FATE & TRANSPORT
BASE MAP GRAPH OUTPUT-GERAGHTY & MILLER MODFLOW



LEGEND

- GROUNDWATER ELEVATION
- ● PARTICLE TRACK

→ **Groundwater Flow**

GERAGHTY & MILLER, INC.
Environmental Services

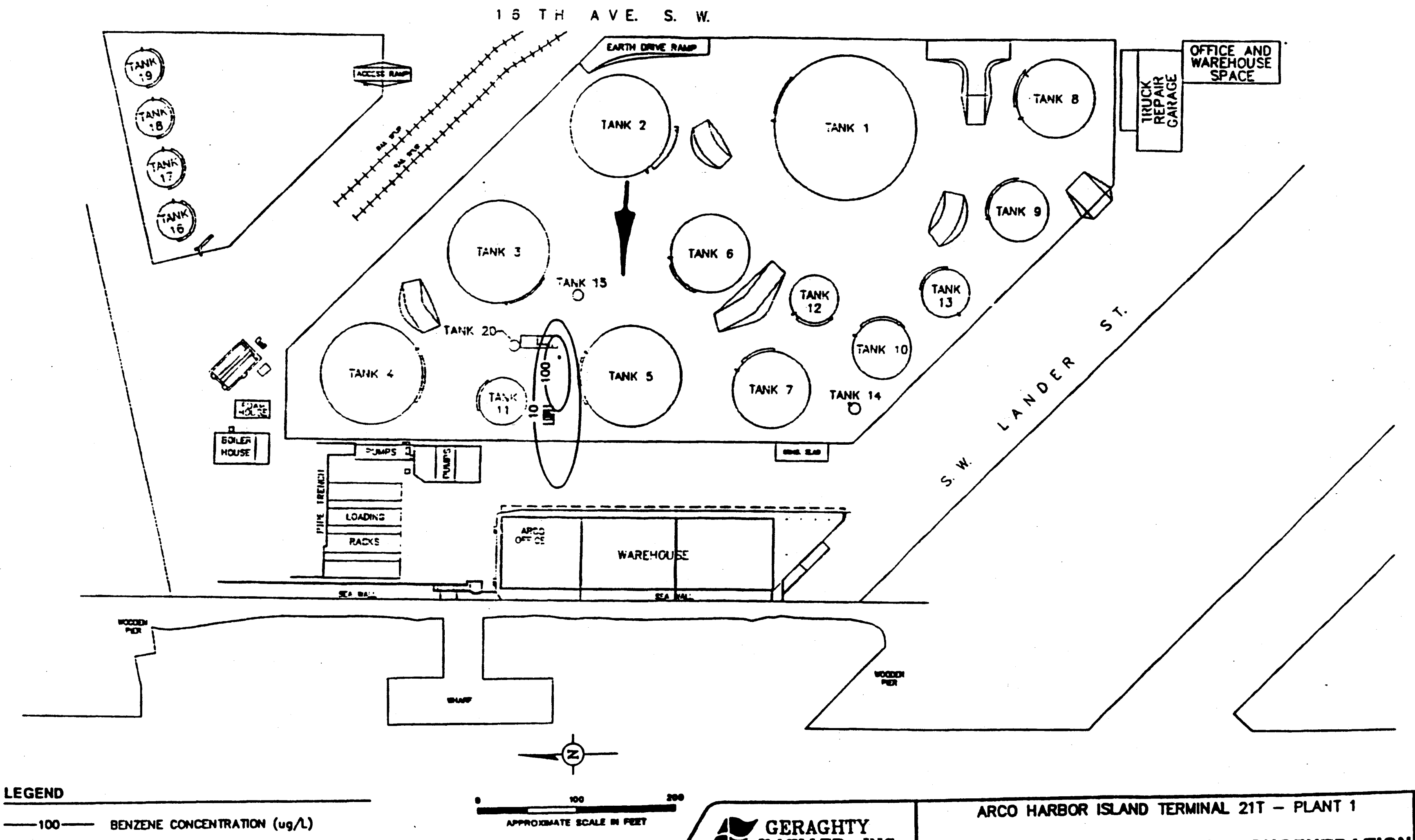
DRAWING NO. 400-303

ARCO HARBOR ISLAND TERMINAL 21T – PLANT 1

PARTICLE TRACES SHOWING PATHWAYS

FIGURE
2-10

FILENAME: S11433\11433CD2.DWG CREATED: MAY 07 1993 09:16:22 UPDATED: NOV 04 1996 14:21:33 PLOTTED: DEC 04 1996 13:37:51 (VS831/N)



→ Groundwater Flow

GERAGHTY & MILLER, INC.
Environmental Services

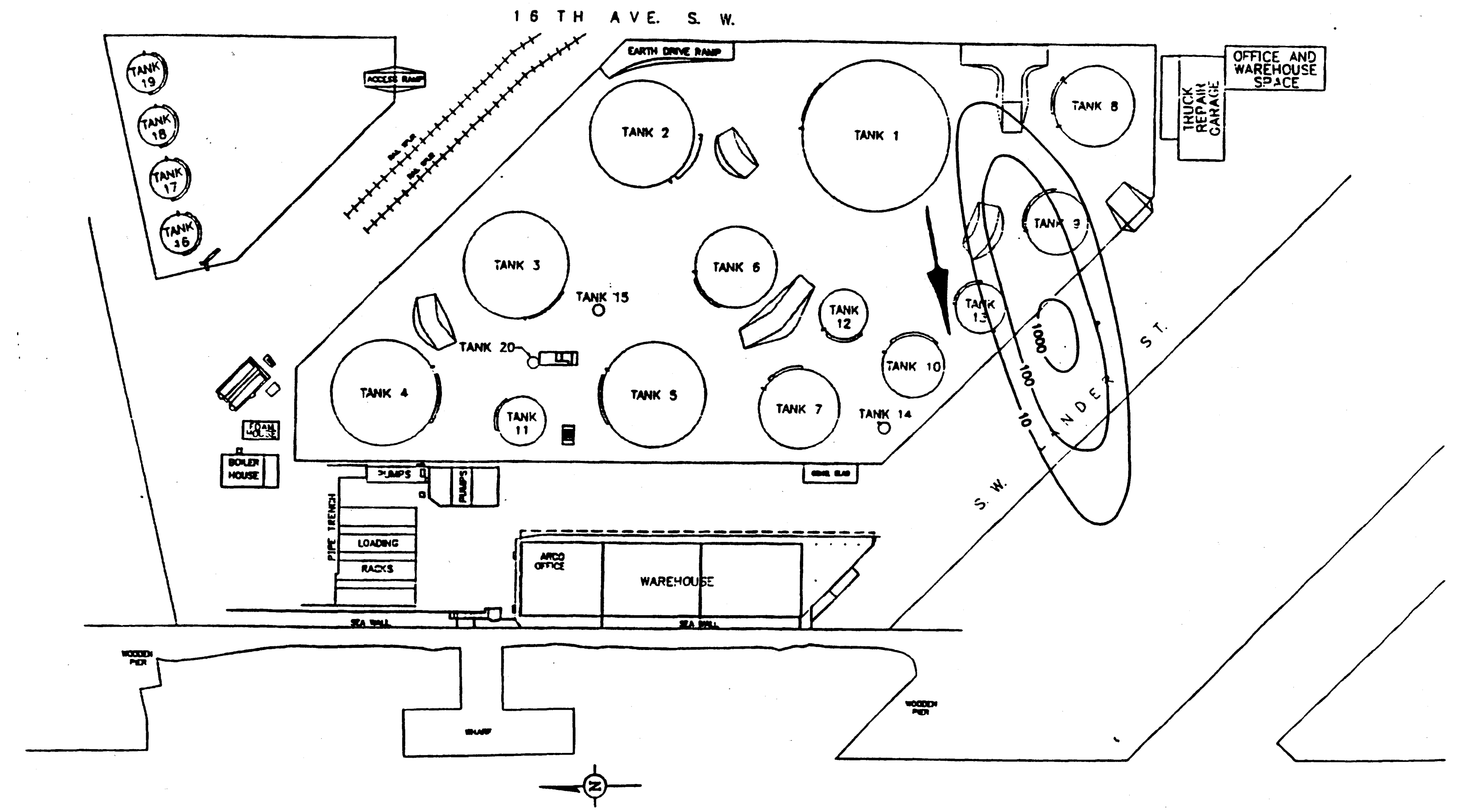
DRAWING NO. 400-304

ARCO HARBOR ISLAND TERMINAL 21T – PLANT 1

TRANSPORT MODEL INITIAL CONCENTRATION NEAR TANK 11

FIGURE 2-11

FILENAME: S11433\11433CD2.DWG CREATED: MAY 07 1993 09:16:22 UPDATED: NOV 04 1996 14:21:33 PLOTTED: DEC 04 1996 13:37:51 (VSB31/N)



LEGEND

——100—— BENZENE CONCENTRATION (ug/L)

→ **Groundwater Flow**

0 100 200
APPROXIMATE SCALE IN FEET

GERAGHTY & MILLER, INC.
Environmental Services

DRAWING NO. 400-305

ARCO HARBOR ISLAND TERMINAL 21T – PLANT 1

TRANSPORT MODEL INITIAL CONCENTRATION NEAR TANK 9

FIGURE 2-12

FILENAME: S11433\11433C02.DWG CREATED: MAY 07 1993 09:16:22 UPDATED: NOV 04 1996 14:21:33 PLOTTED: DEC 04 1996 13:37:51 (VS831/N)

APPENDIX. C

ARCO, GATX, and TEXACO, FATE & TRANSPORT ANALYTICAL OUTPUT GRAPHS and REPORT FILES

ARCO

ARCO OIL HI. Analytical Fate & Transport Modeling (benzene) at GM-14s

Fig.1: ARCO GM-14s at Hot Spot

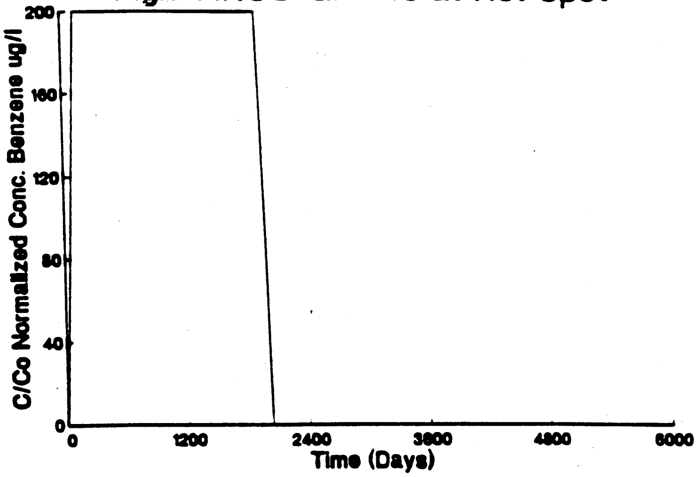


Fig.2: GM-14s at E.Warehouse, 96ft.

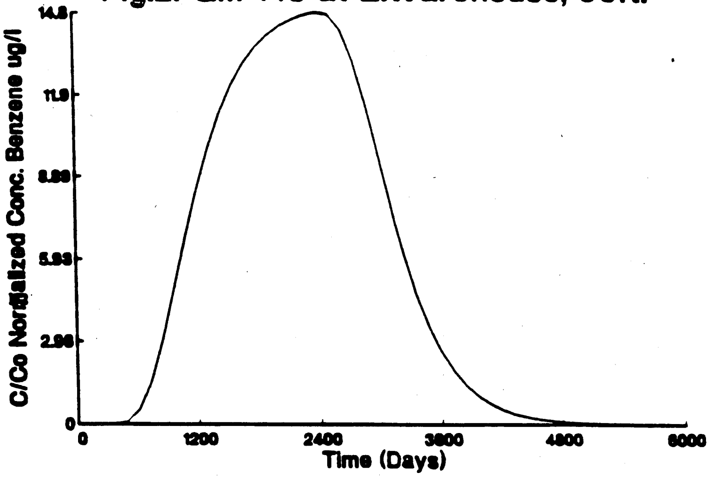
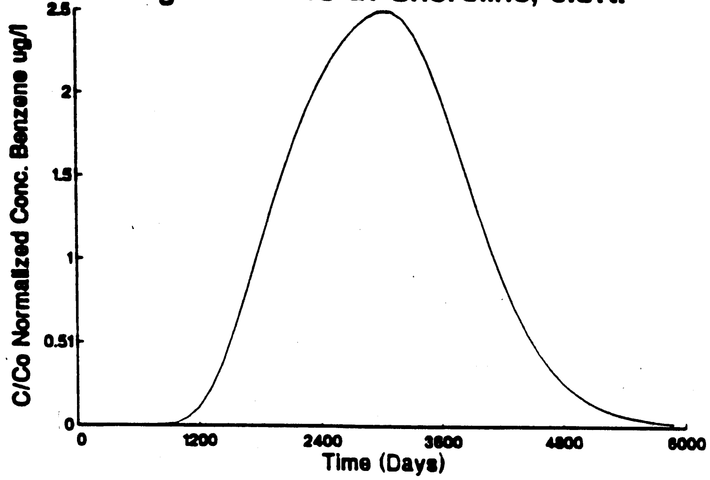


Fig.3: GM-14s at Shoreline, 0.5ft.



Department of Ecology
Toxics Cleanup Program, NWRO

Modeler: Nnamdi Madakor
Date: April 28, 1997

Fig.1: ARCO GM-14s at Hot Spot

```
                THE  PRINCETON  MODELS

                  2D MT Gaussian B.C.

                        MODEL 5


K     = 0.001733
GAMMA = 0.000000
RD    = 1.300000
X0    = 369.000000
Y0    = 240.000000
DX    = 1.500000
DY    = 0.150000
V     = 0.100000
THETA = 270.000000
TON   = 0.000000

TOFF  = 2000.000000
S     = 80.000000
CP    = 200.000000


X-coor = 369.00     Y-coor = 240.00


      T              CONC

      0           0.0000e+00
    120           2.0000e+02
    240           2.0000e+02
    360           2.0000e+02
    480           2.0000e+02
    600           2.0000e+02
    720           2.0000e+02
    840           2.0000e+02
    960           2.0000e+02
    1080            2.0000e+02
    1200            2.0000e+02
    1320            2.0000e+02
    1440            2.0000e+02
    1560            2.0000e+02
    1680            2.0000e+02
    1800            2.0000e+02
    1920            2.0000e+02
    2040            0.0000e+00
    2160            0.0000e+00
    2280            0.0000e+00
    2400            0.0000e+00
    2520            0.0000e+00
    2640            0.0000e+00
    2760            0.0000e+00
    2880            0.0000e+00
    3000            0.0000e+00
    3120            0.0000e+00
    3240            0.0000e+00
```

Fig.2: GM-14s at E.Warehouse, 96ft.

```
                THE   PRINCETON   MODELS

                     2D MT Gaussian B.C.

                          MODEL 5


K     = 0.001733
GAMMA = 0.000000
RD    = 1.300000
X0    = 369.000000
Y0    = 240.000000
DX    = 1.500000
DY    = 0.150000
V     = 0.100000
THETA = 270.000000
TON   = 0.000000

TOFF  = 2000.000000
S     = 80.000000
CP    = 200.000000


X-coor = 369.00      Y-coor =  96.00


     T             CONC

     0           0.0000e+00
   120           8.5253e-14
   240           1.1458e-05                    3360          4.7267e+00
   360           5.1505e-03                    3480          3.5563e+00
   480           9.7827e-02                    3600          2.6335e+00
   600           5.2394e-01                    3720          1.9250e+00
   720           1.4941e+00                    3840          1.3924e+00
   840           2.9825e+00                    3960          9.9837e-01
   960           4.7822e+00                    4080          7.1075e-01
   1080            6.6502e+00                  4200          5.0297e-01
   1200            8.4001e+00                  4320          3.5417e-01
   1320            9.9257e+00                  4440          2.4834e-01
   1440            1.1189e+01                  4560          1.7352e-01
   1560            1.2194e+01                  4680          1.2088e-01
   1680            1.2973e+01                  4800          8.3997e-02
   1800            1.3561e+01                  4920          5.8240e-02
   1920            1.3999e+01                  5040          4.0306e-02
   2040            1.4320e+01                  5160          2.7850e-02
   2160            1.4552e+01                  5280          1.9218e-02
   2280            1.4719e+01                  5400          1.3245e-02
   2400            1.4821e+01                  5520          9.1198e-03
   2520            1.4733e+01                  5640          6.2738e-03
   2640            1.4198e+01                  5760          4.3128e-03
   2760            1.3082e+01                  5880          2.9628e-03
   2880            1.1492e+01                  6000          2.0343e-03
   3000            9.6642e+00
   3120            7.8329e+00
   3240            6.1595e+00
```

Fig.3: GM-14s at Shoreline, 0.5ft.

```
                    THE   PRINCETON   MODELS

                       2D MT Gaussian B.C.

                             MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 369.000000
Y0     = 240.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 200.000000


X-coor = 369.00      Y-coor =    0.50


    T              CONC

    0          0.0000e+00
  120          2.3696e-41
  240          7.2244e-19                 3360          2.3838e+00
  360          1.9516e-11                 3480          2.2262e+00
  480          8.9317e-08                 3600          2.0260e+00
  600          1.2616e-05                 3720          1.7980e+00
  720          3.1272e-04                 3840          1.5585e+00
  840          2.8689e-03                 3960          1.3219e+00
  960          1.4156e-02                 4080          1.0994e+00
 1080          4.6261e-02                 4200          8.9837e-01
 1200          1.1348e-01                 4320          7.2260e-01
 1320          2.2636e-01                 4440          5.7309e-01
 1440          3.8730e-01                 4560          4.4884e-01
 1560          5.8997e-01                 4680          3.4762e-01
 1680          8.2178e-01                 4800          2.6655e-01
 1800          1.0675e+00                 4920          2.0257e-01
 1920          1.3126e+00                 5040          1.5272e-01
 2040          1.5453e+00                 5160          1.1432e-01
 2160          1.7573e+00                 5280          8.5022e-02
 2280          1.9441e+00                 5400          6.2867e-02
 2400          2.1040e+00                 5520          4.6242e-02
 2520          2.2377e+00                 5640          3.3852e-02
 2640          2.3472e+00                 5760          2.4676e-02
 2760          2.4346e+00                 5880          1.7916e-02
 2880          2.4999e+00                 6000          1.2962e-02
 3000          2.5378e+00
 3120          2.5377e+00
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ARCO OIL HI. Analytical Fate & Transport Modeling (benzene) at AR-03

Fig. 1: ARCO AR-03 at Hot Spot

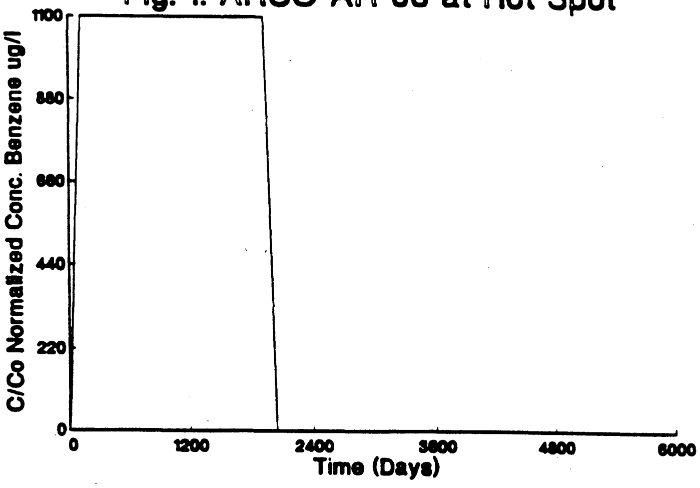


Fig. 2: ARCO AR-03 at 100ft./GM-15s

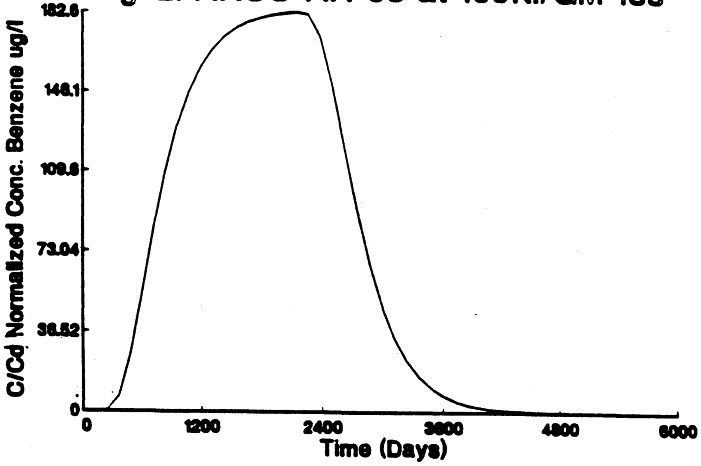
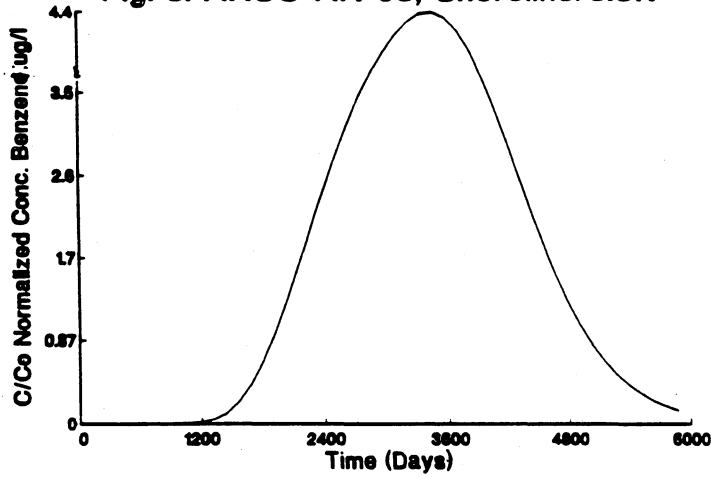


Fig. 3: ARCO AR-03, Shoreline/0.5ft



Department of Ecology
Toxics Cleanup Program, NWRO

Modeler: Nnamdi Madakor
Date: April 28, 1997

Fig. 1: ARCO AR-03 at Hot Spot

```
                    THE  PRINCETON  MODELS

                     2D MT Gaussian B.C.

                          MODEL 5


K     = 0.001733
GAMMA = 0.000000
RD    = 1.300000
X0    = 938.000000
Y0    = 297.000000
DX    = 1.500000
DY    = 0.150000
V     = 0.100000
THETA = 280.000000
TON   = 0.000000

TOFF  = 2000.000000
S     = 80.000000
CP    = 1100.000000


X-coor = 938.00     Y-coor = 297.00


     T            CONC

     0         0.0000e+00
   120         1.1000e+03
   240         1.1000e+03
   360         1.1000e+03
   480         1.1000e+03
   600         1.1000e+03
   720         1.1000e+03
   840         1.1000e+03
   960         1.1000e+03
  1080          1.1000e+03
  1200          1.1000e+03
  1320          1.1000e+03
  1440          1.1000e+03
  1560          1.1000e+03
  1680          1.1000e+03
  1800          1.1000e+03
  1920          1.1000e+03
  2040          0.0000e+00
  2160          0.0000e+00
  2280          0.0000e+00
  2400          0.0000e+00
  2520          0.0000e+00
  2640          0.0000e+00
  2760          0.0000e+00
  2880          0.0000e+00
  3000          0.0000e+00
  3120          0.0000e+00
  3240          0.0000e+00
```

Fig. 2: ARCO AR-03 at 100ft./GM-15s

```
                    THE   PRINCETON   MODELS

                      2D MT Gaussian B.C.

                            MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
XO     = 938.000000
YO     = 297.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 280.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 1100.000000


X-coor = 938.00      Y-coor = 197.00


    T            CONC

    0          0.0000e+00
  120          6.6065e-05
  240          4.2264e-01
  360          7.0227e+00                  3360          1.6204e+01
  480          2.6201e+01                  3480          1.1082e+01
  600          5.3992e+01                  3600          7.5433e+00
  720          8.3145e+01                  3720          5.1169e+00
  840          1.0899e+02                  3840          3.4623e+00
  960          1.2980e+02                  3960          2.3386e+00
 1080          1.4561e+02                  4080          1.5776e+00
 1200          1.5718e+02                  4200          1.0633e+00
 1320          1.6543e+02                  4320          7.1628e-01
 1440          1.7122e+02                  4440          4.8236e-01
 1560          1.7523e+02                  4560          3.2478e-01
 1680          1.7799e+02                  4680          2.1868e-01
 1800          1.7987e+02                  4800          1.4726e-01
 1920          1.8116e+02                  4920          9.9181e-02
 2040          1.8202e+02                  5040          6.6817e-02
 2160          1.8260e+02                  5160          4.5026e-02
 2280          1.8157e+02                  5280          3.0352e-02
 2400          1.7124e+02                  5400          2.0468e-02
 2520          1.4857e+02                  5520          1.3808e-02
 2640          1.1971e+02                  5640          9.3183e-03
 2760          9.1394e+01                  5760          6.2911e-03
 2880          6.7204e+01                  5880          4.2491e-03
 3000          4.8151e+01                  6000          2.8710e-03
 3120          3.3881e+01
 3240          2.3538e+01
```

Fig. 3: ARCO AR-03, Shoreline/0.5ft

```
                THE   PRINCETON   MODELS

                   2D MT Gaussian B.C.

                         MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 938.000000
Y0     = 297.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 280.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 1100.000000


X-coor = 938.00      Y-coor =    0.50


    T             CONC

    0          0.0000e+00
  120          0.0000e+00               3360          4.3355e+00
  240          1.7542e-28               3480          4.3563e+00
  360          2.0933e-17               3600          4.3015e+00
  480          6.3460e-12               3720          4.1655e+00
  600          1.1053e-08               3840          3.9512e+00
  720          1.4563e-06               3960          3.6695e+00
  840          4.3863e-05               4080          3.3372e+00
  960          5.2542e-04               4200          2.9745e+00
 1080          3.4060e-03               4320          2.6011e+00
 1200          1.4378e-02               4440          2.2344e+00
 1320          4.4475e-02               4560          1.8881e+00
 1440          1.0908e-01               4680          1.5714e+00
 1560          2.2406e-01               4800          1.2898e+00
 1680          4.0086e-01               4920          1.0453e+00
 1800          6.4298e-01               5040          8.3747e-01
 1920          9.4498e-01               5160          6.6390e-01
 2040          1.2940e+00               5280          5.2127e-01
 2160          1.6729e+00               5400          4.0570e-01
 2280          2.0630e+00               5520          3.1324e-01
 2400          2.4474e+00               5640          2.4008e-01
 2520          2.8120e+00               5760          1.8278e-01
 2640          3.1470e+00               5880          1.3830e-01
 2760          3.4463e+00               6000          1.0406e-01
 2880          3.7073e+00
 3000          3.9293e+00
 3120          4.1116e+00
 3240          4.2499e+00
```

GATX

GATX HI. Analytical Fate & Transport Modeling (benzene) at T-17

Fig.1: Benzene T-17 at Hot Spot.

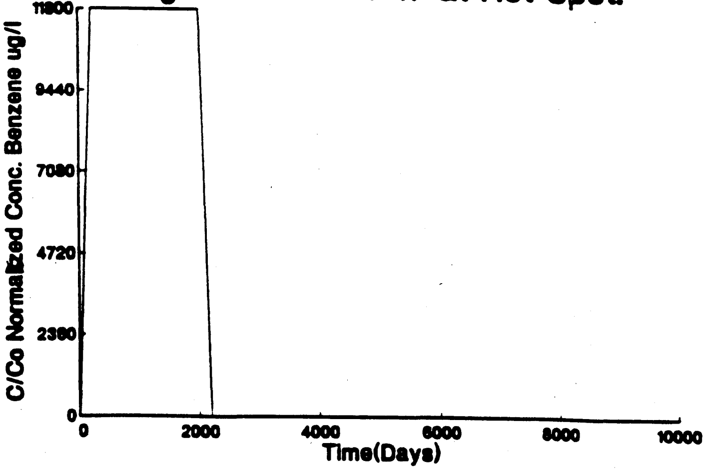


Fig.2: GATX T-17 at 200 Feet.

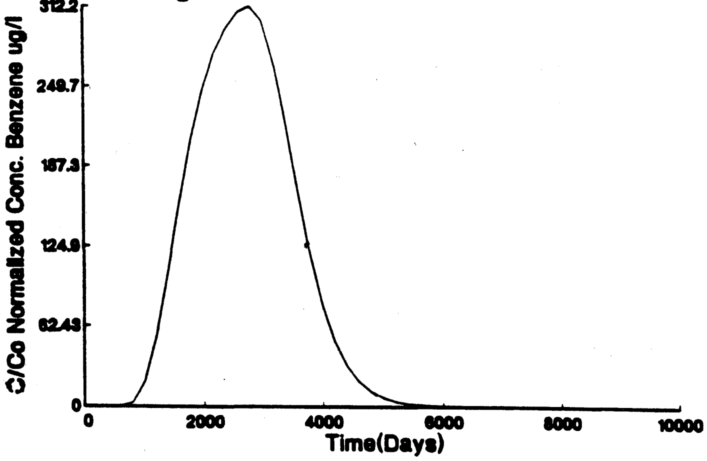
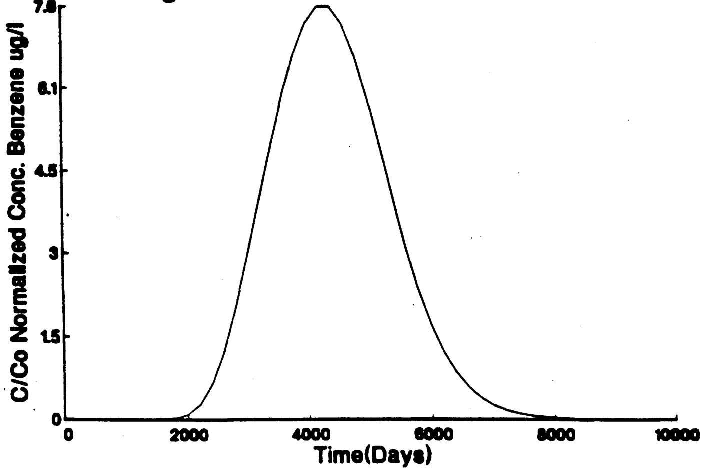


Fig.3: GATX T-17 at 400 Feet.



Department of Ecology Toxics Cleanup Program, NWRO	Modeler: Nnamdi Madakor Date: April 28, 1997

Fig.1: Benzene T-17 at Hot Spot.

```
                    THE  PRINCETON  MODELS

                     2D MT Gaussian B.C.

                          MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 5100.000000
Y0     = 2500.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 11800.000000


X-coor = 5100.00     Y-coor = 2500.00


       T              CONC

       0           0.0000e+00
     200           1.1800e+04
     400           1.1800e+04
     600           1.1800e+04
     800           1.1800e+04
    1000           1.1800e+04
    1200           1.1800e+04
    1400           1.1800e+04
    1600           1.1800e+04
    1800           1.1800e+04
    2000           1.1800e+04
    2200           0.0000e+00
    2400           0.0000e+00
    2600           0.0000e+00
    2800           0.0000e+00
    3000           0.0000e+00
    3200           0.0000e+00
    3400           0.0000e+00
    3600           0.0000e+00
    3800           0.0000e+00
    4000           0.0000e+00
    4200           0.0000e+00
    4400           0.0000e+00
    4600           0.0000e+00
    4800           0.0000e+00
    5000           0.0000e+00
    5200           0.0000e+00
    5400           0.0000e+00
```

Fig.2: GATX T-17 at 200 Feet.

```
                THE   PRINCETON   MODELS

                   2D MT Gaussian B.C.

                         MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
XO     = 5100.000000
YO     = 2500.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 11800.000000


X-coor = 5100.00      Y-coor = 2300.00


   T              CONC

   0           0.0000e+00
 200           6.5808e-14
 400           1.3400e-04
 600           1.2905e-01                 5600          1.2959e+00
 800           3.2436e+00                 5800          7.3094e-01
 1000            1.9084e+01               6000          4.0962e-01
 1200            5.4832e+01               6200          2.2830e-01
 1400            1.0565e+02               6400          1.2665e-01
 1600            1.6019e+02               6600          6.9987e-02
 1800            2.0902e+02               6800          3.8543e-02
 2000            2.4770e+02               7000          2.1164e-02
 2200            2.7581e+02               7200          1.1592e-02
 2400            2.9501e+02               7400          6.3358e-03
 2600            3.0739e+02               7600          3.4563e-03
 2800            3.1215e+02               7800          1.8823e-03
 3000            3.0113e+02               8000          1.0237e-03
 3200            2.6827e+02               8200          5.5603e-04
 3400            2.1915e+02               8400          3.0168e-04
 3600            1.6560e+02               8600          1.6353e-04
 3800            1.1733e+02               8800          8.8565e-05
 4000            7.8976e+01               9000          4.7931e-05
 4200            5.1045e+01               9200          2.5923e-05
 4400            3.1951e+01               9400          1.4013e-05
 4600            1.9495e+01               9600          7.5707e-06
 4800            1.1654e+01               9800          4.0885e-06
 5000            6.8519e+00               10000           2.2072e-0
 5200            3.9746e+00
 5400            2.2800e+00
```

Fig.3: GATX T-17 at 400 Feet.

```
                THE   PRINCETON   MODELS

                    2D MT Gaussian B.C.

                          MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
XO     = 5100.000000
YO     = 2500.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 11800.000000


X-coor = 5100.00      Y-coor = 2100.00


     T              CONC

     0           0.0000e+00
   200           0.0000e+00
   400           3.0395e-30                  5600          3.0817e+00
   600           7.2428e-18                  5800          2.3277e+00
   800           8.7346e-12                  6000          1.7079e+00
  1000           3.1793e-08                  6200          1.2209e+00
  1200           6.3540e-06                  6400          8.5275e-01
  1400           2.4210e-04                  6600          5.8332e-01
  1600           3.2800e-03                  6800          3.9163e-01
  1800           2.2353e-02                  7000          2.5857e-01
  2000           9.4412e-02                  7200          1.6818e-01
  2200           2.8237e-01                  7400          1.0791e-01
  2400           6.5387e-01                  7600          6.8399e-02
  2600           1.2477e+00                  7800          4.2879e-02
  2800           2.0517e+00                  8000          2.6613e-02
  3000           3.0062e+00                  8200          1.6368e-02
  3200           4.0250e+00                  8400          9.9838e-03
  3400           5.0221e+00                  8600          6.0439e-03
  3600           5.9276e+00                  8800          3.6337e-03
  3800           6.6883e+00                  9000          2.1708e-03
  4000           7.2524e+00                  9200          1.2894e-03
  4200           7.5617e+00                  9400          7.6177e-04
  4400           7.5649e+00                  9600          4.4785e-04
  4600           7.2445e+00                  9800          2.6210e-04
  4800           6.6345e+00                  10000          1.5275e-0
  5000           5.8146e+00
  5200           4.8870e+00
  5400           3.9505e+00
```

GATX HI. Analytical Fate & Transport Modeling (benzene) at MW-24

Fig. 1: GATX MW-24 at Hot Spot

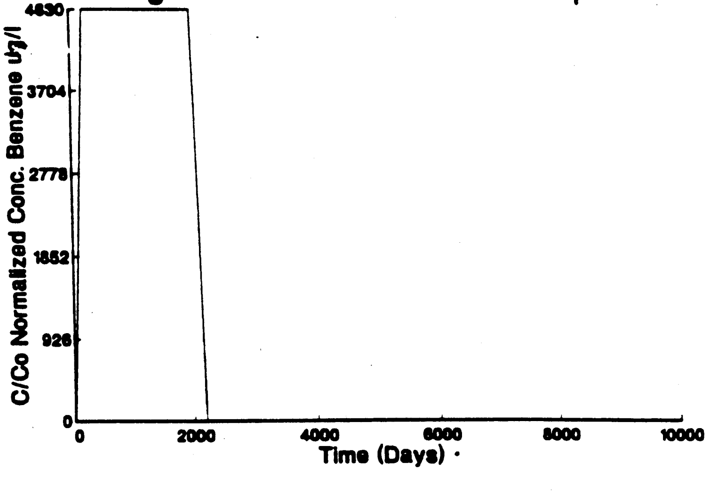


Fig. 2: GATX MW-24 at 200 Feet

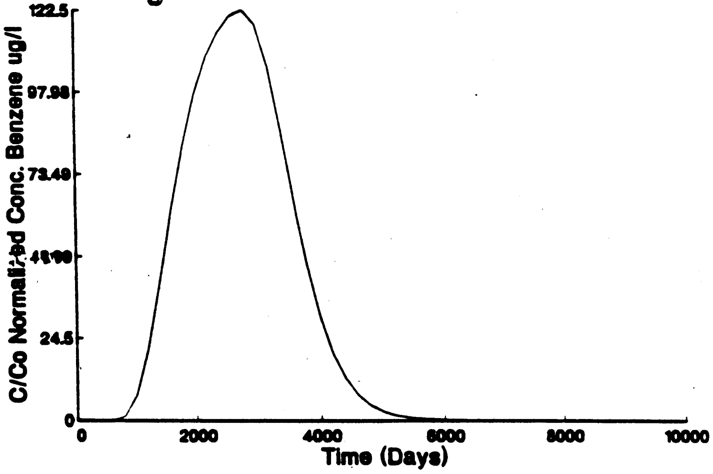
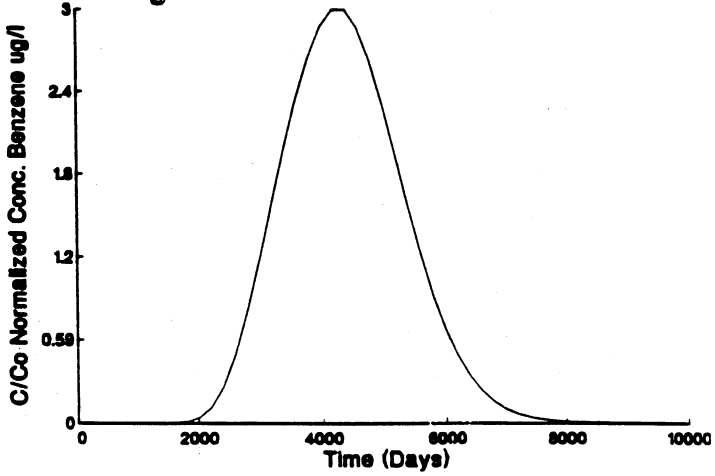


Fig. 3: GATX MW-24 at 400 Feet



Department of Ecology Toxics Cleanup Program, NWRO	Modeler: Nnamdi Madakor Date: April 28, 1997

Fig. 1: GATX MW-24 at Hot Spot

```
                    THE  PRINCETON  MODELS

                      2D MT Gaussian B.C.

                           MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 5000.000000
Y0     = 2550.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 4630.000000


X-coor = 5000.00      Y-coor = 2550.00


     T              CONC

     0           0.0000e+00
   200           4.6300e+03
   400           4.6300e+03
   600           4.6300e+03
   800           4.6300e+03
  1000           4.6300e+03
  1200           4.6300e+03
  1400           4.6300e+03
  1600           4.6300e+03
  1800           4.6300e+03
  2000           4.6300e+03
  2200           0.0000e+00
  2400           0.0000e+00
  2600           0.0000e+00
  2800           0.0000e+00
  3000           0.0000e+00
  3200           0.0000e+00
  3400           0.0000e+00
  3600           0.0000e+00
  3800           0.0000e+00
  4000           0.0000e+00
  4200           0.0000e+00
  4400           0.0000e+00
  4600           0.0000e+00
  4800           0.0000e+00
  5000           0.0000e+00
  5200           0.0000e+00
  5400           0.0000e+00
```

Fig. 2: GATX MW-24 at 200 Feet

```
                    THE   PRINCETON   MODELS

                      2D MT Gaussian B.C.

                            MODEL 5


K     = 0.001733
GAMMA = 0.000000
RD    = 1.300000
X0    = 5000.000000
Y0    = 2550.000000
DX    = 1.500000
DY    = 0.150000
V     = 0.100000
THETA = 270.000000
TON   = 0.000000

TOFF  = 2000.000000
S     = 80.000000
CP    = 4630.000000


X-coor = 5000.00      Y-coor = 2350.00


    T             CONC

    0          0.0000e+00
  200          2.5821e-14
  400          5.2576e-05                 5600          5.0848e-01
  600          5.0637e-02                 5800          2.8680e-01
  800          1.2727e+00                 6000          1.6072e-01
 1000           7.4881e+00                6200          8.9578e-02
 1200           2.1515e+01                6400          4.9696e-02
 1400           4.1455e+01                6600          2.7461e-02
 1600           6.2855e+01                6800          1.5123e-02
 1800           8.2015e+01                7000          8.3043e-03
 2000           9.7191e+01                7200          4.5486e-03
 2200           1.0822e+02                7400          2.4860e-03
 2400           1.1575e+02                7600          1.3561e-03
 2600           1.2061e+02                7800          7.3858e-04
 2800           1.2248e+02                8000          4.0167e-04
 3000           1.1816e+02                8200          2.1817e-04
 3200           1.0526e+02                8400          1.1837e-04
 3400           8.5988e+01                8600          6.4163e-05
 3600           6.4976e+01                8800          3.4750e-05
 3800           4.6038e+01                9000          1.8807e-05
 4000           3.0988e+01                9200          1.0172e-05
 4200           2.0029e+01                9400          5.4982e-06
 4400           1.2537e+01                9600          2.9706e-06
 4600           7.6492e+00                9800          1.6042e-06
 4800           4.5726e+00                10000          8.6603e-07
 5000           2.6885e+00
 5200           1.5595e+00
 5400           8.9461e-01
```

Fig. 3: GATX MW-24 at 400 Feet

```
                    THE  PRINCETON  MODELS

                     2D MT Gaussian B.C.

                          MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 5000.000000
Y0     = 2550.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 4630.000000


X-coor = 5000.00     Y-coor = 2150.


      T              CONC

      0          0.0000e+00
    200          0.0000e+00
    400          1.1926e-30
    600          2.8419e-18
    800          3.4272e-12
   1000            1.2475e-08
   1200            2.4931e-06
   1400            9.4995e-05
   1600            1.2870e-03
   1800            8.7709e-03
   2000            3.7045e-02
   2200            1.1079e-01
   2400            2.5656e-01
   2600            4.8955e-01
   2800            8.0504e-01
   3000            1.1795e+00
   3200            1.5793e+00
   3400            1.9705e+00
   3600            2.3258e+00
   3800            2.6243e+00
   4000            2.8457e+00
   4200            2.9670e+00
   4400            2.9682e+00
   4600            2.8425e+00
   4800            2.6032e+00
   5000            2.2815e+00
   5200            1.9175e+00
   5400            1.5501e+00
```

GATX HI. Analytical Fate & Transport Modeling (benzene) at TX-17

Fig.2b: GATX TX-17 at 200 Feet

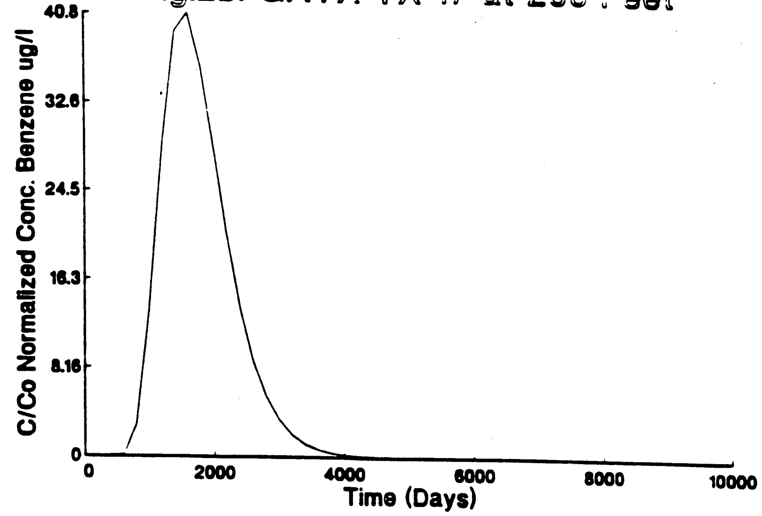


Fig.3b: GATX TX-17 at 400 Feet

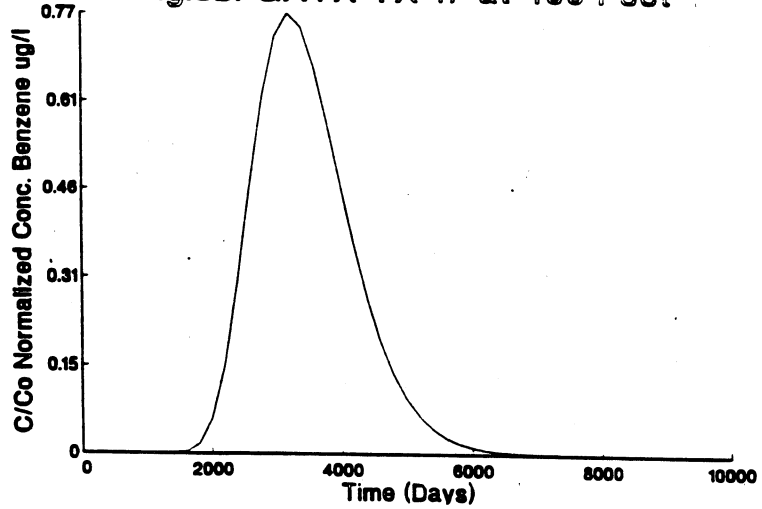
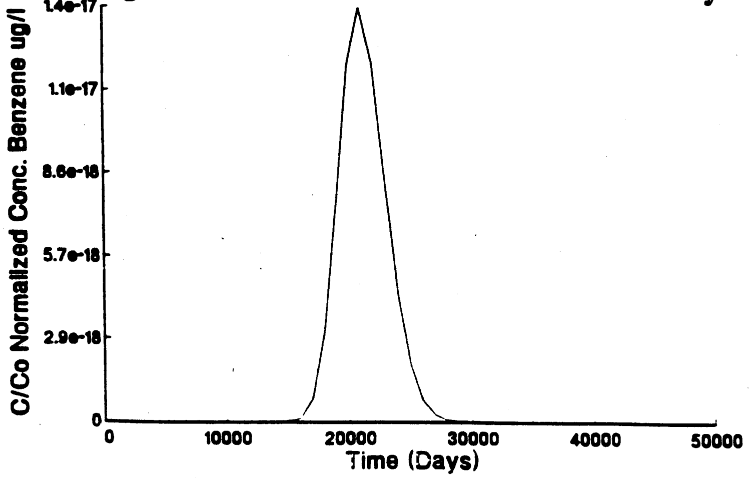


Fig.3c: GATX at Shoreline E.WaterWy



Department of Ecology Toxics Cleanup Program, NWRO	Modeler: Nnamdi Madakor Date: April 28, 1997

Fig.2b: GATX TX-17 at 200 Feet

```
                    THE   PRINCETON   MODELS

                       2D MT Gaussian B.C.

                            MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
XO     = 5100.000000
YO     = 2500.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 150.000000
S      = 80.000000
CP     = 11800.000000


X-coor = 5100.00      Y-coor = 2300.00


     T              CONC

     0           0.0000e+00
   200           6.5808e-14           5600          1.9942e-03
   400           1.3400e-04           5800          1.0896e-03
   600           1.2768e-01           6000          5.9428e-04
   800           2.8870e+00           6200          3.2359e-04
  1000           1.3526e+01           6400          1.7595e-04
  1200           2.8693e+01           6600          9.5557e-05
  1400           3.9117e+01           6800          5.1839e-05
  1600           4.0808e+01           7000          2.8096e-05
  1800           3.5828e+01           7200          1.5215e-05
  2000           2.7988e+01           7400          8.2336e-06
  2200           2.0137e+01           7600          4.4528e-06
  2400           1.3647e+01           7800          2.4068e-06
  2600           8.8443e+00           8000          1.3002e-06
  2800           5.5399e+00           8200          7.0214e-07
  3000           3.3794e+00           8400          3.7903e-07
  3200           2.0188e+00           8600          2.0454e-07
  3400           1.1860e+00           8800          1.1035e-07
  3600           6.8734e-01           9000          5.9516e-08
  3800           3.9397e-01           9200          3.2094e-08
  4000           2.2375e-01           9400          1.7303e-08
  4200           1.2612e-01           9600          9.3277e-09
  4400           7.0632e-02           9800          5.0276e-09
  4600           3.9345e-02          10000          2.7096e-09
  4800           2.1817e-02
  5000           1.2051e-02
  5200           6.6342e-03
  5400           3.6417e-03
```

Fig.3b: GATX TX-17 at 400 Feet

```
                    THE  PRINCETON  MODELS

                      2D MT Gaussian B.C.

                            MODEL 5


K     = 0.001733
GAMMA = 0.000000
RD    = 1.300000
X0    = 5100.000000
Y0    = 2500.000000
DX    = 1.500000
DY    = 0.150000
V     = 0.100000
THETA = 270.000000
TON   = 0.000000

TOFF  = 150.000000
S     = 80.000000
CP    = 11800.000000


X-coor = 5100.00      Y-coor = 2100.00


    T            CONC

    0         0.0000e+00          5600          2.8212e-02
  200         0.0000e+00          5800          1.8174e-02
  400         3.0395e-30          6000          1.1557e-02
  600         7.2428e-18          6200          7.2641e-03
  800         8.7341e-12          6400          4.5181e-03
 1000         3.1693e-08          6600          2.7837e-03
 1200         6.2069e-06          6800          1.7004e-03
 1400         2.2423e-04          7000          1.0307e-03
 1600         2.7768e-03          7200          6.2027e-04
 1800         1.6757e-02          7400          3.7087e-04
 2000         6.1103e-02          7600          2.2044e-04
 2200         1.5465e-01          7800          1.3032e-04
 2400         2.9809e-01          8000          7.6652e-05
 2600         4.6664e-01          8200          4.4880e-05
 2800         6.2111e-01          8400          2.6165e-05
 3000         7.2681e-01          8600          1.5195e-05
 3200         7.6664e-01          8800          8.7917e-06
 3400         7.4289e-01          9000          5.0697e-06
 3600         6.7111e-01          9200          2.9143e-06
 3800         5.7175e-01          9400          1.6704e-06
 4000         4.6359e-01          9600          9.5481e-07
 4200         3.6041e-01          9800          5.4439e-07
 4400         2.7025e-01         10000          3.0965e-07
 4600         1.9644e-01
 4800         1.3897e-01
 5000         9.6011e-02
 5200         6.4968e-02
 5400         4.3162e-02
```

Fig.3c: GATX at Shoreline E.WaterWy

```
                 THE   PRINCETON   MODELS

                    2D MT Gaussian B.C.

                          MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 5100.000000
Y0     = 2500.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 270.000000
TON    = 0.000000

TOFF   = 150.000000
S      = 80.000000
CP     = 11800.000000


X-coor = 5100.00      Y-coor =    0.50


    T            CONC

    0         0.0000e+00        28000        6.5802e-20
 1000         0.0000e+00        29000        1.6225e-20
 2000         0.0000e+00        30000        3.5838e-21
 3000         0.0000e+00        31000        7.1674e-22
 4000         0.0000e+00        32000        1.3102e-22
 5000         0.0000e+00        33000        2.2071e-23
 6000         0.0000e+00        34000        3.4513e-24
 7000         0.0000e+00        35000        5.0423e-25
 8000         1.4013e-45        36000        6.9221e-26
 9000         6.0697e-39        37000        8.9748e-27
10000         1.0131e-33        38000        1.1040e-27
11000         1.0778e-29        39000        1.2937e-28
12000         1.4548e-26        40000        1.4495e-29
13000         4.0141e-24        41000        1.5581e-30
14000         3.1843e-22        42000        1.6114e-31
15000         9.3260e-21        43000        1.6080e-32
16000         1.2165e-19        44000        1.5520e-33
17000         8.1565e-19        45000        1.4520e-34
18000         3.1428e-18        46000        1.3196e-35
19000         7.5982e-18        47000        1.1671e-36
20000         1.2366e-17        48000        1.0064e-37
21000         1.4342e-17        49000        8.4725e-39
22000         1.2417e-17        50000        6.9749e-40
23000         8.3387e-18
24000         4.4851e-18
25000         1.9846e-18
26000         7.3904e-19
27000         2.3612e-19
```

TEXACO

TEXACO OIL HI. Analytical Fate & Transport Modeling (benzene) at TX-03

Fig.1: Benzene TX-03 at Hot Spot

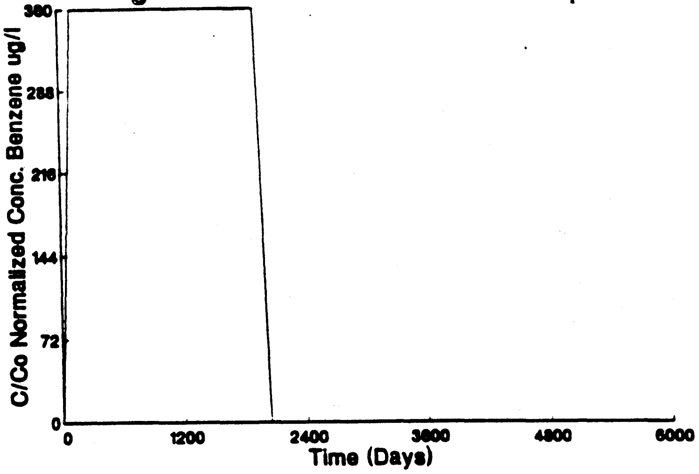


Fig.2: Benzene TX-03 at 100 Feet

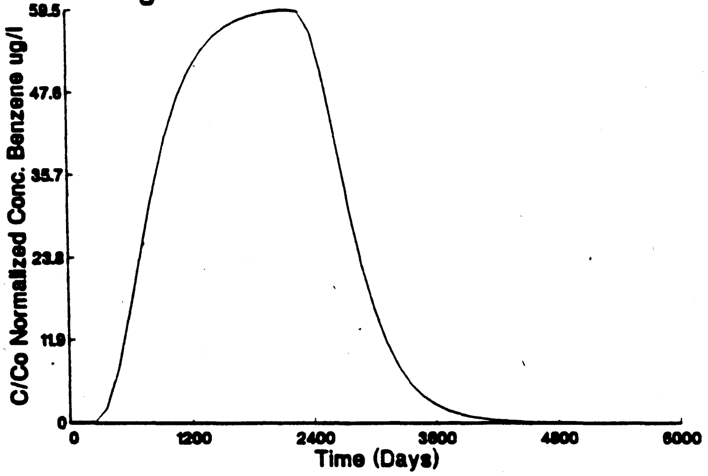
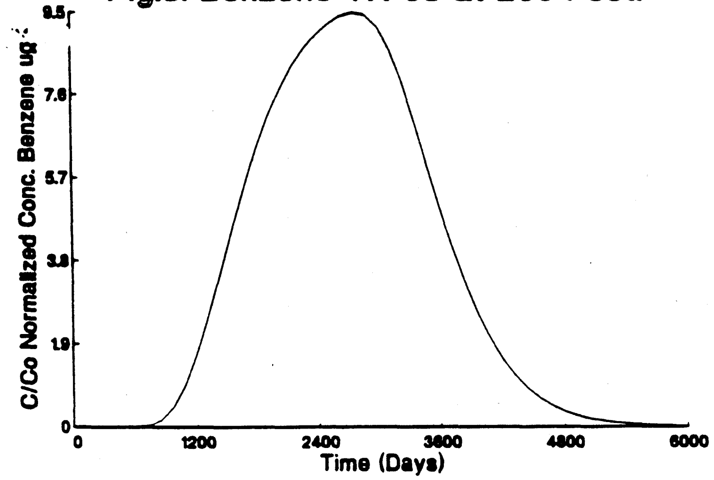


Fig.3: Benzene TX-03 at 200 Feet.



Department of Ecology
Toxics Cleanup Program, NWRO

Modeler: Nnamdi Madakor
Date: April 28, 1997

Fig.1: Benzene TX-03 at Hot Spot

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                              THE  PRINCETON  MODELS

                                 2D MT Gaussian B.C.

                                      MODEL 5


                 K      = 0.001733
                 GAMMA  = 0.000000
                 RD     = 1.300000
                 X0     = 2900.000000
                 Y0     = 3200.000000
                 DX     = 1.500000
                 DY     = 0.150000
                 V      = 0.100000
                 THETA  = 180.000000
                 TON    = 0.000000

                 TOFF   = 2000.000000
                 S      = 80.000000
                 CP     = 360.000000


                 X-coor = 2900.00      Y-coor = 3200.00


                       T             CONC

                       0           0.0000e+00
                      72           3.6000e+02
                     144           3.6000e+02
                     216           3.6000e+02
                     288           3.6000e+02
                     360           3.6000e+02
                     432           3.6000e+02
                     504           3.6000e+02
                     576           3.6000e+02
                     648           3.6000e+02
                     720           3.6000e+02
                     792           3.6000e+02
                     864           3.6000e+02
                     936           3.6000e+02
                    1008           3.6000e+02
                    1080           3.6000e+02
                    1152           3.6000e+02
                    1224           3.6000e+02
                    1296           3.6000e+02
                    1368           3.6000e+02
                    1440           3.6000e+02
                    1512           3.6000e+02
                    1584           3.6000e+02
                    1656           3.6000e+02
                    1728           3.6000e+02
                    1800           3.6000e+02
                    1872           3.6000e+02
                    1944           3.6000e+02
```

Fig.2: Benzene TX-03 at 100 Feet

```
                THE   PRINCETON   MODELS

                  2D MT Gaussian B.C.

                        MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 2900.000000
Y0     = 3200.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 180.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 360.000000


X-coor = 2800.00      Y-coor = 3200.00


     T             CONC

     0           0.0000e+00
    80           1.4704e-09
   160           1.2486e-03
   240           1.1170e-01              2240          5.9487e+01
   320           9.9806e-01              2320          5.8676e+01
   400           3.5395e+00              2400          5.6192e+01
   480           7.9126e+00              2480          5.1863e+01
   560           1.3609e+01              2560          4.6202e+01
   640           1.9902e+01              2640          3.9935e+01
   720           2.6169e+01              2720          3.3687e+01
   800           3.1997e+01              2800          2.7875e+01
   880           3.7165e+01              2880          2.2720e+01
   960           4.1595e+01              2960          1.8299e+01
  1040             4.5300e+01            3040          1.4601e+01
  1120             4.8342e+01            3120          1.1564e+01
  1200             5.0806e+01            3200          9.1041e+00
  1280             5.2779e+01            3280          7.1337e+00
  1360             5.4347e+01            3360          5.5685e+00
  1440             5.5584e+01            3440          4.3332e+00
  1520             5.6555e+01            3520          3.3636e+00
  1600             5.7315e+01            3600          2.6056e+00
  1680             5.7906e+01            3680          2.0151e+00
  1760             5.8365e+01            3760          1.5563e+00
  1840             5.8721e+01            3840          1.2007e+00
  1920             5.8997e+01            3920          9.2549e-01
  2000             5.9210e+01            4000          7.1287e-01
  2080             5.9374e+01
  2160             5.9500e+01
```

Fig.3: Benzene TX-03 at 200 Feet.

```
              THE   PRINCETON   MODELS

                   2D MT Gaussian B.C.

                          MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 2900.000000
Y0     = 3200.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 180.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 360.000000


X-coor = 2700.00      Y-coor = 3200.00


    T              CONC

    0            0.0000e+00
  120            5.6118e-28
  240            2.6775e-12
  360            3.9133e-07                 3360          7.0083e+00
  480            1.3236e-04                 3480          6.0288e+00
  600            3.9372e-03                 3600          5.0521e+00
  720            3.4733e-02                 3720          4.1368e+00
  840            1.5320e-01                 3840          3.3195e+00
  960            4.3901e-01                 3960          2.6172e+00
 1080              9.4584e-01               4080          2.0323e+00
 1200              1.6729e+00               4200          1.5573e+00
 1320              2.5693e+00               4320          1.1797e+00
 1440              3.5582e+00               4440          8.8470e-01
 1560              4.5613e+00               4560          6.5770e-01
 1680              5.5150e+00               4680          4.8520e-01
 1800              6.3769e+00               4800          3.5554e-01
 1920              7.1250e+00               4920          2.5898e-01
 2040              7.7533e+00               5040          1.8766e-01
 2160              8.2670e+00               5160          1.3534e-01
 2280              8.6778e+00               5280          9.7207e-02
 2400              9.0003e+00               5400          6.9559e-02
 2520              9.2491e+00               5520          4.9611e-02
 2640              9.4307e+00               5640          3.5278e-02
 2760              9.5225e+00               5760          2.5020e-02
 2880              9.4637e+00               5880          1.7702e-02
 3000              9.1870e+00               6000          1.2497e-02
 3120              8.6621e+00
 3240              7.9137e+00
```

TEXACO OIL HI. Analytical Fate & Transport Modeling (benzene) at SH-04

Fig.1: Texaco SH-04 at Hot Spot

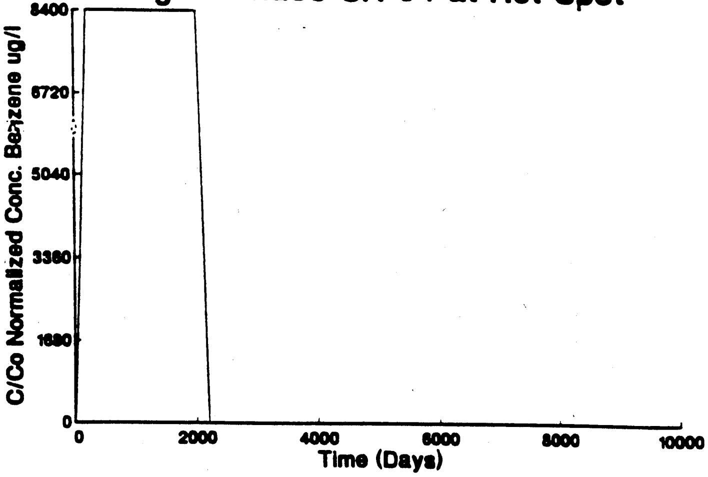


Fig.2: Texaco SH-04 at 200 feet

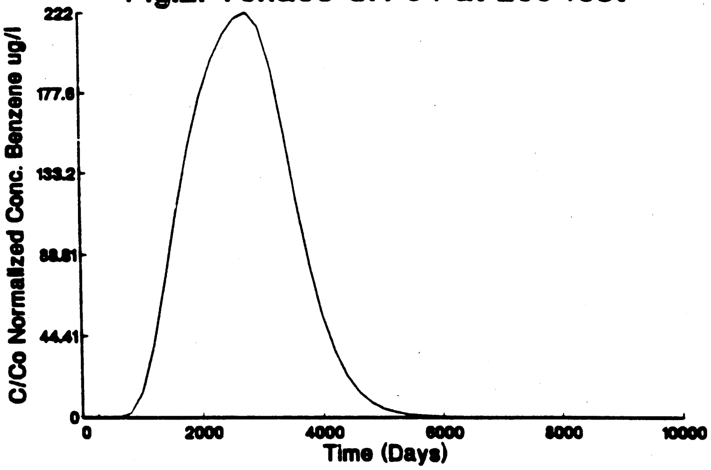
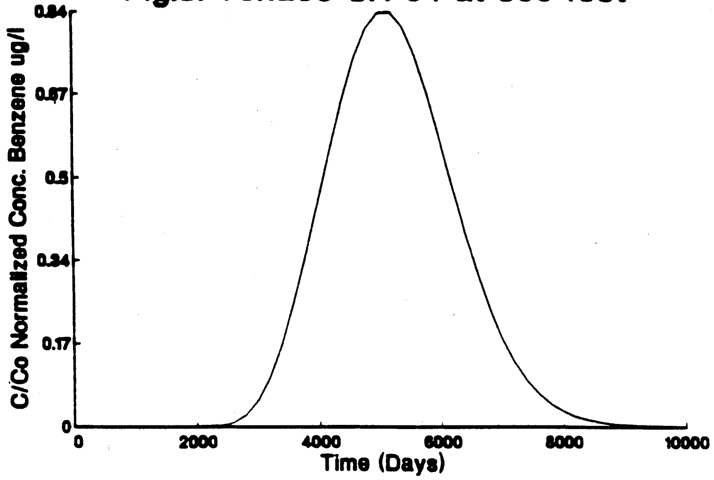


Fig.3: Texaco SH-04 at 500 feet



Department of Ecology
Toxics Cleanup Program, NWRO

Modeler: Nnamdi Madakor
Date: April 28, 1997

Fig.1: Texaco SH-04 at Hot Spot

```
                    THE   PRINCETON   MODELS

                       2D MT Gaussian B.C.

                            MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 6100.000000
Y0     = 3400.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 180.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 8400.000000


X-coor = 6100.00     Y-coor = 3400.00


      T              CONC

      0          0.0000e+00
     72          8.4000e+03
    144          8.4000e+03
    216          8.4000e+03
    288          8.4000e+03
    360          8.4000e+03
    432          8.4000e+03
    504          8.4000e+03
    576          8.4000e+03
    648          8.4000e+03
    720          8.4000e+03
    792          8.4000e+03
    864          8.4000e+03
    936          8.4000e+03
    1008           8.4000e+03
    1080           8.4000e+03
    1152           8.4000e+03
    1224           8.4000e+03
    1296           8.4000e+03
    1368           8.4000e+03
    1440           8.4000e+03
    1512           8.4000e+03
    1584           8.4000e+03
    1656           8.4000e+03
    1728           8.4000e+03
    1800           8.4000e+03
    1872           8.4000e+03
    1944           8.4000e+03
```

Fig.2: Texaco SH-04 at 200 feet

```
                 THE  PRINCETON   MODELS

                    2D MT Gaussian B.C.

                          MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 6100.000000
Y0     = 3400.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 180.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 8400.000000


X-coor = 5900.00      Y-coor = 3400.00


     T             CONC

     0          0.0000e+00
   200          4.6842e-14
   400          9.5368e-05
   600          9.1843e-02                 5600          9.2071e-01
   800          2.3081e+00                 5800          5.1925e-01
  1000            1.3579e+01               6000          2.9096e-01
  1200            3.9013e+01               6200          1.6215e-01
  1400            7.5166e+01               6400          8.9947e-02
  1600            1.1396e+02               6600          4.9698e-02
  1800            1.4869e+02               6800          2.7367e-02
  2000            1.7620e+02               7000          1.5026e-02
  2200            1.9619e+02               7200          8.2295e-03
  2400            2.0984e+02               7400          4.4973e-03
  2600            2.1865e+02               7600          2.4531e-03
  2800            2.2203e+02               7800          1.3359e-03
  3000            2.1418e+02               8000          7.2643e-04
  3200            1.9080e+02               8200          3.9453e-04
  3400            1.5585e+02               8400          2.1404e-04
  3600            1.1776e+02               8600          1.1601e-04
  3800            8.3432e+01               8800          6.2822e-05
  4000            5.6152e+01               9000          3.3996e-05
  4200            3.6290e+01               9200          1.8385e-05
  4400            2.2713e+01               9400          9.9367e-06
  4600            1.3857e+01               9600          5.3680e-06
  4800            8.2827e+00               9800          2.8987e-06
  5000            4.8695e+00               10000           1.5647e-06
  5200            2.8243e+00
  5400            1.6200e+00
```

Fig.3: Texaco SH-04 at 500 feet

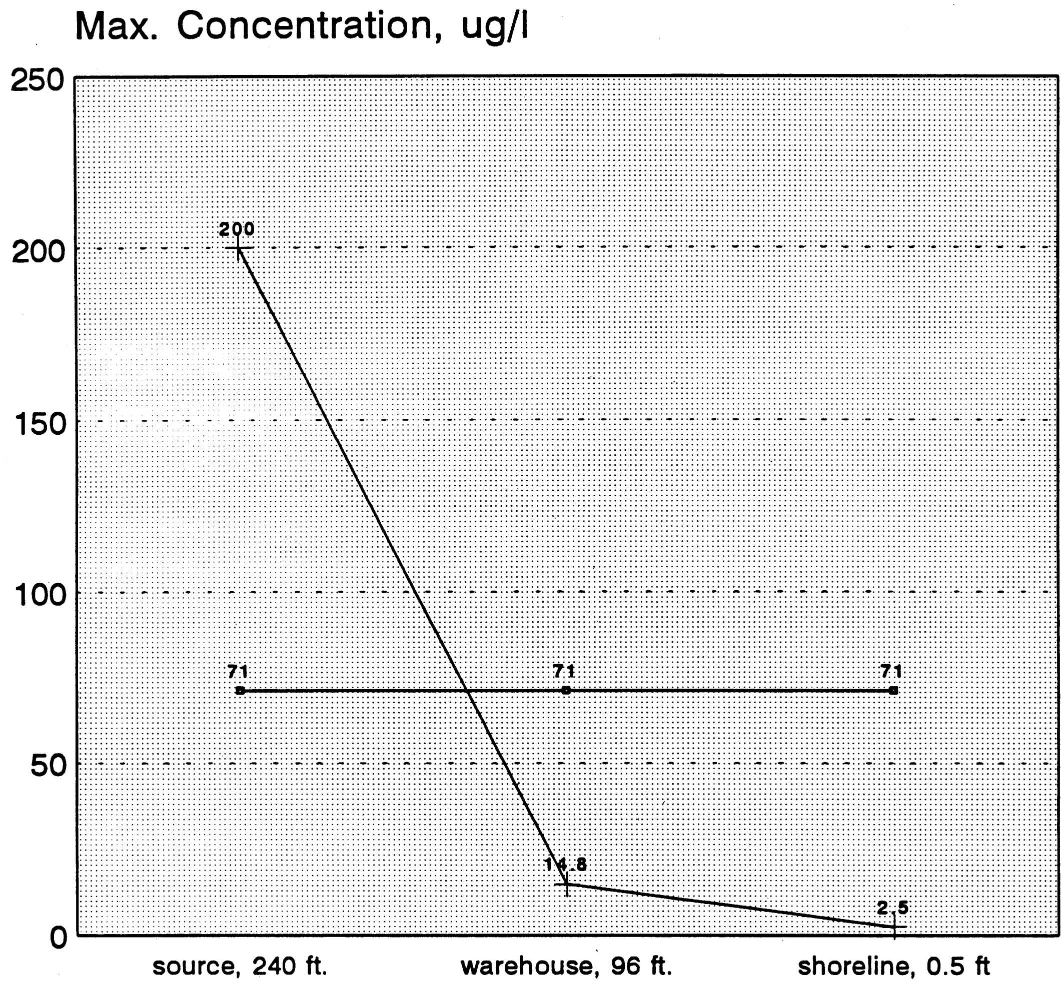
```
                    THE   PRINCETON   MODELS

                      2D MT Gaussian B.C.

                            MODEL 5


K      = 0.001733
GAMMA  = 0.000000
RD     = 1.300000
X0     = 6100.000000
Y0     = 3400.000000
DX     = 1.500000
DY     = 0.150000
V      = 0.100000
THETA  = 180.000000
TON    = 0.000000

TOFF   = 2000.000000
S      = 80.000000
CP     = 8400.000000


X-coor = 5600.00      Y-coor = 3400.00


    T             CONC

    0          0.0000e+00
  200          0.0000e+00            5600          7.5456e-01
  400          0.0000e+00            5800          6.7576e-01
  600          8.8093e-31            6000          5.8427e-01
  800          3.5618e-21            6200          4.8868e-01
 1000            1.6812e-15          6400          3.9628e-01
 1200            8.5576e-12          6600          3.1226e-01
 1400            3.2721e-09          6800          2.3965e-01
 1600            2.4824e-07          7000          1.7952e-01
 1800            6.4124e-06          7200          1.3153e-01
 2000            7.8014e-05          7400          9.4426e-02
 2200            5.4969e-04          7600          6.6543e-02
 2400            2.5753e-03          7800          4.6104e-02
 2600            8.8298e-03          8000          3.1450e-02
 2800            2.3732e-02          8200          2.1150e-02
 3000            5.2603e-02          8400          1.4038e-02
 3200            9.9901e-02          8600          9.2067e-03
 3400            1.6743e-01          8800          5.9716e-03
 3600            2.5347e-01          9000          3.8340e-03
 3800            3.5307e-01          9200          2.4386e-03
 4000            4.5937e-01          9400          1.5376e-03
 4200            5.6493e-01          9600          9.6175e-04
 4400            6.6251e-01          9800          5.9710e-04
 4600            7.4516e-01          10000           3.6815e-04
 4800            8.0614e-01
 5000            8.3955e-01
 5200            8.4166e-01
 5400            8.1213e-01
```

APPENDIX. D

ARCO, GATX, and TEXACO, FATE & TRANSPORT DISTANCE, TIME, and MAXIMUM CONC. vs CRITERIA

Fig. 1: Distance vs. Max. Exit Conc. for GM-14s

ARCO OIL HI. Plant 1. Inland Fate & Transport Simulation, Benzene



Criteria	71	71	71
GM-14s	200	14.8	2.5

Distance from Source

Distance vs. Max. Exit Concerntrations

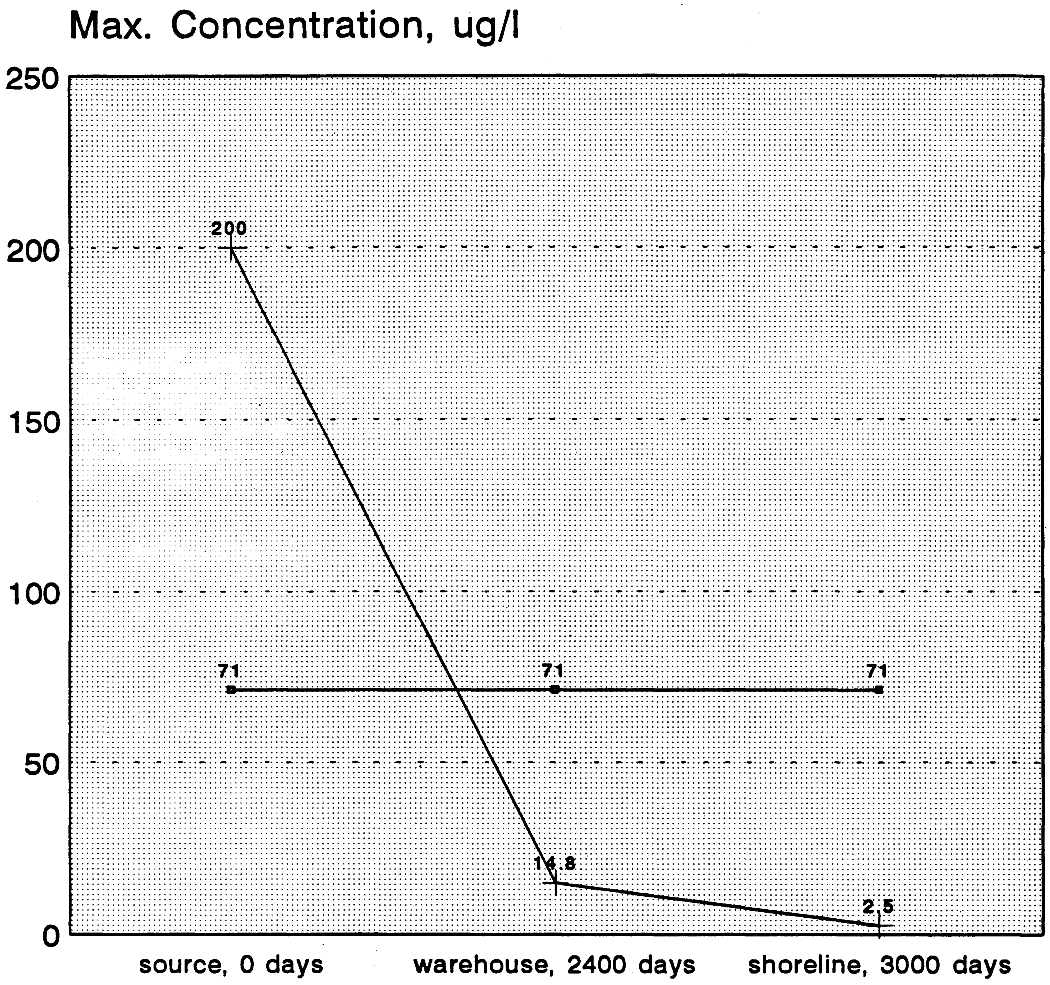
-▫- Criteria + GM-14s

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 2: Time (Days) vs. Max. Exit Conc. for GM-14s

ARCO OIL HI. Plant 1. Inland Fate & Transport Simulation, Benzene



Criteria	71	71	71
GM-14s	200	14.8	2.5

Travel Time from Source

Time (Days) vs. Max. Exit Concerntrations

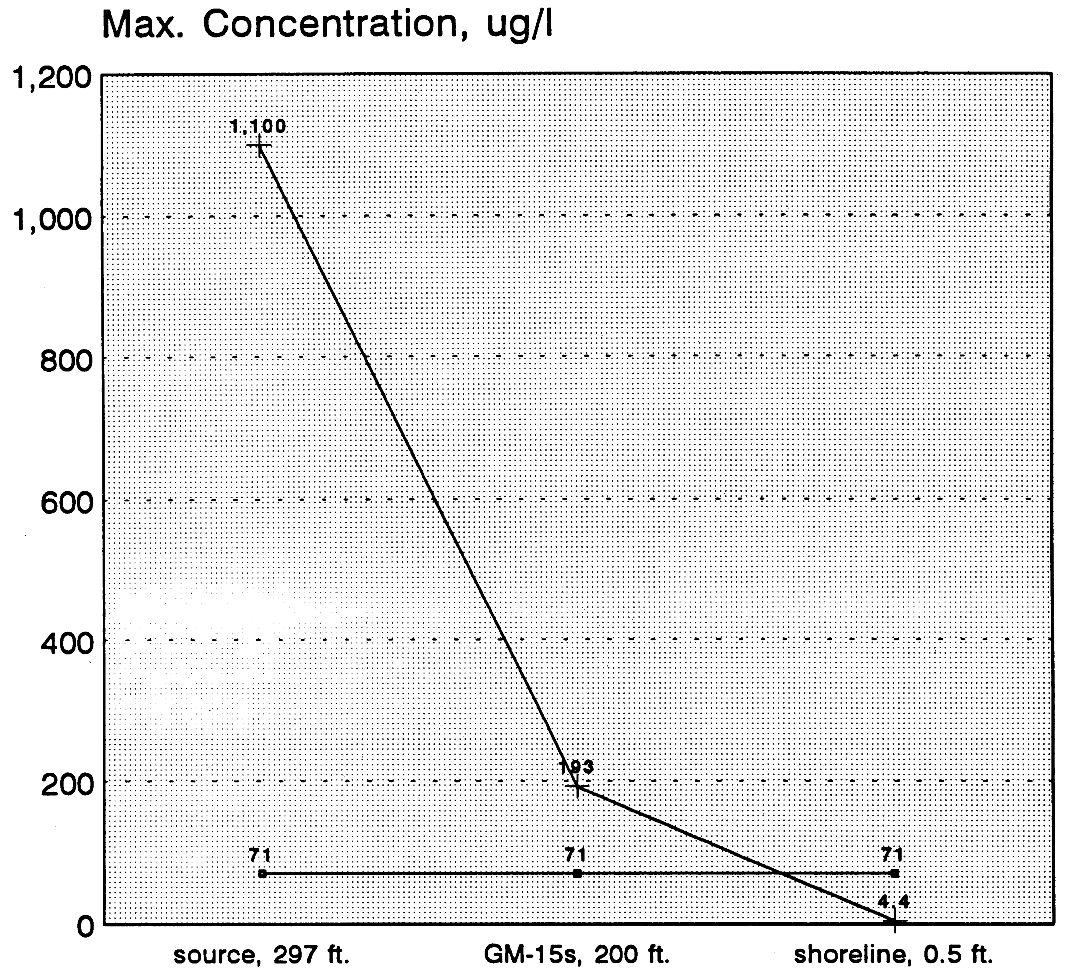
-■- Criteria + GM-14s

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 3: Distance vs. Max. Exit Conc. for AR-03

ARCO OIL HI. Plant 1. Inland Fate & Transport Simulation, Benzene



	source, 297 ft.	GM-15s, 200 ft.	shoreline, 0.5 ft.
Criteria	71	71	71
GM-14s	1,100	193	4.4

Distance from Source

Distance vs. Max. Exit Concerntrations

-▫- Criteria + GM-14s

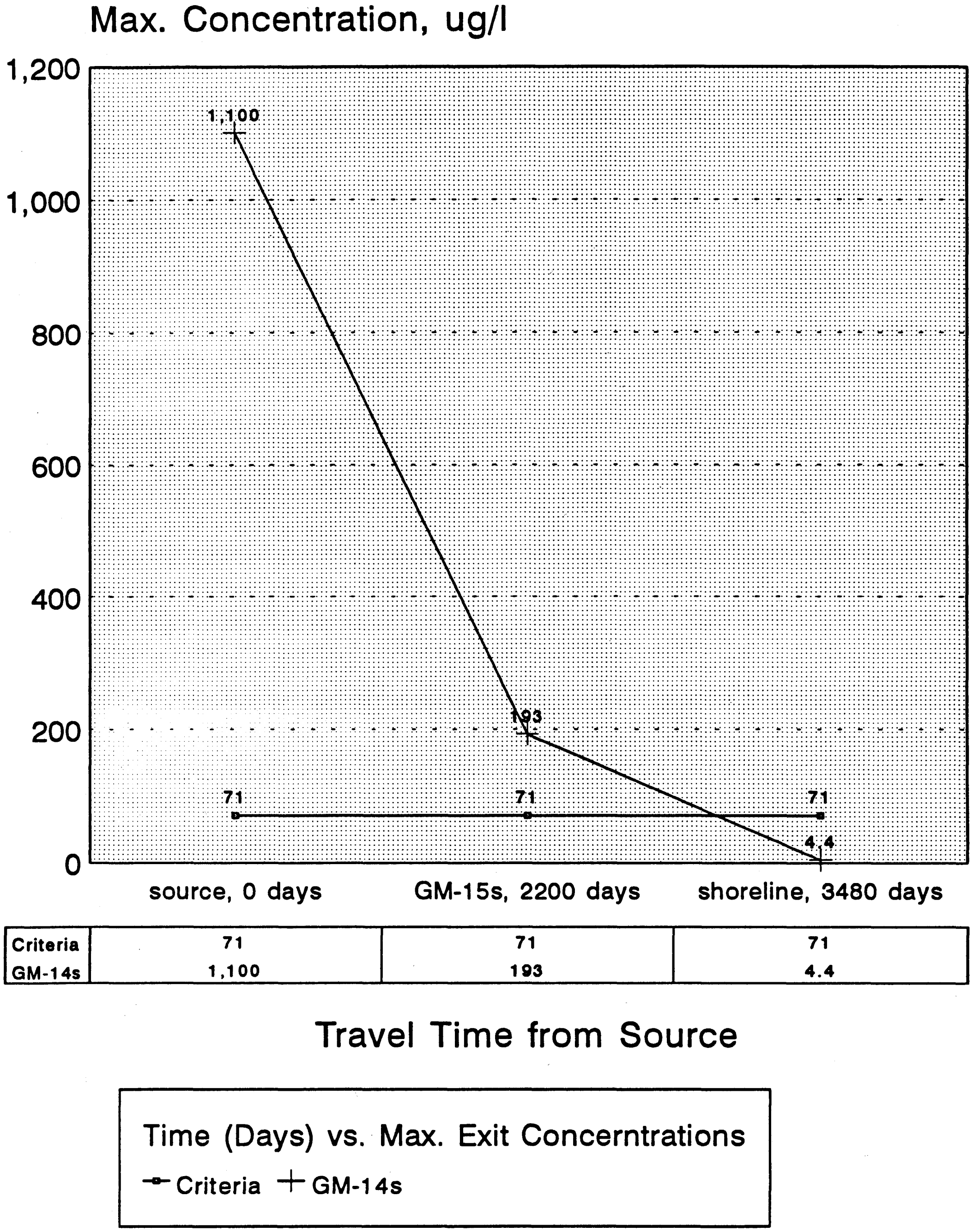
Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology,
Toxics Cleanup Program, NWRO

Drawn: Nnamdi Madakor
Date: April 27, 1997

Fig. 4: Time (Days) vs. Max. Exit Conc. for AR-03

ARCO OIL HI. Plant 1. Inland Fate & Transport Simulation, Benzene



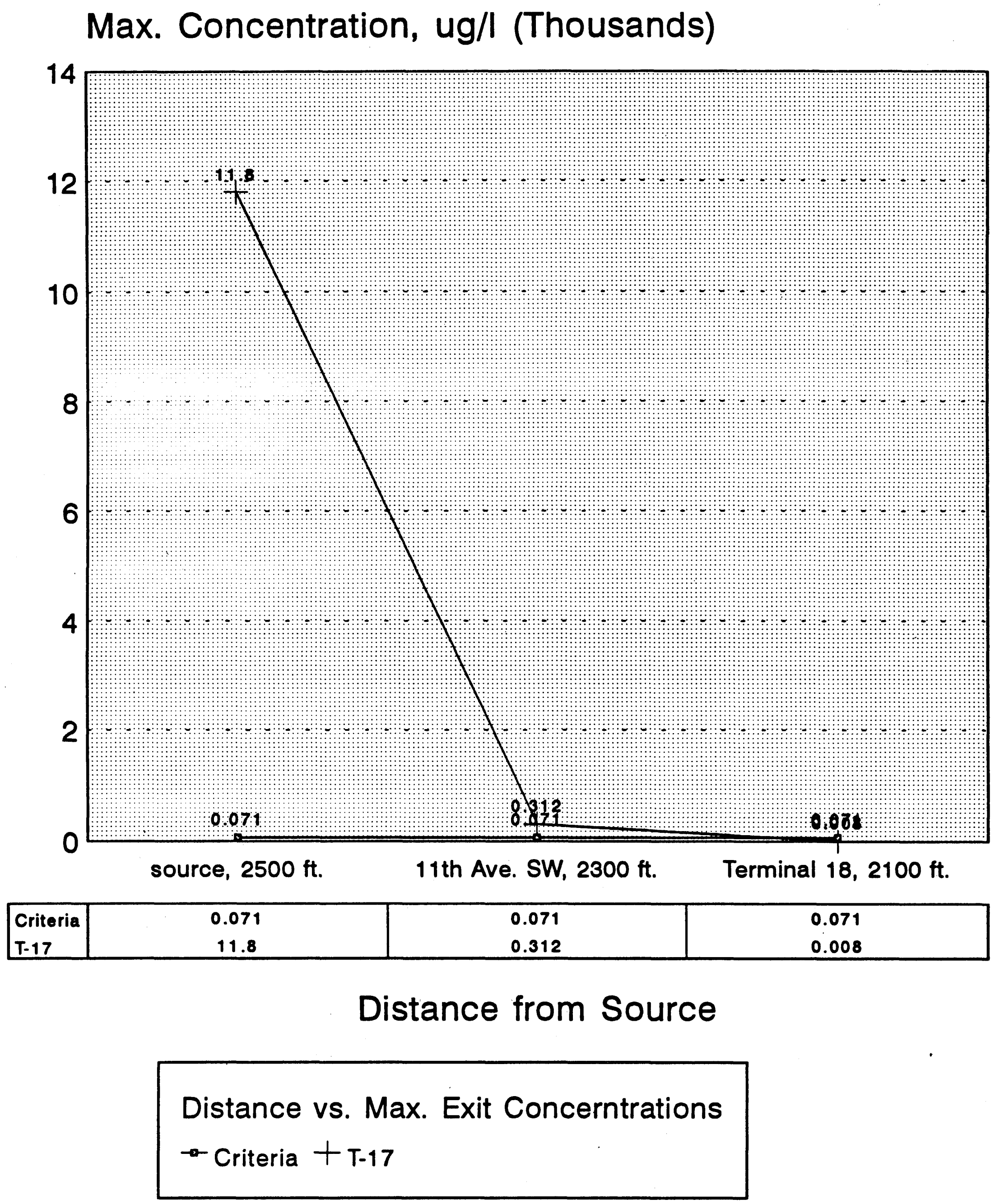
Criteria	71	71	71
GM-14s	1,100	193	4.4

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 1: Distance vs. Max. Exit Conc. for T-17

GATX (Former Shell) HI. Fate & Transport Simulation, Benzene



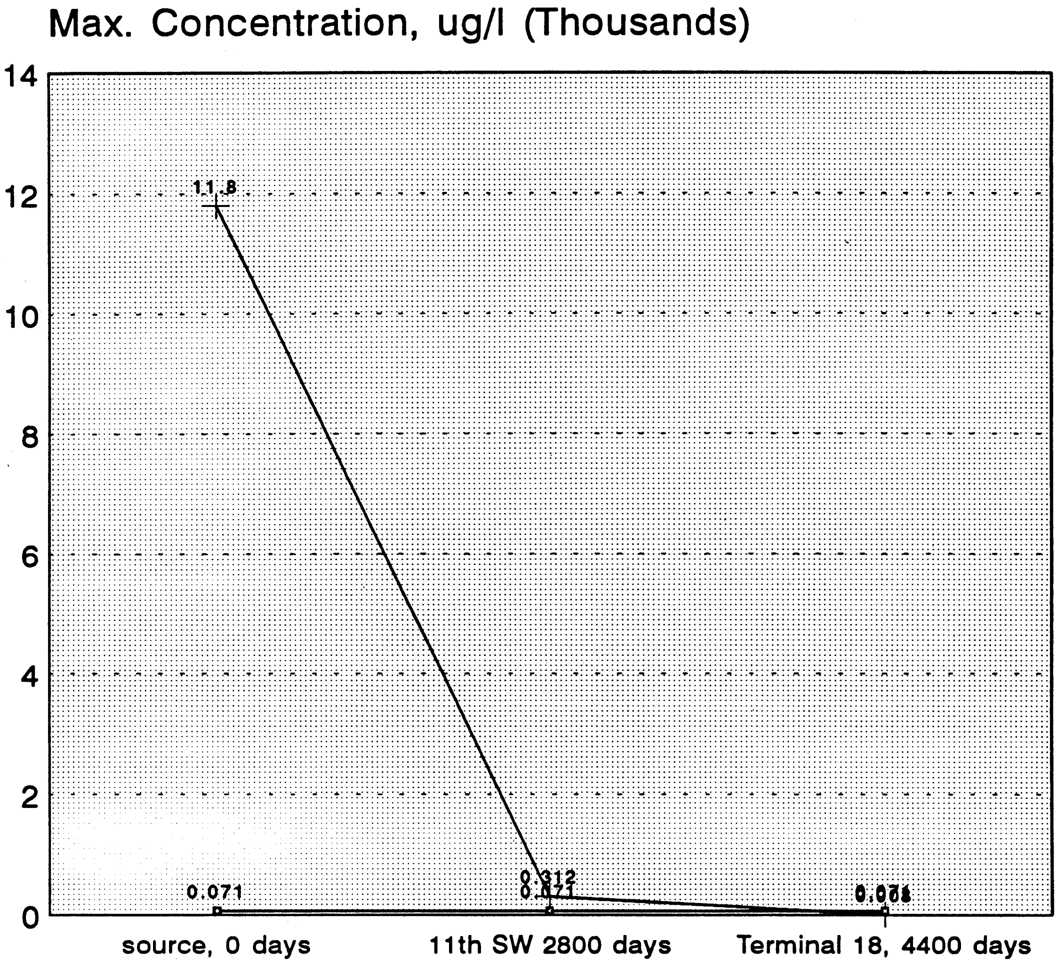
	source, 2500 ft.	11th Ave. SW, 2300 ft.	Terminal 18, 2100 ft.
Criteria	0.071	0.071	0.071
T-17	11.8	0.312	0.008

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 2: Time (Days) vs. Max. Exit Conc. for T-17

GATX (Former SHELL) HI. Inland Fate & Transport Simulation, Benzene



Criteria	0.071	0.071	0.071
T-17	11.8	0.312	0.008

Travel Time from Source

Time (Days) vs. Max. Exit Concerntrations

-▫- Criteria + T-17

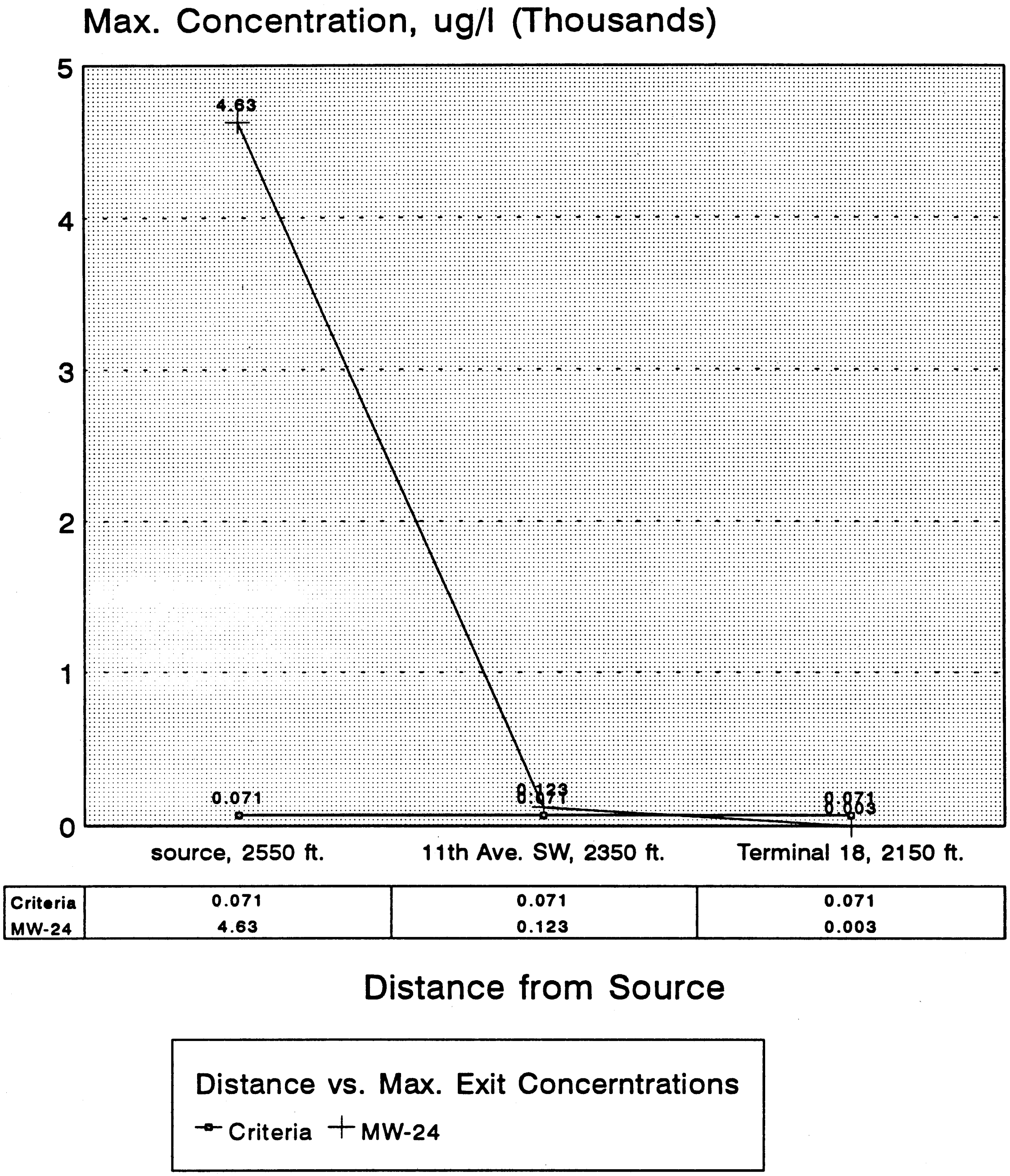
Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology,
Toxics Cleanup Program, NWRO

Drawn: Nnamdi Madakor
Date: April 27, 1997

Fig. 3: Distance vs. Max. Exit Conc. for MW-24

GATX (Former SHELL) HI. Inland Fate & Transport Simulation, Benzene



	source, 2550 ft.	11th Ave. SW, 2350 ft.	Terminal 18, 2150 ft.
Criteria	0.071	0.071	0.071
MW-24	4.63	0.123	0.003

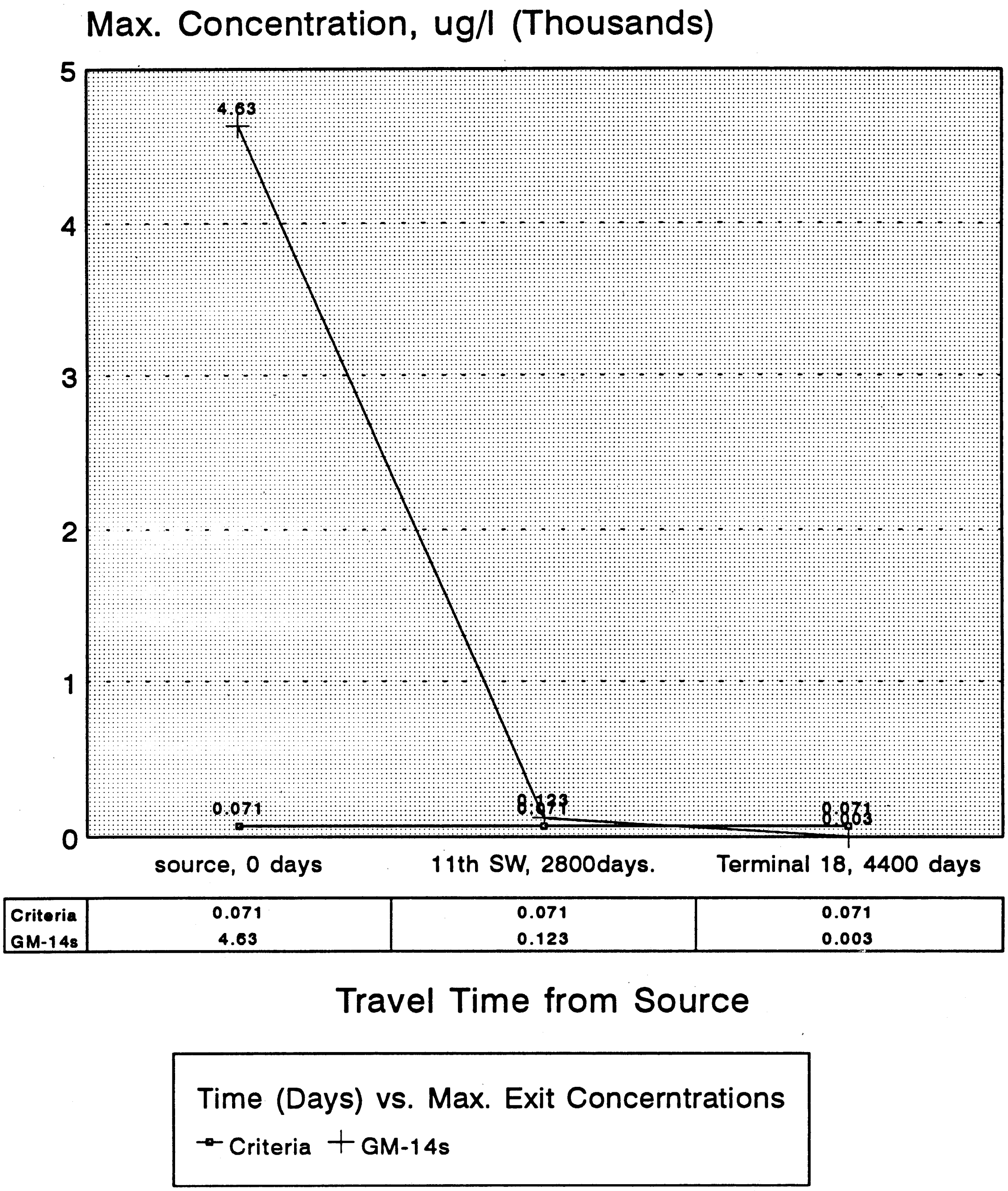
Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology,
Toxics Cleanup Program, NWRO

Drawn: Nnamdi Madakor
Date: April 27, 1997

Fig. 4: Time (Days) vs. Max. Exit Conc. for MW-24

GATX (Former SHELL) HI. Inland Fate & Transport Simulation, Benzene



	source, 0 days	11th SW, 2800days.	Terminal 18, 4400 days
Criteria	0.071	0.071	0.071
GM-14s	4.63	0.123	0.003

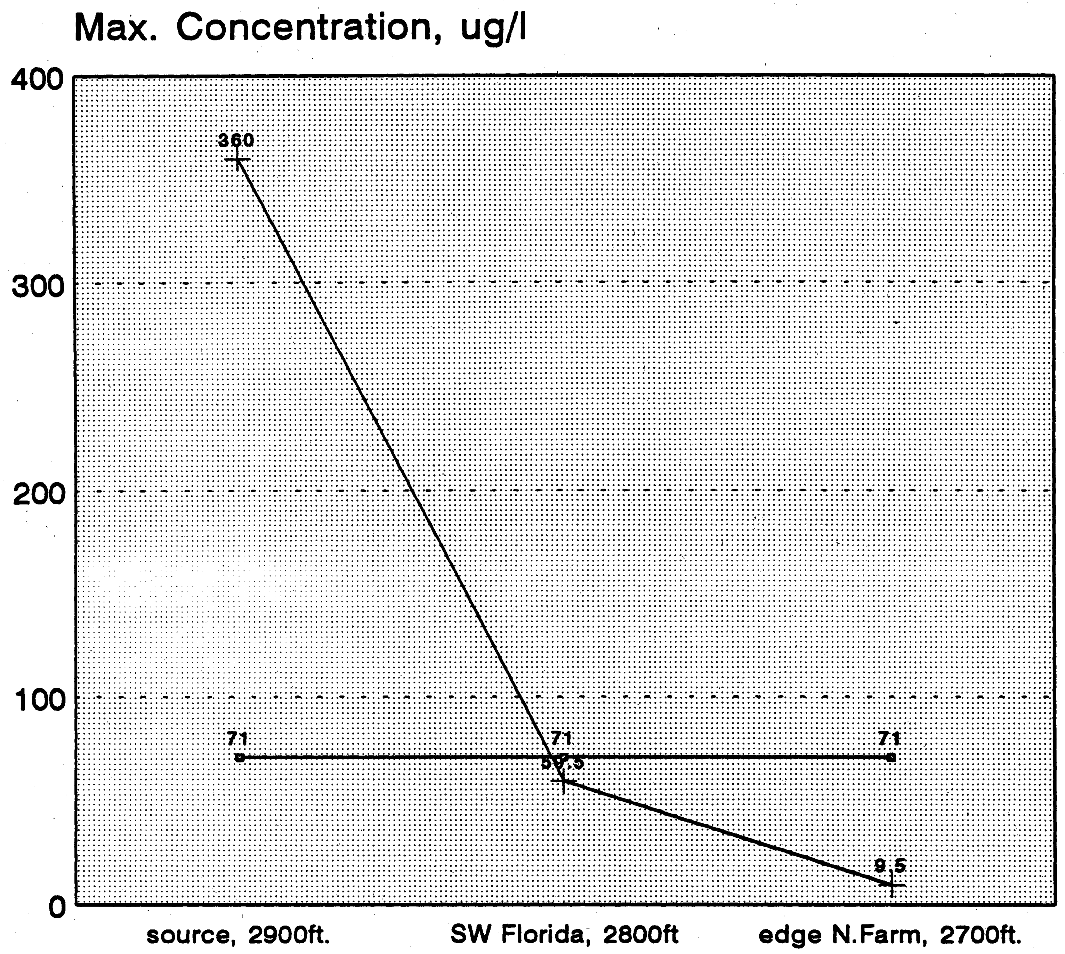
Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology,
Toxics Cleanup Program, NWRO

Drawn: Nnamdi Madakor
Date: April 27, 1997

Fig. 1: Distance vs. Max. Exit Conc. for TX-03

TEXACO OIL HI. Inland Fate & Transport Simulation, Benzene



Criteria	71	71	71
TX-03	360	59.5	9.5

Distance from Source

Distance vs. Max. Exit Concerntrations

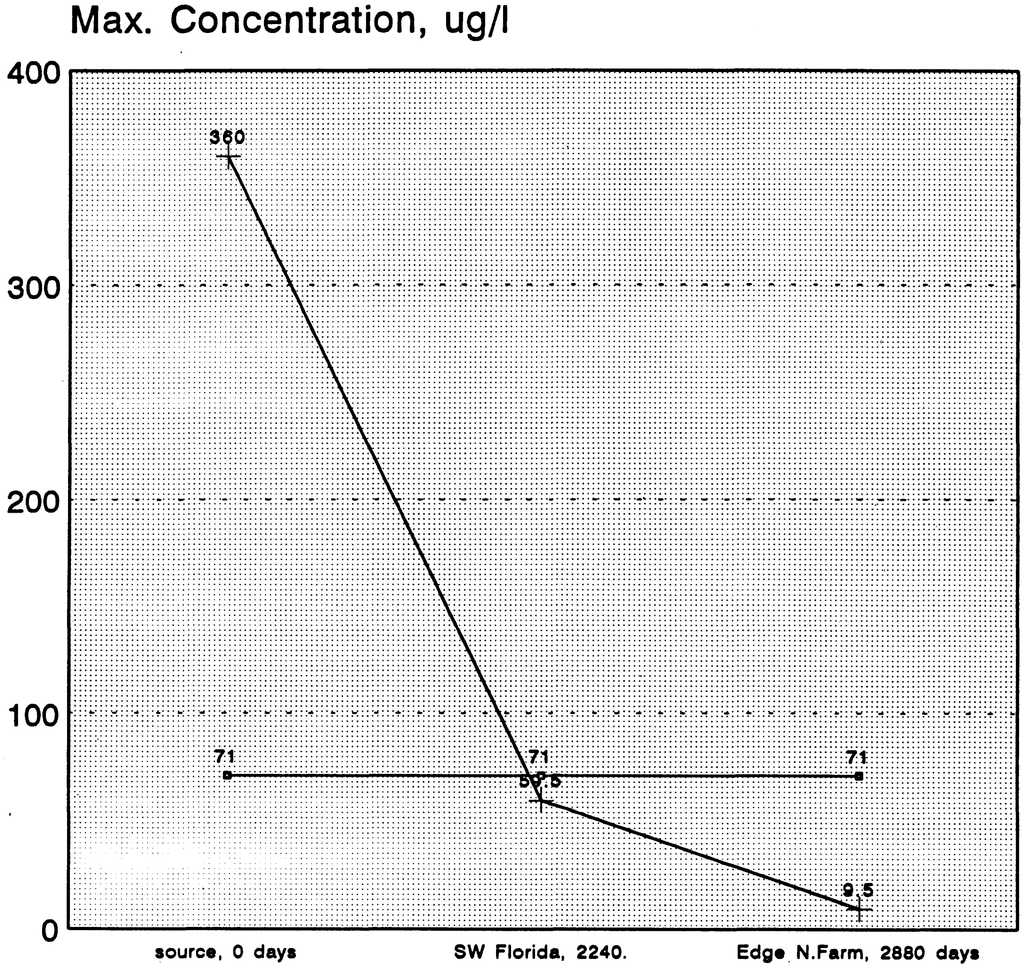
-▪- Criteria + TX-03

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 2: Time (Days) vs. Max. Exit Conc. for TX-03

TEXACO OIL HI. Inland Fate & Transport Simulation, Benzene



Criteria	71	71	71
TX-03	360	59.5	9.5

Travel Time from Source

Time (Days) vs. Max. Exit Concerntrations

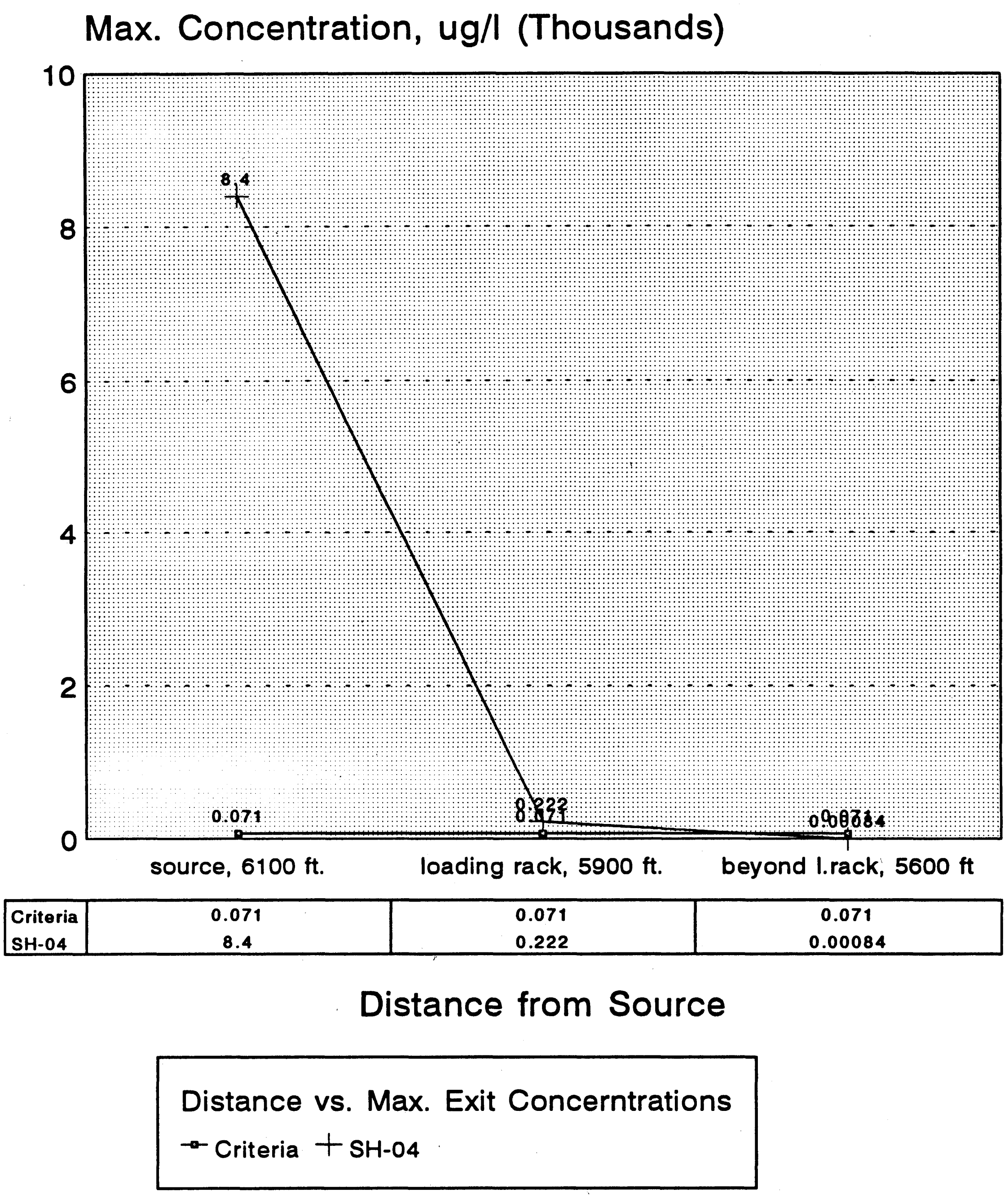
-▫- Criteria + TX-03

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 3: Distance vs. Max. Exit Conc. for SH-04

TEXACO OIL HI. Inland Fate & Transport Simulation, Benzene

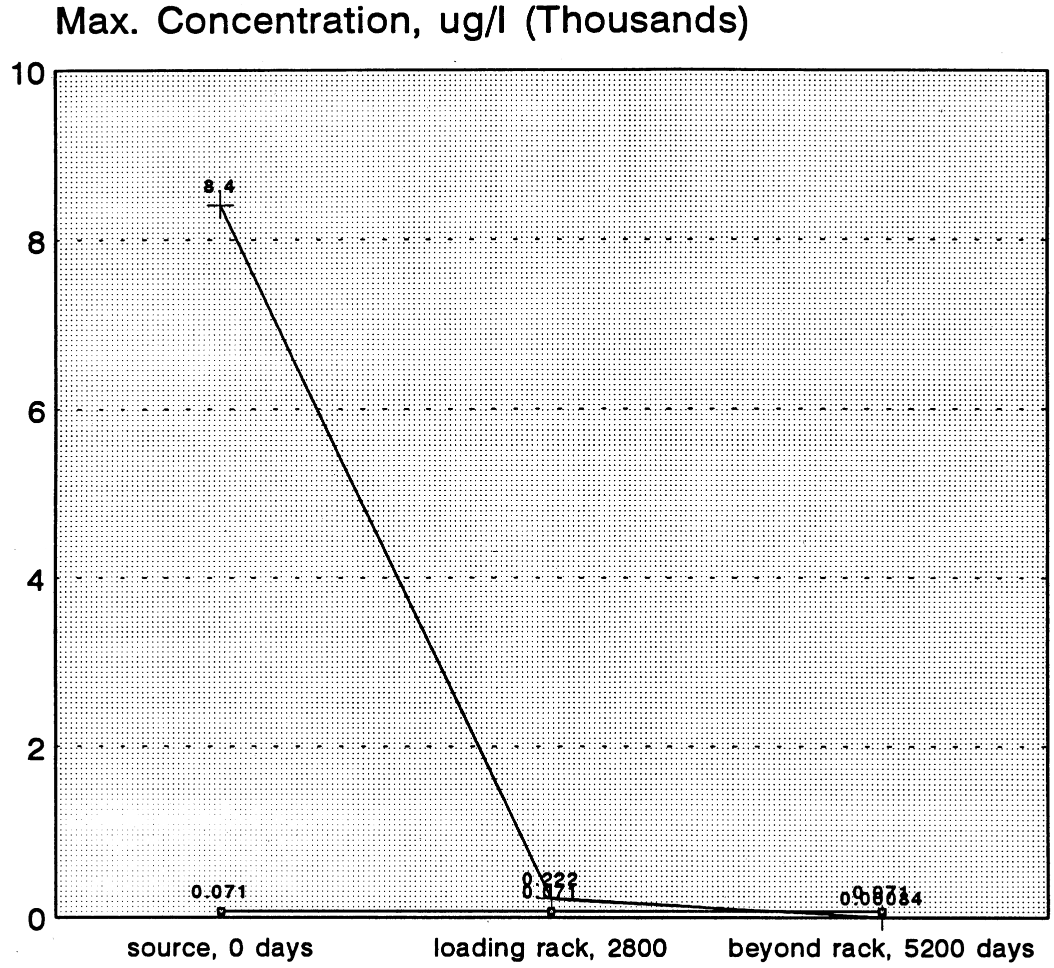


	source, 6100 ft.	loading rack, 5900 ft.	beyond l.rack, 5600 ft
Criteria	0.071	0.071	0.071
SH-04	8.4	0.222	0.00084

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology, **Toxics Cleanup Program, NWRO**	**Drawn: Nnamdi Madakor** **Date: April 27, 1997**

Fig. 4: Time (Days) vs. Max. Exit Conc. for SH-04
TEXACO OIL HI. Inland Fate & Transport Simulation, Benzene



Criteria	0.071	0.071	0.071
SH-04	8.4	0.222	0.00084

Travel Time from Source

Time (Days) vs. Max. Exit Concerntrations

-▫- Criteria + SH-04

Surface Water Criteria, Shorelines (Point of Compliance) = 71 ug/l

Department of Ecology,
Toxics Cleanup Program, NWRO

Drawn: Nnamdi Madakor
Date: April 27, 1997

APPENDIX. E

MODEL DESCRIPTION

I. INTRODUCTION: PRINCE MODEL 5

Model 5 of the Princeton Analytical Model is a two-dimensional mass transport model of an infinite aquifer using the gaussian source. The model solves the two-dimensional solute transport equation as a function of distance from the source and of time. The code predicts solute concentrations as a fraction of the initial maximum source concentration. The model calculates these relative maximum source concentrations beneath a source and downgradient of the source. It assumed that the aquifer is of infinite width and distances downgradient are much larger than the length of the analysis. This assumption is not met by the case studies presented in this article, because aquifer analysis terminates at the shoreline.

II. ASSUMPTIONS AND LIMITATIONS

A. Aquifer has a finite width (shorelines) in both the x and y directions.

B. Pollutant source is a Gaussian (i.e., bell-shaped) source lying along the y-axis at X=0. Source concentration is largest at the center, and at a maximum at the initial time of the analysis. The extent of the source is governed by the source spread factor.

C. Ground water flow is two-dimensional in the area of interest with specified velocities in the x and y directions.

D. Aquifer parameters are constant temporally and spatially.

III. BOUNDARY CONDITIONS

1. Source releases solute into the aquifer system at a rate that is controlled by two terms; for any time t, the maximum source concentration (located at YO) is CP(t); the source concentration around CP(t) is modeled by a Gaussian shape curve

2. Background concentration is zero

3. Concentration is at the background level for distances far from the source.

Since the model approach of the fate and transport presented in this article assumed that the source of the contaminant solute is located downgrdient of a known hot spot, the boundary conditions of 2 and 3 of the above are not met. See Section 1.2, page 2, Model Approach.

IV. PROCESSES MODELLED

1. Major transport mechanism for solute transport is advection

2. Dispersion of the solute plume occurs in both x and y directions

3. Solute retardation or decay as a first order reaction equation

A. Dispersion:

As a contaminant fluid flows through a porous medium, it will mix with uncontaminated water. The result will be a dilution of the contaminant by a process known as dispersion. Dispersion is an important attenuation mechanism which results in the dilution of a contaminant. The degree of spreading or dilution is proportional to the size of the dispersion coefficient in mass transport models.

Benzene was addressed by this model. The migration of this contaminant was evaluated by specifying a concentration of the chemical at monitoring well locations where constituents are detected. Transport simulation is then evaluated from these points to a potential receptor at the shoreline.

A.1. Longitudinal Dispersivity (α_l):

The mixing that occurs along the streamline of fluid flow is called longitudinal dispersion and it is a scale dependent parameter within an aquifer which produces spreading of the contaminant front due to permeability variations (hetergenity). There are three basic causes of longitudinal dispersion:

- As fluid moves through pores, it will move faster through the center of the pore than along the edges

- Some of the fluid will travel in longer pathways than other fluid

- Fluid that travels through larger pores (sorted sand, gravel, sandstones) will travel faster than fluid movement in smaller pores (clays, silts, glacial till)

A.2. EPA "1/10" Rule:

EPA has recommended the "1/10" rule where the longitudinal dispersivity is defined as:

$\propto_x = 0.1X$ (where X is the distance of interest)

The one-tenth rule recommended by EPA estimates dispersivities in screening studies where no data exist. Typically longitudinal dispersity is set equal to 1/10th of the modelled flow length.

For example, longitudinal dispersion of a contaminant (benzene) at Arco Plant 1, Harbor Island located at a coordinate X,Y defined as monitoring point, GM-14s, within a distance of about of 240 ft. from the shoreline of the West Waterway is:

$$\begin{aligned} {}^1\propto_x &= 0.1X \\ &= 0.1 \times 240 \text{ ft.} \\ &= 24 \text{ ft.} \end{aligned}$$

A.3. [1]Prof. Shlomo Nueman:

Prof. Nueman recommends using the following empirical relationship to determine longitudinal dispersion:

$\propto_x = 0.0175 \text{ L1.46}$ (where L is the flow length)

$$\begin{aligned} {}^2\propto_x &= 0.0175 \times 240 \times 1.46 \text{ (for X,Y at GM-14s)} \\ &= 6.132 \text{ ft.} \end{aligned}$$

Values of $\propto_x$ range from 1.476 to 3.15 ft. (0.45 to 0.96 m) in carefully controlled field experiments in sandy aquifers using tracers. However, larger values of $\propto_x$ typically in the range of 9.843 to 98.43 ft. (3 to 30 m) have been published in numerical modeling studies where the dispersivity was determined by calibrating the numerical model to field data.

The Harbor Island area-wide model conducted by EPA used 1.64 ft (0.5 m) for $\propto_x$. Prof. Neuman's approach falls within this range.

A.4. Scheidegger Relationship:

The longitudinal dispersion coefficient, Dx, in units of L^2/T

---

[1] Waterloo Hydrogeologic Software

from the Scheidegger relationship is defined as:

$Dx = \alpha_x V$

where:

α_x = is the longitudinal dispersivity (L)

V = is the seepage velocity (L/T)

Dx for site maximum groundwater velocity, when V = 0.14 ft/day is:

^1Dx = 24 ft. x 0.14 ft/day (EPA at location GM-14s)
= 7.7 ft^2/day

^2Dx = 6.13 ft. x 0.14 ft/day (Prof. Neuman at GM-14s)
= 0.854 ft^2/day

Dx for site minimum groundwater velocity, when V = 0.04 ft/day is:

^3Dx = 24 ft. x 0.04 ft/day (EPA at location GM-14s)
= 0.96 ft^2/day

^4Dx = 6.13 ft. x 0.04 ft/day (Prof. Neuman at GM-14s)
= 0.244 ft^2/day

A.5. Transverse dispersity (α_T):

Lateral dispersion is branching or splitting of flow paths as fluids containing contaminants flow through a porous medium. Lateral dispersion occurs even in the laminar flow conditions that are prevalent in ground water flow.

Dy is the transverse longitudinal dispersion coefficient in units of L^2/T and from the modified Scheidegger relationship is defined as:

$Dy = \alpha_y V$

where:

α_y = is the transverse longitudinal dispersivity (L)

V = is the seepage velocity (L/T)

Values of α_y range from 0.00328 to 0.16 ft. (0.001 to 0.05 m) in carefully controlled field experiments in sandy aquifers using tracers. However, larger values of α_y typically in the range of 3.281 to 32.81 ft. (1 to 10 m) have been published in numerical modeling studies where the dispersivity was determined by calibrating the numerical model to field data.

B. Advection:

Contaminants that are advecting are traveling at the same rate as the average linear velocity of the ground water, and the rate of flowing ground water can be determined from Darcy's law as;

$$V_x = \frac{K}{n_e}\frac{dh}{dl}$$

where:

V_x = average linear velocity
K = hydraulic conductivity
n_e = effective porosity
$\frac{dh}{dl}$ = hydraulic gradient

Table B.1: Arco Oil HI Velocity Calculations

Hydraulic Condty. (K) 7.5 ft/day

Porosity (n) 0.35

	Maximum		**Minimum**		**Across**	**Extent**
	Gradient	**Velocity**	Gradient	**Velocity**	Gradient	**Velocity**
East	0.00549	0.1176429	0.00119	0.0255	0.00163	0.0349286
West	0.00935	0.2003571	0.00259	0.0555	0.00466	0.0998571
North	0.00775	0.1660714	0.00312	0.06685714	0.00215	0.0460714
South	0.00275	0.0589286	0.00096	0.02057143	0.00097	0.0207857
Ave.		0.13575		0.042107		0.0504107

VELOCITY SELECTED FOR THE FATE AND TRANSPORT IS 0.1 FT/DAY

Table B.2: Velocity Summary Calculations for K, and n Values Arco Oil Harbor Island

K (ft/d)	n	Velocity
7.5	0.35	0.0504107
6.2	0.35	0.0416729
32	0.35	0.2150857
7.5	0.3	0.0588125
6.2	0.3	0.0486183
32	0.3	0.2509333

Source Geraghty & Miller Arco RI Report.

Table B.3: Harbor Island Velocity, Hydraulic Conductivity and Porosity Summary Calculations

PARAMETER	MODEL*	EPA- RI	LOCKHD.-RI	ARCO-RI	TEXACO-RI	GATX-RI
Shallow K	1) 7.5 ft/day	0.0022 cm/s (6.2 ft/d) 0.003 cm/s 8.5 ft/d ** 0.015 cm/s (42 ft/d)	0.29 ft/d 34 ft/d 7 ft/d**	0.0113 cm/s 32 ft/d	0.022 cm/s 62 ft/d 0.01 cm/s 28 ft/d	Yd. B. 0.003cm/s 8.5 ft/d Yd. C. 0.008cm/s 22 ft/d Yd. D. 0.01cm/s 28 ft/d
Sy	0.21			0.21		
Ss	0.0001			0.00033cm 0.0001ft.		
Porosity	.35			.35		.41
Recharge/yr.	15"		34.2"	31"	31"	35-39"
Aquifer Thickness	35 - 80'	25'	33'	21'		

Source: EPA, Lockheed, Arco, GATX, Texaco RI/FS
** Used in flow model baseline respectively
* Values used in flow model calibration to empirical field data

C. First Order Decay:

K is first order decay constant in units of (1/T). It is difficult to determine in the field due to the multitude of factors affecting it. Typical values for BTEX compounds have been reported in the range of 0.0002/day to 0.025/day. For chlorinated aliphatic compounds such as PCE, TCE, 1,1-DCE, 1,1,1-TCA, typical reported values have been between 0.00013/day and 0.0038/day (after Salanitro, 1993 and Olsen & Davis, 1990).

Many abiotic and biodegradation reactions decay according to first order kinetics. Abiotic reactions include hydrolyzation of chlorinated hydrocarbons known as reductive dechlorination and radioactive decay. Examples of natural biodegradation in soils include the decay of petroleum hydrocarbons such as BTEX.

The half life of benzene ranges from 10 days to 730 days
EPA used a half life of 400 days for benzene to compute the first order decay constant for the Harbor Island-wide fate and transport model simulation.

First Order Decay constant;

K = 0.693/T per day
T = half life of the contaminant/day
T = 400 days
K = 0.693/400
K = 0.001733

D. Gamma:

Gamma is the first order decay constant for the Gaussian distribution boundary condition source. It has units of (1/T). This boundary condition is expressed mathematically as C = Cmax exp [- GAMMA X t][Gaussian distribution]

When gamma is zero, one has only a Gaussian distribution boundary condition. When Gamma is greater than zero, the Gaussian distribution boundary condition decays exponentially with time.

Gamma is used when the source strength dilutes (for example, by rainfall infiltration) or decays (for example, by biodegradation or reductive dechlorination) exponentially with time.

Microbial organisms in the soil will degrade hydrocarbons which serve as energy and carbon sources. Oxygen is required for significant microbial degradation of hydrocarbon which is carried out largely by aerobic bacteria. Normal alkanes seem to be most subject to microbial degradation, followed by cycloalkanes and aromatics (Calabrese, 1993)

Upland areas of the Tank Farms presented in this simulation are not paved, hence subject to infiltration, dilution, and further degradation. By setting gamma to zero, (assuming no infiltration, no dilution, no further degradation), a conservative or worst case condition is presented in this exercise.

E. Retardation:

RD, sometimes given the symbol R_f or R, is the retardation factor. Retardation results when a solute sorbs to soil particles or organic matter in soil. It is defined as the water velocity divided by the solute velocity.

When the solute travels at a velocity less than the ground water velocity, R_f is > 1.0. However, if the solute travels faster than the ground water velocity (very rare, but can occur for viruses), R_f is < 1.0. When the solute travels at the same velocity with the ground water, R_f = 1.0 (no retardation)

The retardation factor is also expressed by the following equation;

$$R_f = 1 + \frac{\rho_b K_d}{\eta} = \frac{V_w}{V_c} = \frac{X}{X^*}$$

where:

R_f = retardation factor, dimensionless

K_d = distribution (adsorption) coefficient, gram/mL
ρ_b = bulk density of soil, gram/cm^3
V_w = velocity of ground water (L/T)
V_c = velocity of solute or contaminant
η = effective porosity, dimensionless
X = distance traveled by uncontaminated ground water
X^* = distance traveled by contaminant (solute) for a given time

Solutes are considered in two broad classes: *conservative* and *reactive*.

Conservative solutes do not react with the soil and/or native ground water or undergo biological or radioactive decay. The chloride ion is a good example of a conservative solute. These substances will have a retardation factor close to 1.

Reactive substances can undergo chemical, biological, or radioactive change that will tend to reduce the concentration of the solute or slow their movement through soil. Chemical reactions include cation exchange, precipitation-dissolution, and oxidation-reduction. Many of the heavy metals are readily adsorbed onto solid surfaces or trapped by clays through ion exchange. Biological reactions may be either aerobic, in the presence of oxygen or anaerobic, in the absence of oxygen.

The distribution/absorption (K_d) coefficient for an organic compound in a specific soil can be approximated by the organic carbon partitioning coefficient (K_{oc}) for that compound times the dry weight fraction or percent of solid organic carbon in the soil (TOC). If the soil is pure silica sand there will be very limited retardation.

E.1 Sorption:

K_d describes the tendency of a chemical to adsorb to soil from solution. Adsorption refers to the process by which a chemical species passes from one bulk phase to the surface of another phase and accumulates on the structure (Fetter, 1988). The higher the K_d value for a chemical, the greater is its potential adsorption to solid phase materials and conversely, the lesser its potential to stay in aqueous solution.

Adsorption by porous media may reduce the total amount of oil transport to ground water, reduce concentrations in the groundwater, and delay transport. Several halogenated aliphatic hydrocarbons, polynuclear aromatic hydrocarbons, and benzene tend to exhibit a linear sorption isotherm for concentrations lower than half their solubility in water.

Some of these dissolved constituents may be adsorbed by some types of soils in the saturated zone, but they could be desorbed by relatively cleaner recharge waters (Calabrese, 1993). *High concentrations of CPAH are observed in the monitoring wells along the shorelines of the ARCO site on Harbor Island. This area of the Harbor Island Waterways is considered tidally influenced with high flux due to groundwater reversals. It is possible that desorbing of CPAH from the soil to groundwater is taking place at this location evidenced by the observed high concentrations in the groundwater monitoring wells.*

When $K_d = 0$ (no adsorption), $K_d < 100$ (adsorption potential is low), > 1000 (high), between 100 to 1000 (intermediate).

The organic carbon partitioning coefficient, K_{oc}, also referred to as the soil sorption (binding) coefficient, is a physio-chemical property that can be used to predict the potential of an organic chemical to partition between soil and water, taking into account the presence of organic carbon in the environment. The K_{oc} provides a prediction of the mobility of an organic chemical because it is largely independent of sediment properties (Lyman et al, 1982).

Typically, K_{oc} values range from one to ten million, with higher values indicative of greater sorption (binding) potential. $K_{oc} <$ 50 (very mobile), 50 to 100 (mobile), 150 to 500 (intermediate), 500 to 2000 (low), and > 2000 are relatively persistent (or relatively immobile) (Fetter, 1988).

E.1.1. Site Specific Kd Calculation:

K_{oc} = 83 (for benzene, EPA 1986, Mercer et al. 1990)

TOC = 994 mg/kg (site specific average of 12 soil samples Shell RI Report, HI. for the Tank Farms)

$1/10^{-6}$ = 1 kg/10^{-6} mg (conversion factor)

*TOC = 1028.7 (*value used by EPA for the Harbor Island-wide fate and transport model)

K_d = $K_{oc} \times TOC \times 1/10^{-6}$
= $83 \times 994 \times 1/10^{-6}$
^1K_d = 0.0825 (benzene's solubility is 1780 ppm, mobility is high, after C.W. Fetter, 1988)

* = 0.0854 (*K_d = benzene value used by EPA HI model)

E.1.2. Site Specific Retardation Factor for Benzene

ρ_b = average bulk density of soil, gram/cm^3, was calculated from 15 shallow soil samples, Arco-RI, 1994
= 95 lb/ft^3 ÷ 62.42796

$= 1.52\ \mathrm{gram/cm^3}$

$* = 1.70\ \mathrm{gram/cm^3}$ (*EPA Harbor Island wide data used)

$\eta = 0.35$ effective porosity-Arco RI, 1994

$* = 0.30$ *EPA Island wide data used

$$^1R_f = 1 + \frac{\rho_b\ ^1K_d}{\eta} = \frac{V_w}{V_c} = \frac{X}{X^*}$$

$$= 1 + \frac{1.52 \times 0.0825}{0.35}$$

$^1R_f = 1.36$ (benzene)

$* = 1.48$ (*R_f value used by EPA HI wide model)

EPA Harbor Island wide fate and transport model used $R_f = 1$ (no retardation) for all organic materials for comparison purposes against inorganic materials that were assigned the following retardation factors (R_f); zinc = 1, 60, 130, cadmium = 1, 77, 170, for all other inorganics the same range of 1, 77, and 170 were assigned.

F. Ton:

Ton is Time on and it represents the initial time of source release. It is the initial starting time (in any consistent time units) when the concentrations along the Gaussian distribution are activated.

G. Toff:

Toff is Time off. It is the ending time (in any consistent time units) when the concentrations along the Gaussian distribution source are turned off or set to zero.
For steady state problems, Toff is set to a very high value or a value greater than the time selected later to graph the results to guarantee the source will always be present.

If Toff is less than the time selected in the Graph Parameters menu later, one will have a separated plume downgradient from the location of the strip source. This is the case when cleanup is initiated and Toff equals the time the source was removed.

Times greater than Toff then show the residual contamination moving and attenuating downgradient from the removed source.

A Time off that range from 2000 to 4000 days was evaluated in this model with the exception of GATX where 150 days was evaluated due to the fresh hydrocarbons present at the site.

H. C_{MAX}:

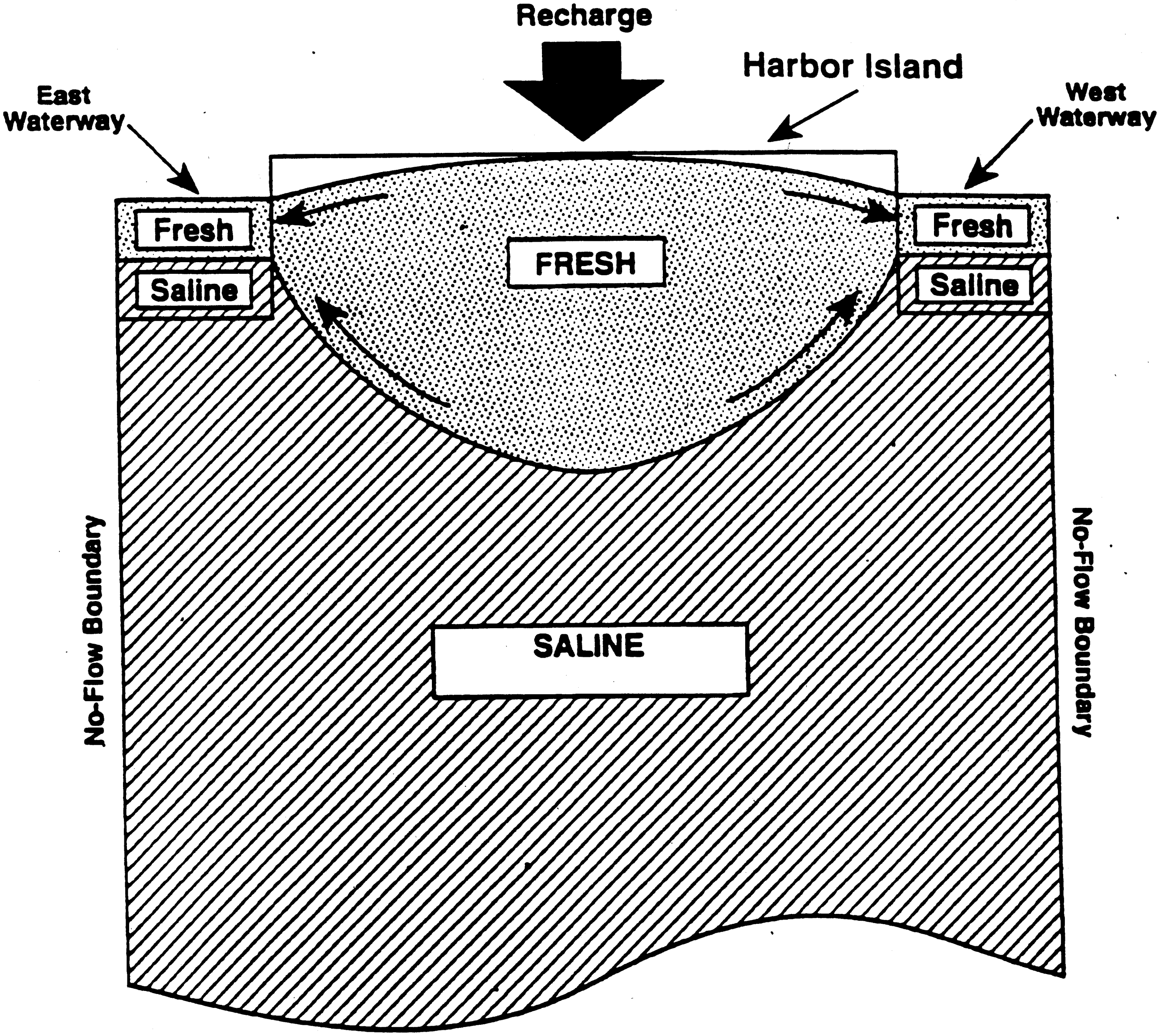
C_{MAX} is the maximum concentration of the Gaussian distribution and occurs at the center of the source located at Xo,Yo. Any concentration units may be used or C_{MAX} may be set to 1.0 in the case of normalized concentrations.

J. Theta:

Theta is the direction of the uniform ground water velocity measured positive counterclockwise from the X-axis in degrees from 0 to 360 (X-axis lies on the line with the horizontal coordinate of the DXF site map). For example, 0 = due East, 90 = due North, 180 = due West, and 270 = due South.

APPENDIX. F

HARBOR ISLAND CONCEPTUAL GROUNDWATER FLOW DYNAMIC (After EPA RI, R. Weston, 1993)



Conceptual Model for Groundwater Flow andTransport

FIGURE

F-1

WESTON

DATE. January 1993