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**OILFIELD PRODUCED WATER TREATMENT USING
CONSTRUCTED SURFACE FLOW
AND WETLAND SYSTEMS**

by

Daniel Gelb

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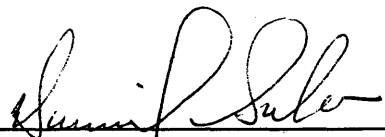
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Ecological Engineering).

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ABSTRACT

Produced water is the largest volume waste associated with oil and gas production and requires reliable means of disposal or treatment. In October, 1990, the State of Wyoming, Marathon Oil Company and the Colorado School of Mines entered into a cooperative venture to assess the potential of constructed surface flow and wetland systems for the treatment of produced water for surface discharge.

Marathon's Pitchfork Field, located near Cody, Wyoming, was selected as the site for a pilot treatment system. This field discharges about 10,000 to 18,000 barrels of produced water per day. The TDS of this discharge ranges from 2340 - 2580 mg/l and is comprised of mostly bicarbonate, calcium, magnesium, chloride, sodium and sulfate. The effluent is toxic and tests yield an LC 50 for Ceriodaphnia of 53.59% and an LC 50 for Fathead Minnow of 61.56%. Sulfide concentration ranges from 16.8 - 48 mg/l. Radium 226 ranges from 19.7 - 42.2 pCi/l. Total phenolics range from 130 - 150 ug/l.

Four 5000 sqft surface flow cells and one 33,000 sqft wetland were constructed for the pilot system in May, 1991. The system utilizes a combination of mechanical, chemical and biological processes for treatment. The treatment mechanisms include: air stripping; precipitation of carbonates and radium; ion exchange; and microbial degradation and oxidation.

Field measurements and constituent analysis were performed on the inflow and outflow of each cell to assess treatment performance. The sampling occurred from July 1991 through January 1992 at flows of 1000, 2000, 3000 and 4000 BPD. Thirteen sets of data were produced.

The data indicate that the system generally improves water quality, though the results are variable. Bicarbonate was removed by an average 6%, radium by an average 21%, sulfide by an average 39%, BTEX by an average 82% and total phenolics by an average 31%.

Many variables affect the system performance. Water temperature, pH and wind and solar intensity were identified as influencing performance. Other performance variables are believed to exist, but were not identified.

Design criteria were developed from the study data for the design of future systems. The design method determines the treatment cell size required for a desired constituent concentration reduction, given a constituent mass loading and flow rate.

Constructed surface flow and wetland systems provide an inexpensive means of produced water treatment using available technology and materials. They have been shown in this study to remove constituents of concern from produced water. The ultimate feasibility of these systems hinges on a better understanding of system performance variables and safety issues regarding the accumulation and release of removed constituents.

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DEDICATION

This work is dedicated to my family for their unending encouragement and support of not only this work, but all of my endeavors. It is especially dedicated to my father and grandfather whose inventiveness and craftsmanship have always inspired me.

Chapter 1 INTRODUCTION

1.1 Purpose and Objectives

This thesis is the result of research on an experimental system designed to treat oilfield produced water. The research is a joint effort between the Colorado School of Mines, Marathon Oil Company, the U. S. Environmental Protection Agency, the Wyoming Department of Environmental Quality, and the Wyoming Game and Fish Department. It is believed that produced water can be modified in a cost-effective, engineered treatment system such that it meets all permit standards and can be safely released into the environment.

Many benefits may be realized if such a system is successful. Oil and gas producers may gain more flexibility in the handling and disposal of this production waste. As well, treatment systems of this type may provide a more affordable means of produced water disposal than those currently employed. In arid regions, federal, state and local governments may benefit from a clean source of water for wildlife habitat. Residents in the proximity of oil and gas production facilities may be able to use this source of water for livestock watering or irrigation.

The treatment system studied in this thesis is located at a Marathon Oil Company facility in northwest Wyoming. Marathon is subject to a National Pollutant Discharge Elimination System (NPDES) permit for the surface discharge of produced water generated at this facility. The deadline for discharge permit

compliance is July 1, 1992. The discharge presently exceeds the permit limitations for radium 226 and toxicity. Given this deadline, the primary goal of this study is to assess the feasibility of immediate application of these treatment systems.

To achieve this goal in the time available, a broad-based approach was used to study the system. All major constituents typical to produced water were monitored under a wide range of flow rate and ambient conditions. Within this broad-based study, there were several specific objectives.

They include:

- assess the integrity of the treatment system and components
- assess the removal of typical produced water constituents
- identify treatment system performance influences and trends
- develop design criteria for future surface flow and wetland based produced water treatment systems
- address feasibility of surface flow and wetland treatment systems

1.2 Scope and Characteristics of Produced Water

The United States oil and gas industry is a multi-billion dollar industry producing some 8 million barrels of crude oil and 44 billion standard cubic feet of natural gas per day from nearly 800,000 wells at over 70,000 sites (Perry and Gigliello, 1989). However 2 to 99% of all the fluids produced from oil and gas wells are formation water. This formation water, referred to here as "produced water", is also known as connate, brine or saltwater. Nearly 21 billion barrels of produced water are pumped to the surface each year, representing the largest

volume of waste associated with oil and gas production (Perry and Gigliello, 1989).

Produced water is believed to originate as sea water present at the time of sediment deposition in the petroleum bearing formation. Due to physical and chemical reactions before, during and after sediment consolidation, the chemical characteristics of this water are modified (Van Sickle, 1989). Produced water typically contains varying concentrations of organic hydrocarbons, salts, heavy metals and radioactivity. Due to the presence of these constituents, produced water is generally considered toxic.

Hydrocarbons are typically present as oil and grease, benzene, toluene, ethylbenzene, xylenes and polycyclic aromatic hydrocarbons. Ions generally present in significant quantities include: sodium, potassium, calcium, magnesium, silicon, chloride, barium, strontium, bicarbonate, sulfate and sulfide. Metals that occur in produced water vary widely between regions but may include some of the following: iron, zinc, molybdenum, manganese, and arsenic. Radioactivity is present as radium 224, 226 and 228. Radium 224 decays relatively quickly. Because Ra 226 and Ra 228 exhibit similar chemical behaviors, Ra 226 is typically used for radium activity measurements (Subramonian, et al, 1990).

Concentrations of these constituents varies widely between regions or even from well to well in a given field. Water quality ranges from potable to over 20% total contaminants. Table 1 gives several examples of constituent concentration in produced water.

Table 1 - Examples of various produced water constituent concentrations

Location: Alberta/Saskatchewan, Canada

TDS	12,000 - 64,000	(mg/l)
Conductivity	16,000 - 74,000	(mg/l)
Sodium	3,500 - 20,000	(mg/l)
Chloride	5,900 - 38,000	(mg/l)
Oil and Grease	10 - 310	(mg/l)

Source: Kok, et al, 1989

Location: Offshore Louisiana

TDS	152,660 - 212,100	(mg/l)
Sodium	52,248 - 76,300	(mg/l)
Calcium	3,840 - 3,850	(mg/l)
Chloride	130,000 - 94,000	(mg/l)
Bicarbonate	87 - 204	(mg/l)
Oil and Grease	27 - 574	(mg/l)

Source: Chen, et al, 1991

Location: State of Wyoming

Radium 226	0 - 2,152	(pCi/l)
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Source: Wagner, 1990

Location: Southeast Louisiana

Radium 226	355 - 567	(pCi/l)
Barium	1,521 - 4,644	(ppb)
96hr Acute Toxicity LC50	2.6 - 5.8	% effluent (mysid)
96hr Acute Toxicity LC50	7.2 - 33.8	% effluent (sheepshead minnow)
Ocean Salinity	35,000	(ppm)

Source: St. Pe, 1990

Location: various, including Texas, Oklahoma, Louisiana

TDS	46,661 - 158,670	(mg/l)
Sodium and Potassium	17,258 - 46,000	(mg/l)
Calcium	881 - 9,226	(mg/l)
Magnesium	498 - 1,791	(mg/l)
Barium	0 - 127	(mg/l)
Chloride	29,573 - 101,479	(mg/l)
Sulfate	0 - 157	(mg/l)

Source: Ostroff, 1979

1.3 Wyoming NPDES Permit Requirements

NPDES permits may be issued by U.S. Environmental Protection Agency (EPA), or that authority may be delegated to the individual states. The State of Wyoming has had primacy in this matter since 1974. NPDES permits are issued by the Wyoming Department of Environmental Quality (DEQ) and are valid for a period of 5 years (Wagner, 1990, 1991). The Wyoming produced water effluent standards were adopted in 1978 and are shown in Table 2.

Table 2 - State of Wyoming produced water effluent standards

<u>Parameter</u>	<u>Standard</u>
Chlorides	2,000 mg/l
Sulfates	3,000 mg/l
Total Dissolved Solids	5,000 mg/l
Oil and Grease	10 mg/l
pH	6.5 - 8.5 standard units
Toxic Substances	None in concentrations or combinations that are toxic to human, animal, or aquatic life

Source: Wagner, 1990

In 1987, the Wyoming DEQ determined that the toxicity standards were generally not being achieved. Under Section 304(1) of the federal Clean Water Act, the state is required to identify its toxic discharges and develop a strategy for eliminating the toxicity by July, 1992 (Wagner, 1990). Wyoming addressed this issue by categorizing the discharges and implementing a strategy to eliminate toxicity on a prioritized basis.

The toxic discharges are prioritized by receiving water type, identified as Class 1, 2, 3 or 4 streams. Within the stream classification, there exists three separate categories for implementation of the NPDES program. These categories are identified by Wagner (1990) as:

- Category 1 - Discharge flows immediately into a class 1, 2, or 3 water.
- Category 2 - Discharge flows into a class 1, 2, or 3 water after travelling significant distance in a class 4 water.
- Category 3 - Discharge will not reach a class 1, 2, or 3 water under dry weather conditions.

Discharges meeting category 1 criteria must be in full compliance of their permit by July 1, 1992, which includes the following modifications (Wagner, 1990):

1. A requirement to conduct two species Ceriodaphnia and fathead minnow acute toxicity tests on at least an annual basis;
2. A requirement to eliminate toxicity by July 1, 1992; and
3. A list of three options for achieving compliance, including:
 - a. Treatment to remove acute toxicity;
 - b. Elimination of the discharge; or
 - c. Passing the two species chronic toxicity tests by utilizing the dilution factor in the receiving stream.

The State will initiate action on category 2 discharges after July 1992 and presently has no intent of addressing category 3 discharges.

The standards for radium are also classified by stream type. Discharges into Class 1 and 2 waters are limited to a maximum concentration of Ra 226 plus Ra 228 of 5 pCi/l, and discharges into Class 3 and 4 waters are limited to 60 pCi/l. Enforcement of this standard will begin in 1992. It will be implemented such that

20% of the discharges will be permitted each year for the next 5 years (Wagner, 1991).

In some cases, radium permit standards allow for dilution by the receiving water. The allowable radium standard may be increased proportionally with the degree of effluent dilution. In this study, the dilution ratio is 38% effluent to 62% receiving water, resulting in an allowable radium discharge of 13.2 pCi/l.

1.4 Produced Water Disposal Alternatives

Many produced water treatment and disposal alternatives are available, though only a few are widely used due to their cost and feasibility. Current disposal methods include: deep well injection for secondary recovery of petroleum; injection into Class 2 disposal wells, evaporation in lined ponds and mechanical evaporators; and surface discharge.

Deep well injection for secondary recovery is an attractive disposal technique, since the produced water is usually injected into the formation zone where it originated, and the costs associated with disposal can be offset by an increase in petroleum production. The problems associated with this method include: water-to-oil production ratios will increase over the life of the field, requiring more water disposal with less cost offsetting by oil production; due to formation characteristics, the formation may not be able to accept all of the water produced; some pretreatment is required before injection; and a surplus of water may result when injection wells are shut-in for service.

Deep well disposal facilities generally consist of a transportation system, collection center, pretreatment facility, injection facility and injection well. They are widely used since they offer a relatively low cost alternative and are presently perceived as a permanent solution. However, in many cases a suitable facility or injection zone is not available, adding significant transportation costs to the disposal. Also, formations vary in their ability to receive injection water. Cavernous limestones may be capable of injection rates of several thousand gallons per minute with minimal injection pressure, while dense sandstones may require 2000 psi to inject 100 GPM (Ostroff, 1979).

Though on the lower end of the cost spectrum, injection wells are not inexpensive. New facility installation costs range from \$1 - \$3 million, and

conversion of production wells runs from \$200,000 to \$300,000 (Pietri, 1992). Operating costs can range from as little as \$0.04 per barrel for on-site disposal (Brus, 1992) to \$1.50 to \$2.50 per barrel if the water is hauled and disposed of at another facility (Crist, 1990).

Evaporation ponds and mechanical evaporators each have their own inherent feasibility problems. Both concentrate the waste and leave a residual slurry or solid requiring disposal. Evaporation ponds are considered an eyesore by the public and can require huge tracts of relatively flat land for their installation. Mechanical evaporators can be prohibitively expensive when large volumes of water are produced. As well, significant operating costs can result from providing the energy required for evaporation and physical handling of solid wastes.

Surface discharge generally requires pretreatment and permitting. Permitting standards have been and will continue to be increasingly stringent, and thus require effective pretreatment methods. Many accepted treatment options are prohibitively expensive and explain the widespread use of injection facilities. Permitting requirements are discussed in section 1.3. Pretreatment options are discussed below.

There are many treatment options available. Each employs a chemical or mechanical means (or some combination) of separating solids from the produced water, and thus results in some form of residual waste requiring disposal. Treatment alternatives include: membrane separation (reverse osmosis, cross flow ultrafiltration/microfiltration); ion exchange resins; freeze desalination; electrodialysis and multistage flash distillation. Each of these methods requires some form of pretreatment. Pretreatment requirements may include: oil separation; induced gas flotation; air stripping; pH adjustment; filtration; softening; and microbial control.

The addition of these pretreatment processes can significantly add to the cost and complexity of a treatment system and may contribute to variability in treatment results. Kok, et al, (1989), performed a technical and economical comparison of various treatment technologies. They identified evaporation, membrane processes and freeze desalination as the most attractive for removing TDS from produced water. Vapor compression evaporation was selected as the most competitive alternative. Cost estimates for this type of system treating 3800 m³/day, with 15,000-64,500 mg/l TDS were \$8.9 million for the initial capital costs and \$1.2 to \$1.9 million annual operating costs. Simmons (1991) identified the costs associated with reverse osmosis as \$0.40 to \$2.00 per barrel depending on the volume of water to treat, contaminant loading, location and amortization period of capital expenditures.

Constructed wetlands have been shown to improve water quality and are gaining popularity as a potential treatment alternative for acid mine drainage, municipal wastes, urban runoff and other point and nonpoint source water pollution. They yield positive results when applied to waters contaminated with metals, organic compounds, mineral forming ions, suspended solids and acidity. Wetland systems utilize a dynamic combination of physical, chemical and biological processes. These processes support treatment mechanisms such as precipitation and sorption of metals and minerals, microbial degradation of organic compounds, filtering and settling of suspended sediments and buffering of acidity. Wetland systems are inexpensive to construct and operate, and thus are an attractive treatment option. However, their treatment processes are not fully understood and performance optimization criteria are not well defined.

The surface flow/wetland treatment system studied here employs many of the same chemical, physical and biological processes used in other technologies, namely: air stripping, precipitation, ion exchange, biological uptake and biological

degradation. It also treats produced water by removing and concentrating undesirable solids, thus it will require final disposal of accumulated solids and closure of the site. It differs from other alternatives by being relatively inexpensive and passive, requiring no energy inputs and little or no maintenance.

Chapter 2

TREATMENT MECHANISMS

2.1 Preliminary Study

To identify treatment mechanisms required for the system design, researchers from the Colorado School of Mines performed a preliminary study of naturally occurring surface flow/wetland conditions to isolate the components necessary for a successful system (Cohen, 1990 and Emerick, 1990). Prior to the beginning of the study, water analysis had been performed on the produced water discharges at Marathon's Half Moon and Pitchfork fields located near Cody, Wyoming. The Half Moon discharge flows through a series of surface flow and wetland reaches, while the Pitchfork discharge flows through a narrow channel. Results of the water analysis indicated greater improvement in the character of the Half Moon effluent than that of Pitchfork. For this reason, these two fields were selected for a preliminary study to identify natural treatment mechanisms and establish design criteria for the treatment system.

At Half Moon, produced water flows from a skimming pond and travels down a natural wash for approximately 100 yards. A travertine-like crust forms a system of natural terraces on the soil and rocks. The flow is turbulent as it passes over these cascades. The flow is approximately 10 feet wide, and the depth ranges from 6-12 inches in pools and 1 inch over cascades. A substantial but discontinuous slime of blue-green cyanobacteria grows throughout the system. The flow proceeds into a small pond having various wetland vegetation,

including cattails, rushes and sedges around the perimeter. The effluent exits the pond and flows in a less channelized fashion for another 250 yards and enters a second wetlands pond. Samples were collected at three points along the wash to assess the treatment capabilities of this reach.

At Pitchfork, the discharge flows in a narrow, channelized fashion for approximately 300 yards to the end of the lease property. The channel is approximately 24 inches wide and 6 inches deep for most of the reach. The flow is turbulent with some blue-green cyanobacteria lining the channel. Except for two travertine cascades less than 10 feet in length, this discharge lacks the dynamic features of the Half-Moon discharge. To compare the treatment capabilities of both reaches, the Pitchfork discharge was also sampled at three points over the length of the reach. The results of these analyses are given in Tables 3A and 3B.

Examination of the data revealed that the combination surface flow/wetlands system at Half Moon was more effective at improving the general character of the effluent than the Pitchfork channel.

At Half Moon, conductance dropped 40% from 5,000 to 3000 umhos/cm. Calcium concentration dropped over 45% from 541 to 289 mg/l. The reduction of these two constituents is believed to be the result of calcium carbonate precipitation. Radium 226 decreased from 21.1 to 8.9 pCi/l. The hypothesized removal mechanism is coprecipitation with calcium as scale. Sulfide decreased from 20 mg/l to below detection limits. The oxidation of sulfide appears to correspond to an increase in sulfate from 1060 to 1100 mg/l.

The Pitchfork site reduced sulfide from 28.7 to 8.4 mg/l, but had a lesser affect on conductance, ion concentrations or radium 226 concentrations.

In general, the Half Moon site demonstrated greater improvements in water quality than Pitchfork, supporting the use of surface flow, cascade and

Table 3A - Preliminary study results: Half Moon and Pitchfork discharges**Field Measurements**

	Conductance (umho / cm)		pH		Temperature (deg C)		Eh (mV)	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	5000	3700	7.4	8.0	48	31	-140	-180
Midstream	3500	3600	8.3	7.8	34	31	90	90
Downstream	3000	3600	7.9	7.9	30	31	180	250

Analytical Data (mg/l)

	TDS		Carbonate		Bicarbonate		Sulfide		pH	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	3210	2680	<1	70	1580	1040	20.0	28.7	7.50	8.12
Midstream	2710	2620	<1	61	881	838	2.8	12.8	7.24	7.09
Downstream	2550	2640	<1	98	671	740	<0.01	8.4	7.60	7.83

Ion Chromatography (mg/l)

	Fluoride		Chloride		Phosphate	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	4.88	4.93	142	208	0.31	0.23
Midstream	3.89	4.95	141	213	<0.02	0.05
Downstream	3.48	4.81	142	214	<0.02	<0.02

	Bromide		Nitrate		Sulfate	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	0.44	5.17	0.09	0.03	1060	943
Midstream	0.47	4.88	0.14	<0.01	1100	830
Downstream	0.47	4.99	0.18	0.22	1100	961

Radiometric Analysis (pCi/l), Detection Limit = 0.2, reading +/- 1.2 pCi/l

	Ra 226 - Total		Ra 226 - Dissolved	
	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	21.1	32.8	19.5	29.1
Midstream	25.2	26.2	N/A	26.4
Downstream	8.9	29.6	8.5	25.4

N/A = data not available

Table 3B - Preliminary study results: Half Moon and Pitchfork discharges

Cation Concentration - Total Solids (mg/l)

	Sodium		Magnesium		Calcium		Strontium		Silicon	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	200	380	131	104	545	318	7.3	6.1	5.1	4.8
Midstream	209	374	132	104	397	277	6.4	5.4	5.7	4.8
Downstream	227	378	134	105	295	274	5.9	5.4	6.4	4.7

	Potassium		Boron		Lithium		Barium		Iron	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	50	69	1.4	1.4	0.69	1.43	0.044	0.045	<0.020	0.029
Midstream	57	67	1.6	1.3	0.72	1.44	0.026	0.036	0.024	0.043
Downstream	62	68	1.7	1.3	0.73	1.45	0.021	0.039	0.046	0.052

Cadmium - less than 0.01 mg/l, all locations

Selenium - less than 0.13 mg/l, all locations

Copper, Zinc, Chromium - less than 0.02 mg/l, all locations

Aluminum - less than 0.1 mg/l, all locations

Cation Concentration - Dissolved Solids (mg/l)

	Sodium		Magnesium		Calcium		Strontium		Silicon	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	208	375	133	103	541	324	6.2	6.1	6.4	5.4
Midstream	216	373	133	104	380	277	6.9	5.7	6.8	5.4
Downstream	226	381	132	105	289	274	6.1	5.7	6.4	5.5

	Potassium		Boron		Lithium		Barium		Iron	
	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork	Half Moon	Pitchfork
Discharge	56	82	1.7	1.4	0.72	1.48	0.047	0.052	<0.02	<0.02
Midstream	59	77	1.7	1.4	0.72	1.48	0.028	0.045	<0.02	<0.02
Downstream	64	73	1.7	1.5	0.74	1.47	0.021	0.043	0.024	0.024

Cadmium - less than 0.01 mg/l, all locations

Selenium - less than 0.13 mg/l, all locations

Copper, Zinc, Chromium - less than 0.02 mg/l, all locations

Aluminum - less than 0.1 mg/l, all locations

wetland elements in a passive treatment system. The surface flow and cascade elements, and the turbulent flow that results, are believed to aid in stripping hydrogen sulfide, volatile hydrocarbons and carbon dioxide. Reducing sulfides and volatile hydrocarbons should improve the toxicity of the effluent, though no toxicity testing was performed during the preliminary study. The reduction in carbon dioxide partial pressure in the effluent enhances the precipitation of carbonates and coprecipitation of radium. The wetland elements are believed to support ion exchange and biodegradation of persistent hydrocarbons.

2.2 Air Stripping and Volatilization

Air stripping is well established as a means of adding gases such as oxygen to water or removing various constituents from water such as volatile organic compounds (VOCs), hydrogen sulfide and other dissolved gases. The mass transfer rate of a compound between water and air depends upon the relative volatility of the compound, the temperature, its concentration at the air-water interface and the rate at which new air-water surfaces are formed. Dissolved salts in the water affect the solubility of some gases and will reduce the dissolved gas concentrations.

Henry's law defines the relative volatility of various substances. It states that the partial pressure of a constituent in solution is proportional to the concentration of the constituent in air (Corbitt, 1989). Henry's constant determines the saturation concentration of a compound in a liquid at a given temperature.

Henry's law is given by:

$$P_a = H_a * X_a$$

where:

P_a = the partial pressure of constituent a in air

H_a = Henry's constant for constituent a, (atm)

X_a = the solution concentration of contaminant a

Thus, the larger the Henry's constant, the more readily a constituent may be air stripped. When many constituents are present in a wastewater, each having a different Henry's constant, air strippers are typically designed to remove the most persistent constituent. Values for Henry's constants may be obtained from handbooks or determined experimentally. Table 4 gives the Henry's constant for some of the constituents of concern in this study.

Table 4 - Henry's Constant for Selected Compounds

<u>Constituent</u>	<u>Henry's Constant @ 20°C, atm</u>
oxygen	4.3 X 10 ⁴
carbon dioxide	1.51 X 10 ³
hydrogen sulfide	5.15 X 10 ²
benzene	2.4 X 10 ²

Source: Corbitt, 1989

Henry's constants are highly temperature dependant. For example, the Henry's constant for most VOCs increases about threefold for every 10°C temperature rise (Corbitt, 1989). This temperature relationship is given by:

$$\log_{10} H = (-H^\circ / RT) + K$$

where:

H = the Henry's constant

H° = the change in enthalpy due to dissolution of constituent a in water, kcal/kmol

R = the universal gas constant, 1.987 kcal/kmol-°K

T = absolute temperature, °K

K = a constant

Values of H° and K for selected constituents are given in Table 5.

Table 5 - Temperature Dependence of Henry's Constant

<u>Compound</u>	<u>H°, kcal/kmol</u>	<u>K</u>
oxygen	1.45 X 10 ⁻³	7.11
carbon dioxide	2.07 X 10 ⁻³	6.73
hydrogen sulfide	2.0 X 10 ⁻⁵	5.84
benzene	3.68 X 10 ⁻³	8.68

Source: Corbitt, 1989

Higher temperatures increase the volatility of constituents and decrease their saturation concentrations. Thus, volatile materials are more readily stripped in warm water than in cold. Similarly, the removal of some materials is pH dependant. Low pH can aid in the removal of hydrogen sulfide, carbon dioxide and ammonia.

The two-film theory describes the mass transfer across the air-water contact area. It states that mass transfer occurs between a thin film at the liquid-gas interface, and that the bulk of the gas and liquid are not directly involved (Heilshorn, 1991). Since mass transfer occurs at the air-water interface, it is desirable to facilitate as much interfacial area as possible. Ostroff, (1979) explains how a water surface film acts as a barrier to mass transfer. It is believed that oils, soaps, detergents, organic acids and some organisms enhance this barrier. Conversely, increased temperatures and agitation are believed to reduce the resistance of this film.

At a given temperature and pressure, Haney (1954), defines the rate equation for gas released from water as:

$$\log_{10} [(S - C_t) / (S - C_0)] = -K(A/V)t$$

where:

S = saturation concentration of the gas in water, (ppm)

C_t = the concentration at time t, (ppm)

C₀ = the initial gas concentration at t = 0, (ppm)

A = the area of gas-water interface. (cm²)

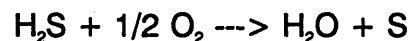
V = the volume of water, (ml)

K = a constant

This relationship describes a gas in a supersaturated state. As the gas is released, the concentration approaches the saturation concentration, S. The rate

of release decreases logarithmically as the saturation concentration is approached. Also, at a given temperature and pressure, increasing the area of the gas-water interface allows a proportional decrease in the treatment time.

Air stripping hydrogen sulfide depends largely on the characteristics of the water and the amount of carbon dioxide present. Hydrogen sulfide is roughly three times more soluble in water than carbon dioxide. Thus, carbon dioxide will be released before hydrogen sulfide during aeration. This can lead to an increase in pH in waters having significant source of alkalinity, such as bicarbonate, and no source of mineral acidity. At pH 5.0, the sulfide present is 98.0% hydrogen sulfide gas and is readily stripped. At pH 8.0, the sulfide present is only 6.0% hydrogen sulfide gas. In this case the sulfide ion persists and is not effectively stripped (Ostroff, 1979). When the sulfide ion persists, some of it may oxidized to elemental sulfur. This is illustrated by the equation:



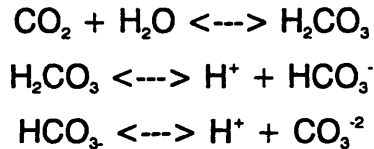
When carbon dioxide is present in concentrations greater than 5 ppm, it may be reduced by air stripping. As discussed above, stripping carbon dioxide may lead to an increase in pH. If the bicarbonate concentration is greater than 200 ppm, some calcium carbonate precipitates (Ostroff, 1979).

2.3 Carbonate Precipitation

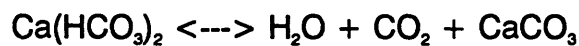
Calcium carbonate precipitation can provide a desirable means to remove calcium and bicarbonate ions from produced water. Additionally, radium concentrations may be reduced via coprecipitation with calcium. Under

conditions of supersaturation, these ions will precipitate to form a scale. Calcium carbonate generally forms large crystals, but in the presence of impurities, the crystals are finely divided and appear uniform (Ostroff, 1979).

Carbon dioxide, and its function in carbonate equilibrium, plays a key role in calcium carbonate precipitation. All natural water systems have some dissolved carbon dioxide, and in the case of produced water, the carbon dioxide is primarily derived from the decay of organic material. Carbonic acid forms when dissolved carbon dioxide reacts with water. The carbonic acid undergoes further dissociation to form bicarbonate and carbonate ions. These reversible reactions are given by:



Since the second equilibrium constant for the dissociation of carbonic acid is much smaller than the first, the ionized hydrogen from the first reaction would combine with the free carbonate ion in the water. For this reason, it is believed that dissolved calcium carbonate exists only as calcium and bicarbonate ions (Ostroff, 1979). This assumption is applied in the following reversible equation describing the precipitation of calcium carbonate.



This relationship illustrates the role of carbon dioxide in the solubility of calcium carbonate. At equilibrium, a decrease in carbon dioxide will yield an increase in calcium carbonate precipitate. As determined by Miller (1952), at 24°C, calcium carbonate solubility tripled from roughly 1 g/l to 3 g/l when the

partial pressure of carbon dioxide was increased from 1 atmosphere to 50 atmospheres.

The solubility of various substances dissolved in water is dependant on temperature, pressure, pH, redox potential, the relative concentrations of other constituents and the characteristics of the substance itself. Though all of these factors influence the solubility of calcium carbonate, temperature, due to its effect on the other variables, has the greatest influence on precipitation (Cowan, 1976).

According to Cowan and Weintritt (1976), the formation of mineral scales depends upon:

(the) degree of supersaturation of the water, rate of temperature change, degree of agitation of the mineralized water during the formation of crystals, size and number of seed crystals used (organic and inorganic), presence of impurities, changes in pH of the solution, and changes in pressure.

Supersaturated solutions contain higher constituent concentrations than at equilibrium. Supersaturation must exist for scale precipitation to occur. As well, the rate of scale deposition corresponds to the degree of supersaturation. Temperature, pH, pressure, flow rates and seed material are all controlling factors of supersaturation.

Calcium carbonate has an inverse solubility. That is, it is less soluble at high temperatures than it is at low temperatures. The amount of scale produced therefore increases with an increase in temperature. This is evident as calcium carbonate often creates scale problems in heat exchangers and boilers.

Turbulence and agitation tend to precipitate scale more readily than still conditions. Agitation also tends to produce larger crystals. This is demonstrated as scale is more likely to occur in valves and ells, than in straight reaches of pipe. Hostomsky and Jones (1990) attribute this phenomena to the increased frequency

of ionic particle collisions. They have observed both increased crystal growth rates and increased rates of crystal nucleation to result from increased agitation.

The formation of seed crystals, or nucleation, is essential to development of scale. When nucleation occurs, individual molecules agglomerate and orient themselves into a crystal lattice (Cowan, 1976). Nuclei under a certain minimum size may be redissolved. Those that persist become stable and promote further agglomeration. Hostomsky and Jones (1990) found the agglomeration of previously formed crystals, rather than the growth of new crystals, to be the primary mechanism for increasing particle size.

Salts and other impurities in solution increase the solubility of calcium carbonate. Xyla, et al (1991) found the presence of metal ions or other foreign substances to reduce the rate of precipitation. They attribute this result to the blocking of active crystal growth sites by foreign anionic and cationic substances.

pH is a measure of the free hydrogen ions in solution and thus describes the state of carbonate equilibrium and relative fraction of dissolved carbon dioxide. Lower pH indicates relatively higher concentrations of carbon dioxide in solution. This acidity tends to keep scale forming solids in solution. Increasing pH tends to precipitate these solids.

Produced water may originate in subsurface formations having pressures as high as 20,000 psi (Cowan, 1976). Under these conditions, extremely high concentrations of dissolved carbon dioxide may exist. As this water is brought to the surface, this gas is liberated. As discussed previously, this reduction in carbon dioxide leads to the precipitation of calcium carbonate scale.

Though the above factors regulate precipitation, they do not describe whether or not the precipitate will adhere to something and form a scale. At high levels of supersaturation, and to some degree at higher temperatures, calcium carbonate may form as a nonadherent particle. Little is known about the cause

of precipitation adherence. Cowan (1976) reports that greater wetting of surfaces increases adhesion, though after scale is established, this has less of an influence. Also noted, was a tendency for scale to adhere better at gas-liquid-solid interfaces, such as tank walls, and on corroded surfaces.

Barium sulfate, calcium carbonate and calcium sulfate are typical constituents of produced water. Yet, at 25°C, in distilled water, they each have distinctly different solubilities of 0.0023 g/l, 0.053 g/l and 2.08 g/l respectively. Oxygen, carbon dioxide and hydrogen sulfide are highly reactive in water and can contribute to the formation of solids when equilibrium conditions are altered.

Saturation indexes have been developed to predict whether a given water will precipitate or dissolve calcium carbonate scale. Most saturation indexes are not suited for the high salt concentrations of produced water. Stiff and Davis (Ostroff, 1979) developed a relationship commonly used in the oilfield, termed the stability index. The Stiff and Davis stability index is given by:

$$SI = pH - K - pCa - pAlk$$

where:

SI = the stability index

pH = pH of the water, standard units

K = an empirical constant to compensate for various ionic strengths and temperatures

pCa = the negative logarithm of the calcium ion concentration in moles per liter

pAlk = is the negative logarithm of the total alkalinity, titrated to the methyl orange end point, expressed in terms of titratable equivalents per liter

A positive stability index indicates that scale will be precipitated and a negative index indicates that scale will be dissolved. This prediction is not always correct, but some inaccuracies are believed to be due to faulty water analyses. The index should not be used to determine the volume of scale that results. For more on the stability index, see Ostroff, 1979.

2.4 Biological Mechanisms

Bacteria are found nearly everywhere on earth and thus are usually present in produced water. Many forms of organic and inorganic materials are present in produced water and the environments it contacts. These materials provide nutrients and energy for the bacteria and promote their growth. Ostroff (1979) notes that bacteria flourish best under the following conditions: pH from 5 to 9; temperature from 0 to 180 °F; and brine concentrations under 100,000 ppm. He groups bacteria present in produced water into three classifications: obligate aerobes, that grow only in the presence of molecular oxygen; obligate anaerobes, that grow in the absence of oxygen; and facultative anaerobes, that grow with or without oxygen.

Caswell, (1992) has identified some of the bacteria present in this treatment system and the treatment mechanisms they provide. These mechanisms include microbial degradation of hydrocarbons and microbial oxidation of sulfur. In his study, he attributes microbial degradation to an average reduction in total phenolics of 85 ppb across the treatment system. He has theorized that up to 70% of the sulfur removed from the system is due to microbial oxidation of sulfur to sulfate. For more on the identification of these bacteria and the treatment mechanisms they provide, see the work of Caswell, 1992.

Chapter 3

TREATMENT SYSTEM DESIGN

3.1 Background and Layout

Marathon's Pitchfork Field was selected as the location for the treatment facility. The Pitchfork Field is located in the Bighorn Basin near Meeteetse, Wyoming and covers roughly 800 acres. The land is leased from the of Bureau of Land Management and private parties. The well field consists of 58 producing wells and 31 injection wells yielding approximately 5500 barrels of oil and 110,000 barrels of water per day. The bulk of the produced water at this field is used for secondary recovery. A surplus of 10,000 to 18,000 barrels of water per day is surface discharged. The effluent travels down two miles of dry wash until its confluence with Rawhide Creek, a Class 2 stream. Rawhide Creek flows for approximately ten miles before discharging into the Greybull River.

The treatment system is built on ten acres of lease property near the field tank battery. A portion of the surface discharge is used for evaluation of the system. The remaining portion of the effluent is diverted around the treatment system. Both effluents come together near the lease property boundary and proceed down the wash.

The water analysis results from the preliminary study supported an engineered surface flow/wetlands system design. A two stage system was designed utilizing a surface flow component and a wetland component. The surface flow component is designed to provide aeration and gas stripping under

turbulent flow conditions. These mechanisms will strip hydrogen sulfide and promote the oxidation of sulfide to sulfate. In the presence of nucleation sites, these mechanisms will also encourage the precipitation of carbonates and coprecipitation of radium. The wetland stage is designed to provide an environment for microbial degradation of hydrocarbons, and may support ion exchange with sediments and ion uptake by aquatic vegetation.

There was, and continues to be, debate over the order in which these components should be placed in the system. Wetlands often utilize subsurface flow and can be primarily anaerobic. As such, if placed downstream of the surface flow stage, the wetland could reduce sulfate to sulfide, potentially increasing the toxicity of the effluent. Also, carbonates and radium may be remobilized. Conversely, if the wetland were placed above the surface flow stage, it would receive untreated water. It was believed that the toxicity of the effluent at this point might be detrimental to microorganisms and aquatic vegetation. For this reason, the wetland stage was constructed downstream of the surface flow stage. The system was positioned on the site such that a second surface flow stage could be constructed below the wetland if treatment results warrant it. The overall system layout is shown in Figure 1.

3.2 Skimming Ponds

The produced water and crude oil are separated using API separators and heater treaters at the tank battery. The produced water then flows through a series of three constructed ponds designed to allow remaining oil to float to the surface and be skimmed off. Water for the treatment system is drawn off of the

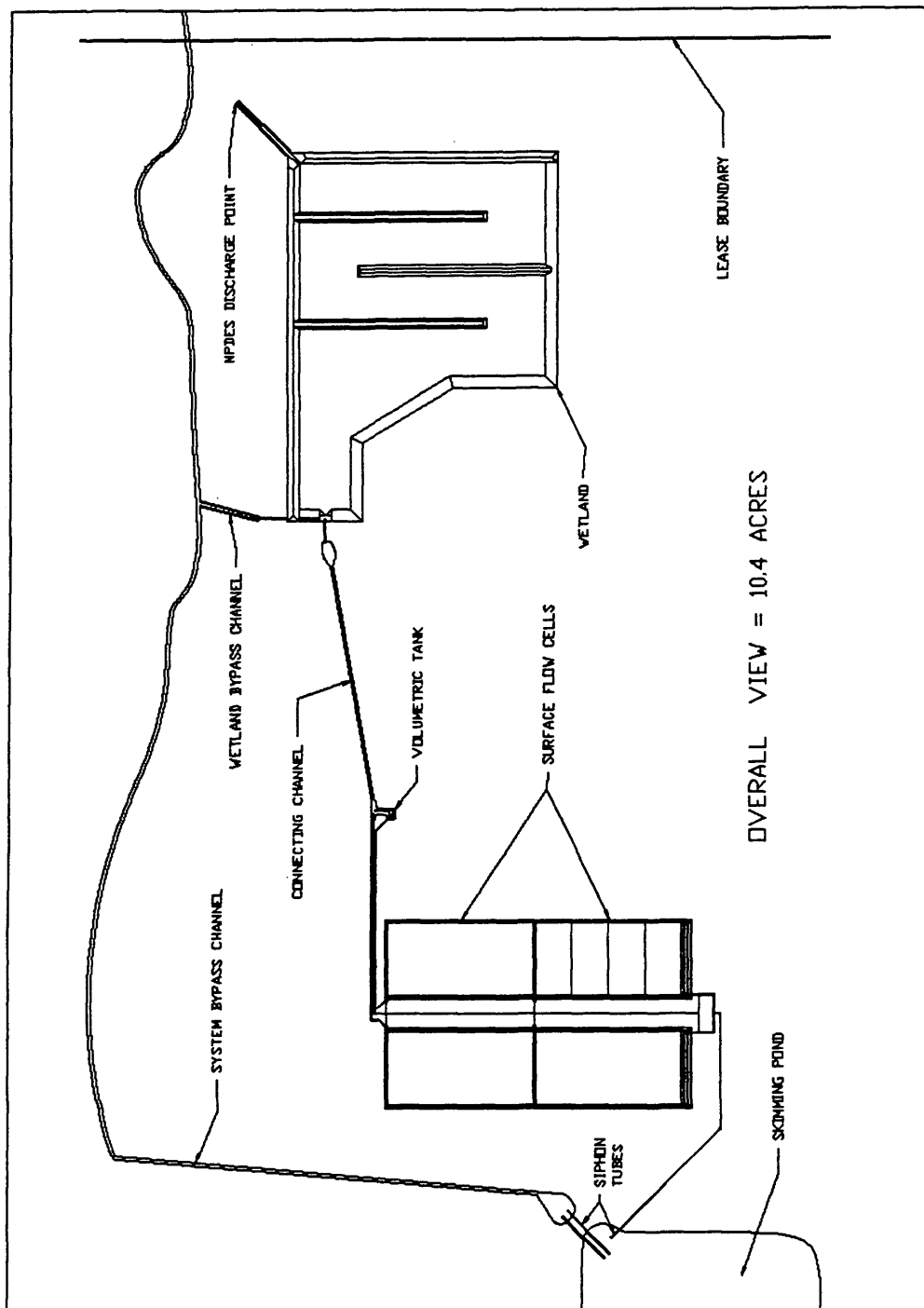


Figure 1 - Overall system layout

third skimming pond through a siphon tube. The siphon tube allows water to be drawn from the pond without the encroachment of floating oil. The siphon consists of 8" PVC pipe assembled in a tee and rotated such that arms of the tee are vertical. The lower arm of the tee extends two feet below the water surface to reduce the chance of oil being drawn in from the surface. The upper arm of the siphon extends above the pond retaining wall to prevent any oil contamination in the event of the pond overflowing. The siphon is situated below the elevation of two existing bypass siphons to ensure primary draw for the treatment system. The bypass siphons discharge excess effluent not entering the treatment system into a bypass channel routed around the system.

3.3 The Surface Flow Stage

To assess the treatment efficiency of various surface contours, four different surface flow cells were constructed. These are shown in Figure 2. Each cell is 50 feet wide and 100 feet long. The upper two cells are constructed on a 3% grade. One of the cells is planar through its entire length and the other has three constructed terraces to enhance aeration. The terraces are each 12 inches high and are spaced at 25 foot intervals down the length of the cell. The terrace construction detail is shown in Figure 3.

Each of the upper cells is lined with 20 mil chlorinated polyethylene, covered by a 12 ounce geotextile and topped with 1 and 2 inch angular gravel. The gravel depth is typically 1 to 3 inches, but is much more in some cases. In particular, the planar cell has gravel depths in excess of 6 inches in some places due to ruts caused by the loader used to distribute the gravel.

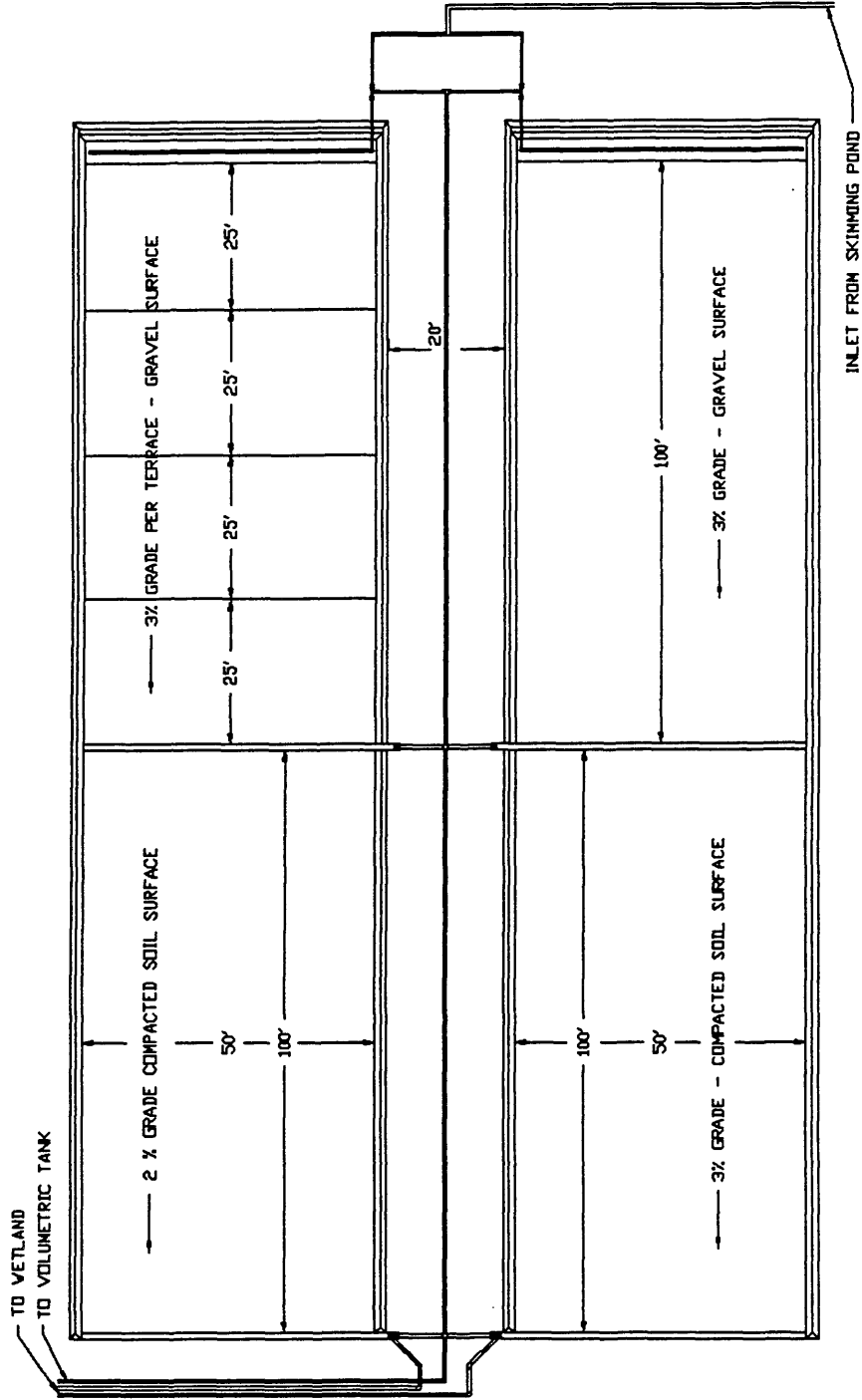


Figure 2 - Surface flow cells

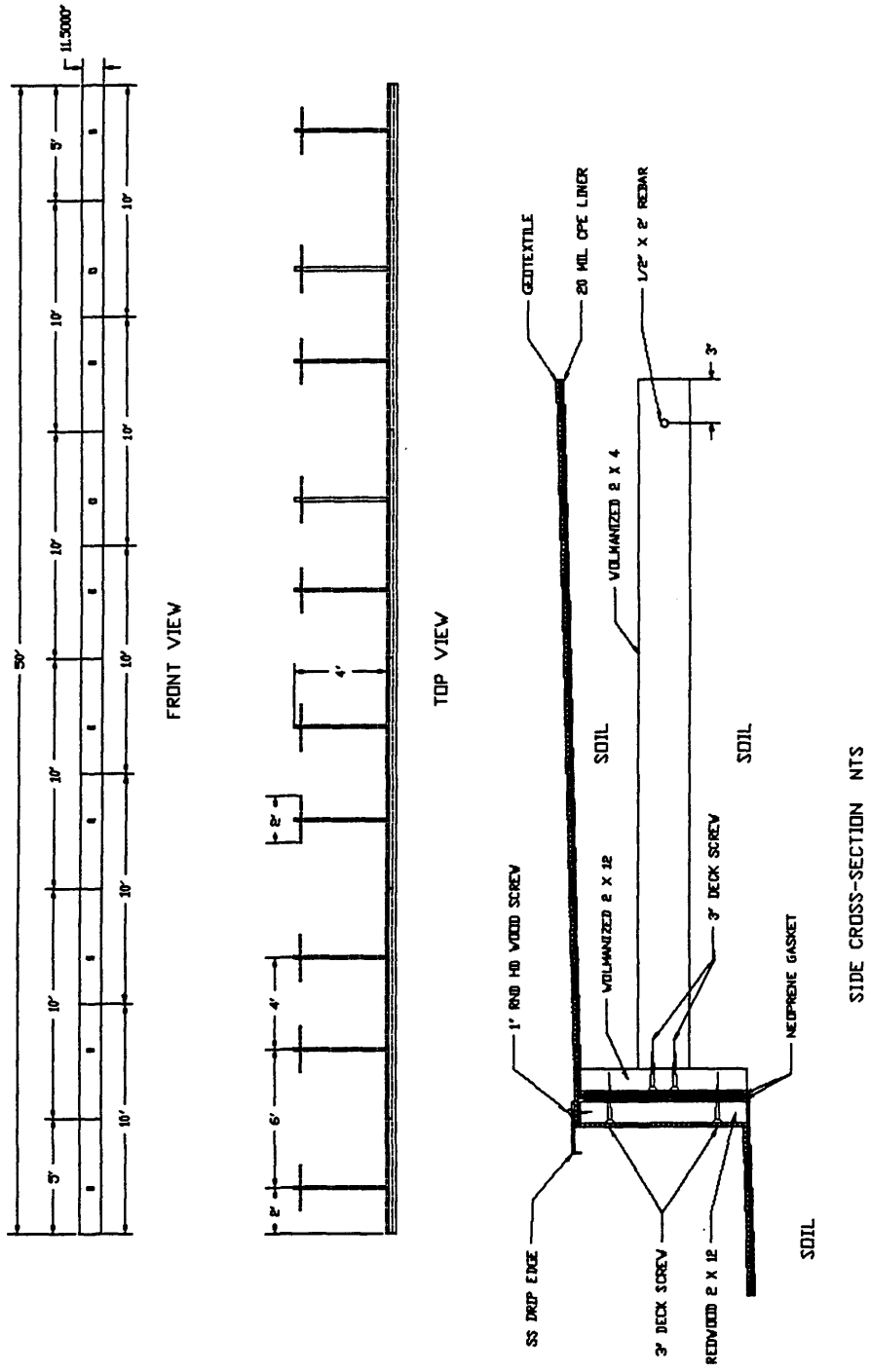


Figure 3 - Terrace construction detail

The lower two cells are directly below the upper cells and receive the effluent exiting the upper cells. When constituent removal occurs in the upper two cells, the lower cells receive water with lower constituent concentrations than the upper cells. These differences in constituent loading to the upper and lower cells should be considered when examining the treatment results.

The lower cells consist of compacted native soil and are not lined. One of the lower cells is constructed on a 3% grade and the other on a 2% grade. A more extreme difference in grades between these two cells was originally planned, but was not possible due to site topography and budget constraints.

The effluent leaving the upper cells is evenly distributed over the width of the lower cells through an intermediate channel. The effluent is collected in this channel and spills over weir strips fastened to the channel. The height of the weir strips is adjustable to compensate for settling of the channel. The effluent exiting the lower cells is received by discharge channels located at the bottom of each cell. Both the intermediate and discharge channels are fitted with drains to measure the flow leaving each of the four cells. These drains are routed to the volumetric tank for measurement. Figure 4 shows the construction detail of these channels.

The perimeter of the surface flow stage is surrounded with berms to contain the treatment water within the cells. The berms are constructed of native soil and are 8 to 12 inches high. The lined cells have lined berms. The liner and geotextile are keyed into the top berms to prevent downslope movement.

The different cell designs were constructed as such to compare the relative treatment value associated with terraces, a lined gravel surface, a soil surface and increased retention time.

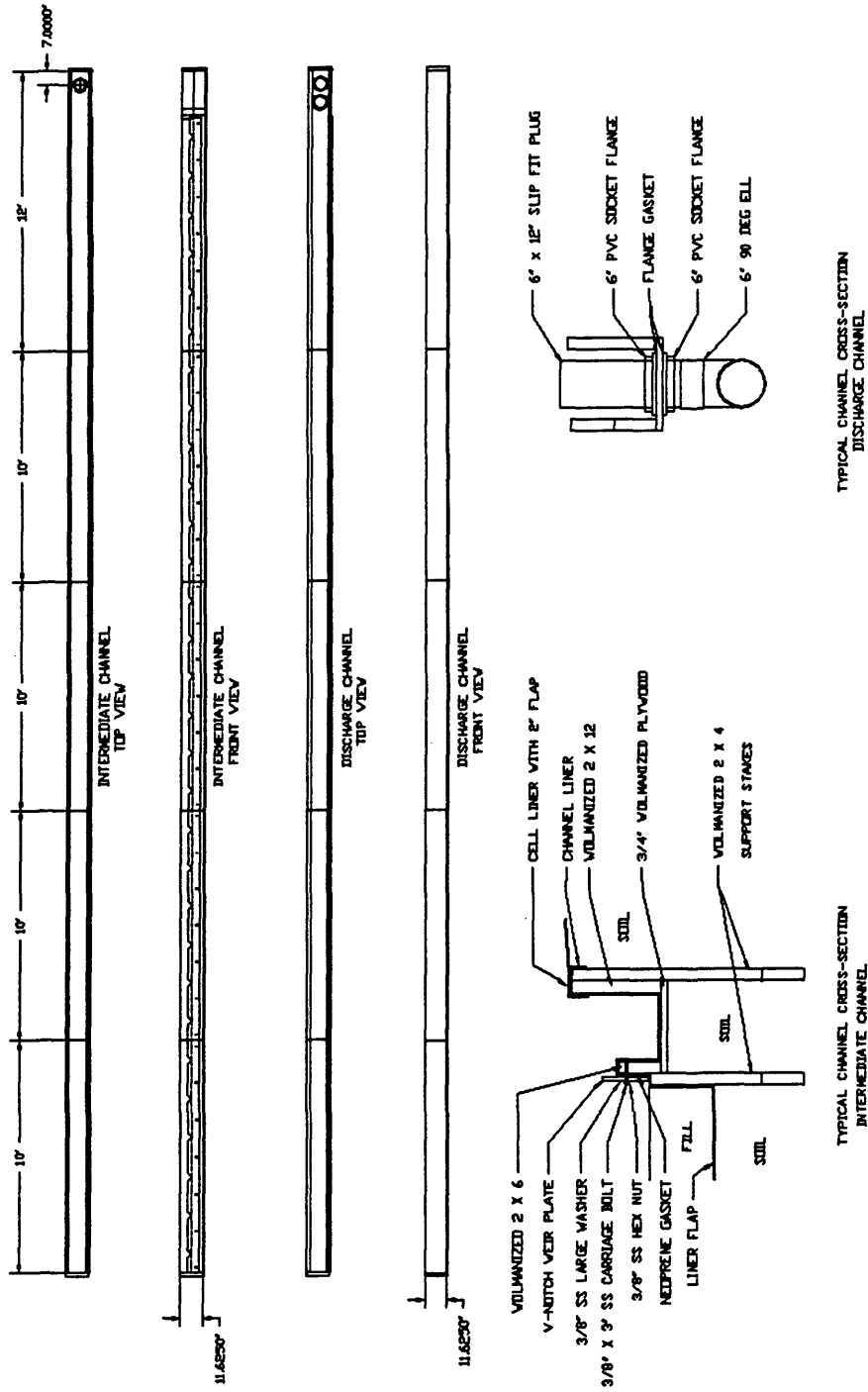


Figure 4 - Intermediate and discharge channel detail

3.4 The Distribution System

The distribution system controls the flow entering the surface flow cells. The effluent flows from the skimming pond siphon 175 feet to the head of the surface flow stage in 8" PVC pipe. There, it enters a tee where it is divided into two legs and reduced down to 4" PVC that feeds the system. Each 4" leg leads into a control manifold. Each manifold consists of a gate valve for flow control, a system shut-off valve and a bypass shut-off valve.

In bypass mode, the effluent is diverted through a 6" PVC drain to the volumetric flow measurement tank. The flow measurement tank is installed to assess treatment efficiency under various flow rates and would not necessarily be a part of an operational system. In operational mode, the effluent enters the surface flow system. Water is distributed evenly across the width of each cell using 6" PVC gated irrigation pipe with 20" gate spacing. The irrigation pipe rests on 4 X 4 timbers to assist in aeration as the water exits the pipe. The distribution system detail is shown in Figure 5.

3.5 The Connecting Channel

A constructed channel carries the combined effluent from the surface flow stage to the wetland. The channel is 20 inches wide, 185 feet long and runs on approximately 5% grade. It is lined with 6 inch river rock and 1 and 2 inch gravel. Water depth ranges from 1 to 12 inches as the flow cascades over the rocks.

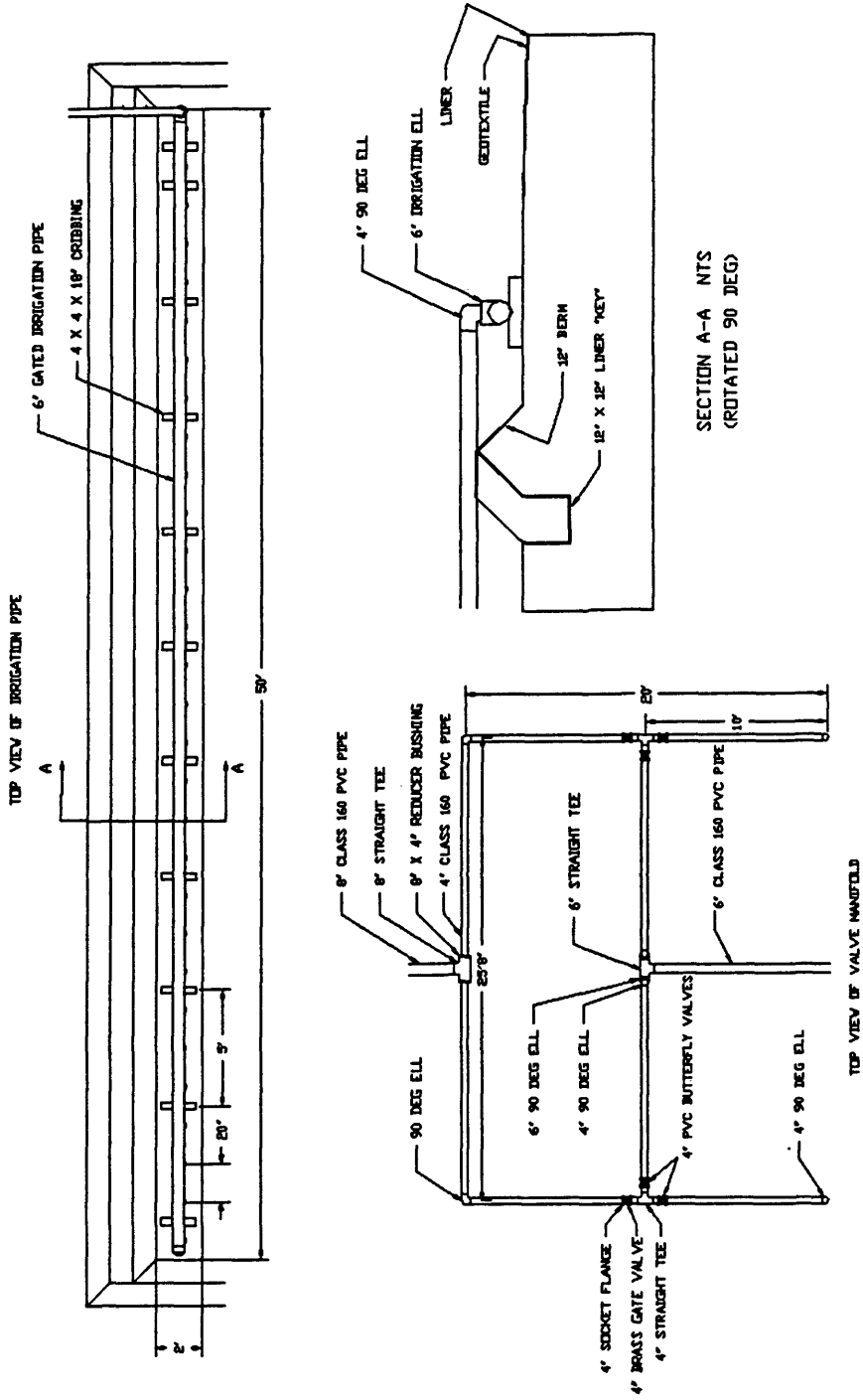


Figure 5 - Surface flow stage distribution system

The channel empties into a small sedimentation pond where the flow velocity slows. The pond is approximately 18 feet long, 10 feet wide and 2 feet deep. The pond was constructed to retain nonadherent scale particles and eroded sediments from the compacted soil cells. After 8 months of operation the pond was full of sediment and was dredged out.

The volumetric flow measurement tank is located at the head of the channel. The tank has a 300 gallon capacity and is made of PVC. The tank was calibrated in the field to 10 gallon increments to measure flow rates. Before performing a flow measurement, the representative flow is run through the tank for 15 minutes to allow equilibration of the flow lines. Flow measurements are performed by plugging the tank drain and recording the time it takes to fill the tank with 100 gallons of water.

The connecting channel is detailed in Figure 6.

3.6 The Wetland Stage

The wetland stage covers roughly three quarters of an acre. It is flat and was brought to grade with roughly 50% cut and 50% fill of material. Its shape is largely due to site topography. Treatment water is contained in the wetland with compacted berms on the fill portions and with cut slopes elsewhere. Three interior berms force the water to flow in a sinuous pattern. This increases the retention time of flow through the wetland. All berms and fill materials consist of native soil. Figure 7 shows the wetland layout.

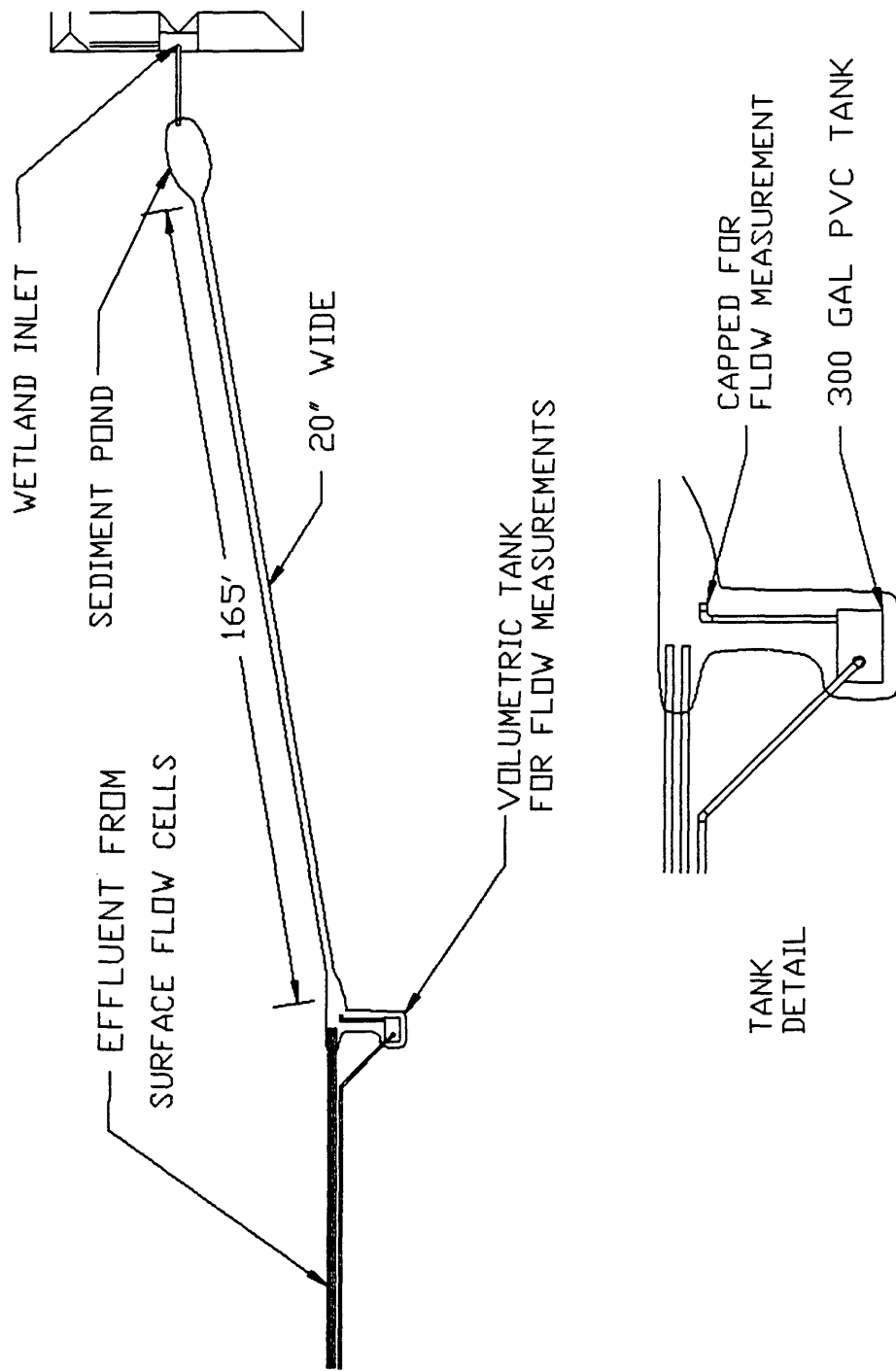


Figure 6 - Connecting channel

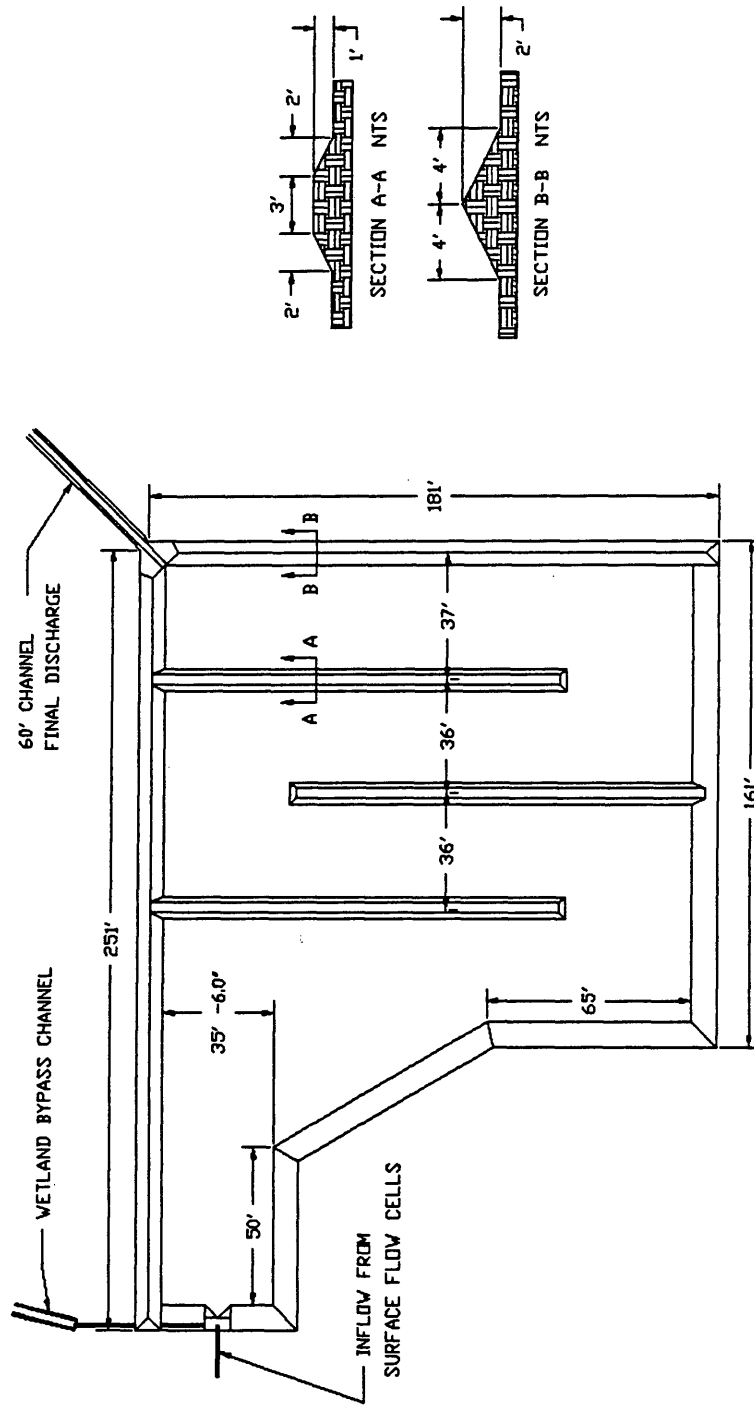


Figure 7 - Wetland layout

After the wetland was excavated to its present shape, organic material was incorporated into the soil to aid in the establishment of aquatic vegetation. Roughly 190 cubic yards of cow manure and 90 bales of straw were spread over the wetland surface. This material was then ripped into the soil to a depth of 12 inches using a bulldozer.

Wetlands vegetation was transported from Marathon's Oregon Basin Field and transplanted into the wetland. Approximately 30 cubic yards of plugs consisting of rushes, sedges and cattails were used for transplanting. The wetland was immediately flooded to help the plants get established. It should be noted that this initial flood water was untreated and flowed through the wetland for four weeks. Contrary to concerns over the toxicity of this water, it seemed to have little or no effect on the plants during this early stage of development. After the first four weeks, the surface flow cells were operational and the wetland received the effluent from these cells. Significant plant growth was observed in the wetland after two weeks, increasing to approximately 80% coverage after eleven weeks.

When examining the results data, the reader should keep in mind that the wetland receives the combined flow from both sides of the surface flow stage. When a flow is reported as 1000 BPD in the data tables, the wetland flow is twice that, or 2000 BPD.

3.7 The Wetland Inlet and Outlet

A distribution box is used to regulate and measure the flow entering the wetland. A plastic V-notch weir measures the flow rate into the wetland and an adjustable spillway allows flow to be bypassed around the wetland. The box is

constructed from wolmanized lumber and is lined with 20 mil chlorinated polyethylene. The distribution box construction detail is shown in Figure 8.

An outlet dam is used to measure the flow rate exiting the wetland and regulate its depth. The dam is constructed from wolmanized lumber, lined with 20 mil chlorinated polyethylene and incorporated into the wetland perimeter berm. An adjustable plastic V-notch weir is mounted to the dam. Adjusting the weir height regulates the wetland depth while providing relatively precise flow rate measurements. Figure 9 shows the outlet dam construction detail.

Additional fabrication drawings for various minor components such as weir strips and weir plates are given in Appendix A as Figures A1 - A6.

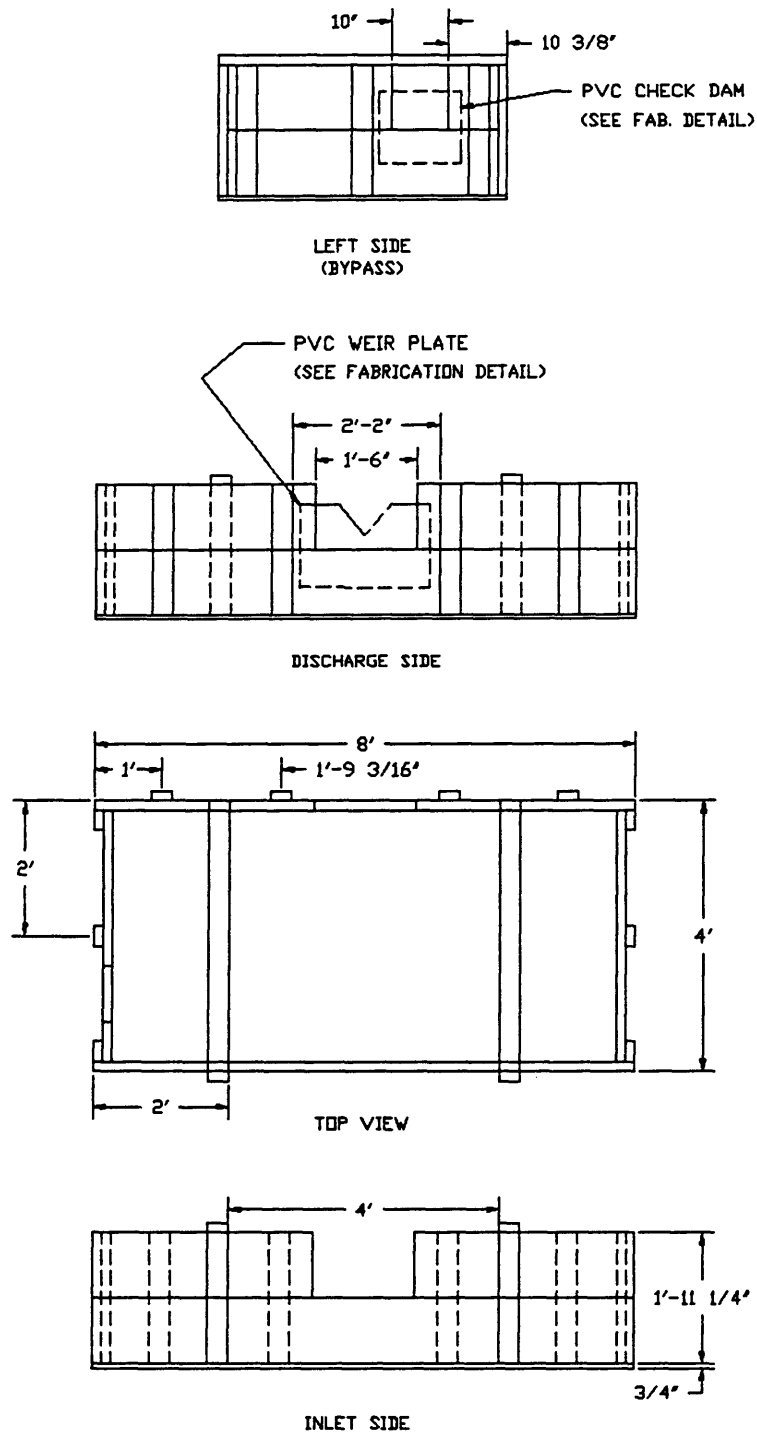
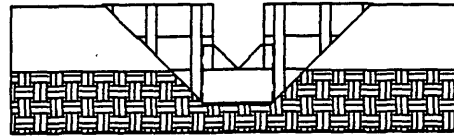


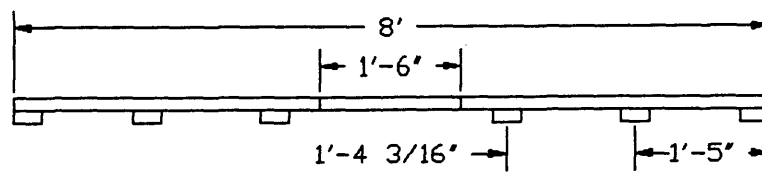
Figure 8 - Distribution box construction detail



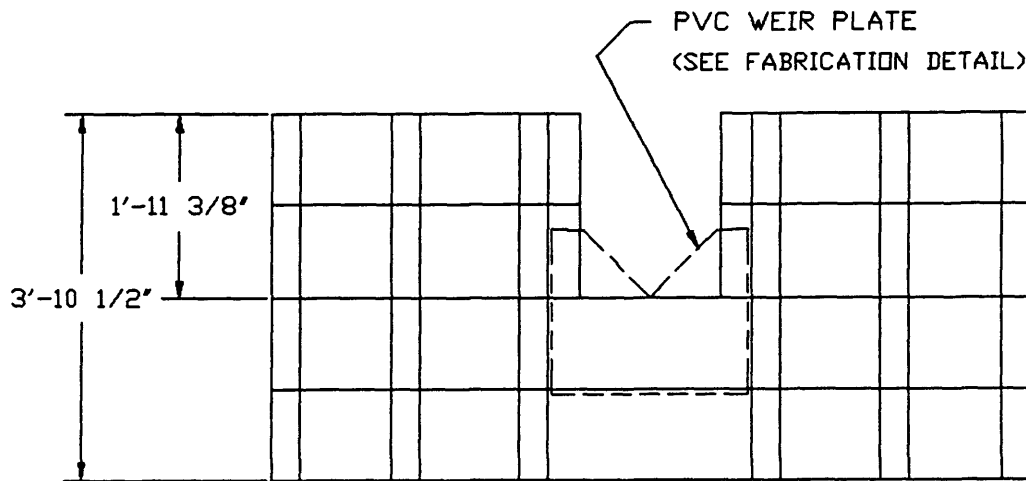
BERM CROSS-SEC.



DAM CROSS-SECTION VIEW



TOP VIEW



OUTLET SIDE

Figure 9 - Outlet dam construction detail

Chapter 4

SAMPLING AND ANALYSIS

4.1 Sampling Objectives

Both field measurements and laboratory analysis were performed on the effluent to assess the efficiency of the treatment system. The field measurements and constituent analyses selected were based on a need to identify the character of the water in the system, define potential treatment indicators and assess the removal of typical produced water constituents. Constituent concentrations were tracked through the system to identify successful system components and ideal flow rates. Field measurements corresponding to these constituent concentrations are used to identify trends in performance and ideal treatment conditions. When components are successful at reducing constituent concentrations, the data are used to develop relationships for future system design criteria.

4.2 Sample Locations

To assess the performance of each component in the treatment system, samples were collected at eight different locations. The locations were selected to provide a measure of the effluent character into and out of each component in the system. These locations are shown in Figure 10.

Legend for Sample Locations, Figure 10

- Sample location (1) is the untreated effluent flowing out of the skimming pond.
- The symbol conventions (T) and (P) are used to identify flows through the terraced cell side and the planar cell side of the surface flow cells.
- Locations (1T) and (1P) represent the effluent entering the two lined, gravel surfaced cells.
- Locations (2T) and (2P) represent the effluent after 100 feet of surface flow over the lined, gravel surfaced cells.
- Locations (3T) and (3P) represent the effluent after another 100 feet of surface flow over the unlined soil cells.
- Location (4) represents the effluent entering the wetland.
- Location (5) is located 60 feet below the outlet of the wetland and represents the final degree of effluent improvement.
- Location (6) represents the natural improvement to the bypass channel as it travels approximately 900 feet.

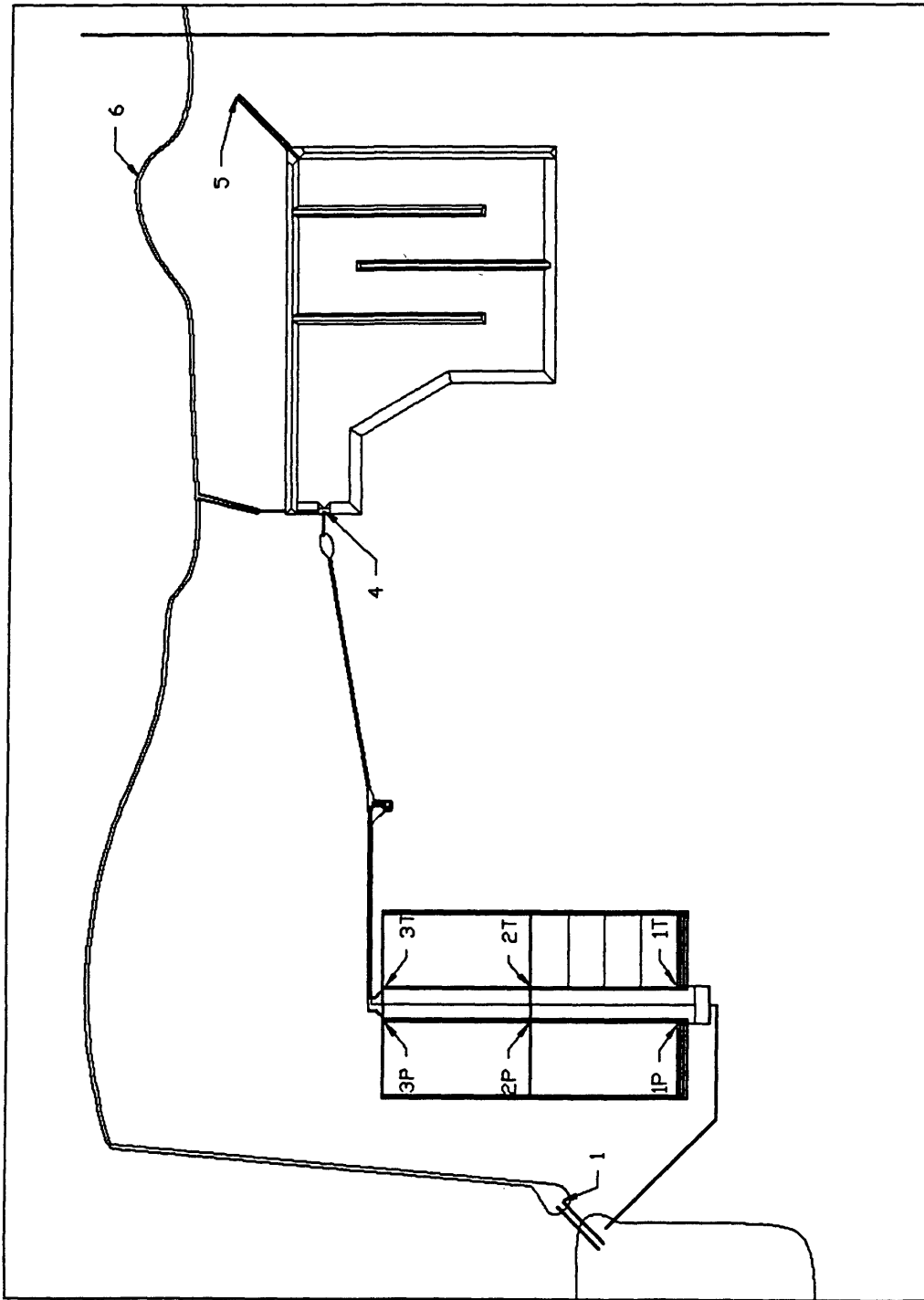


Figure 10 - Sample Locations

4.3 Field Measurements and Constituent Analysis

Thirteen sets of samples were collected from July 25, 1991 through January 23, 1992. Both field measurements and laboratory constituent analysis were performed at each of the sampling dates. Flows tested during this period included: 1000, 2000, 3000, and 4000 BPD into each side of the surface flow cells which yielded combined flows of 2000, 4000, 6000 and 8000 BPD into the wetland. Each flow rate is converted to gallons per minute and cubic feet per second in Table 6. The sampling schedule was designed to assess the treatment capacity of the system at a variety of flows under different seasonal conditions. Two sets of night samples, taken at approximately 1:00 am, were also performed to compare the diurnal performance of the system. One set of samples was taken at dusk, approximately 5:00 pm. Other typical daytime sampling occurred at approximately 1:00 pm.

Typical field measurements include: ambient air temperature, water temperature, pH, redox (Eh), conductivity and dissolved oxygen (DO).

Both water and air temperature measurements were performed with a mercury thermometer measuring degrees Celsius.

pH measurements were performed using an Orion 81-02 probe and model 401 meter. A one point buffer (pH 7) calibration was used. pH measurements were repeated on each sample until the same pH reading was observed twice.

Redox measurements were performed using an Orion 96-78 platinum electrode and model 401 meter. Light's solution was used for calibration. The digital redox meter was allowed to fully stabilize before recording the reading.

Conductivity measurements were performed using a YSI model 33 SCT meter and field probe. A standard KCl solution was used for calibration. The meter was allowed to stabilize for approximately 10 seconds.

Table 6 - Flow Rate Conversions

1 oilfield barrel = 42 gallons
1 gallon = 0.13368 cubic feet

<u>barrels per day</u>	<u>gallons per minute</u>	<u>cubic feet per second</u>
1000	29.17	0.065
2000	58.33	0.130
3000	87.50	0.195
4000	116.67	0.260
6000	175.00	0.390
8000	233.33	0.520

Dissolved oxygen was measured with a YSI 5739 self-stirring probe and a model 51B meter. Dissolved oxygen samples were placed in glass BOD bottles for measurement. The recommended water in air calibration was performed prior to each set of measurements. The DO meter was allowed to stabilize and the reading was not recorded until the meter maintained a steady reading for at least one minute.

These field measurements were taken to describe the condition of the water and the tendency for various chemical and biological reactions to occur in the treatment components. The reactions referred to here are described in Chapter 2.

In staying consistent with a broad based approach to this study, many constituents typical to produced water were analyzed. Laboratory analysis was performed for: potassium, sodium, chloride, calcium, magnesium, carbonate, bicarbonate, radium 226, sulfide, sulfate, BTEX components (benzene, toluene, ethylbenzene and xylenes), total phenolics, total dissolved solids and occasionally toxicity and alkalinity. These analyses were performed to compare the character of this effluent to other produced waters and assess the treatment effectiveness of the system components. The field measurements may allow approximate calculation of constituent removal, however, the analytical data will be used as a more accurate measure of the system's performance.

Energy Laboratories of Billings, Montana performed the constituent analysis. They are certified under the Safe Drinking Water Act by the EPA, region 8 and the States of Montana, Wyoming, North Dakota and South Dakota. Their analytical methods conform to guidelines set forth by the U. S. EPA, the American Society for Testing and Materials (ASTM), the Association of Official Analytical Chemists (AOAC) and the American Public Health Association (APHA). As

provided in their sales literature, Table 7 identifies the analytical methods and detection limits used by Energy Laboratories.

Field measurements were performed by the author and analytical samples were taken by CSM researcher, Peter Caswell. This division of responsibility continued for the duration of the study to maintain consistency in sample location and methodology. Except for DO measurements, the first nine sets of field measurements were performed in the treatment cells. The last four field measurements sets, taken in November and January, were performed in a shed. One liter samples were taken from each sample location and field measurements were performed immediately. Analytical sampling methods were consistent for the entire study. Samples were collected in plastic bottles, labelled and appropriate preservatives were added. The samples were then placed in plastic coolers and packed in ice. The coolers were shipped within 24 hours via overnight delivery to Energy Laboratories.

A quality assurance and quality control scheme was designed for this study by CSM researcher Peter Caswell. It covers areas such as QA/QC objectives, sample handling and storage techniques, sample preservatives, sample identification and chain of custody. For more on the QA/QC used in this study, see the work of Caswell, (1992).

Table 7 - Analytical Methods and Detection Limits Used by Energy Laboratories

<u>Constituent</u>	<u>Method</u>	<u>Detection Limit</u>
potassium	EPA 258.1/200.7	1.0 mg/l
sodium	EPA 200.7	1.0 mg/l
chloride	EPA 325.3	1.0 mg/l
calcium	EPA 215.1/200.7	1.0 mg/l
magnesium	EPA 242.1/200.7	1.0 mg/l
carb/bicarbonate	EPA 130.2	1.0 mg/l
radium 226	EPA 903.1	0.2 pCi/l
sulfide	EPA 376.2	0.04 mg/l
sulfate	EPA 375.3	1.0 mg/l
BTEX	EPA 602/8020	0.5 ug/l
total phenolics	EPA 420.2	0.01 mg/l
TDS	EPA 160.1	1.0 mg/l

Chapter 5

RESULTS AND DISCUSSION

5.1 System Integrity

The overall system performance has been good for the first eight months of operation. No major modifications or repairs have been required. It has sustained a variety of weather conditions and combined flows up to 12,000 BPD. Some berm reconstruction was required on one surface flow cell and the wetland initially, but the berm has not breached or leaked significantly since the repairs.

The surface flow distribution system provides good flow rate control and distributes the water evenly over the width of the cells. The irrigation pipe in the distribution system requires monthly clean out due to an accumulation of bacteria and scale in the gates. The plastic irrigation gates eventually break after some time during clean out and adjustment and must be replaced. Metal gates would help this problem. The inlet pipes below the gate valves have developed approximately 3/8" of scale on the pipe walls after eight months. This has reduced the maximum flow capacity of the system to 12,000 BPD. They will require periodic clean out or replacement.

The lined gravel cells created desired effects of turbulence and aeration. Water depths in the cells ranged from 1/2 to 1 inch. The gravel tends to hold a lot of live and decaying bacteria. Much of the live bacteria is beneficial and converts sulfur to sulfate and degrades hydrocarbons. The decaying material promotes reducing conditions in some areas. Large mats of bacteria cover much

of the cell surface, forcing some of the water to flow underneath the mats. This reduces turbulence and aeration of the water.

The terraces distribute the water evenly over the width the cell. There has been no noticeable settling of the terraces or deterioration of the wooden structures. Aeration appears to be enhanced by the terraces and above average scale growth is evident directly below them.

The intermediate channels do an acceptable job of redistributing the water over the soil cells. Both channels have experienced some settling (1" - 2") out of the range of height adjustment on the weir strips. This reduces the capacity of the channels and limits flow measurements using the channel drains to 3000 BPD. A concrete footer under the channel or more adjustment in the weir strips would improve the present design.

The soil cells have provided some treatment benefits, but are unacceptable as designed. The flow is unobstructed and is well exposed to the atmosphere supporting a large gas/liquid interface. However, channelization and erosion are severe, reducing the contact area over time. Freezing ambient temperatures cause the saturated soil to heave upon freezing. This frost heaving creates large islands covering over 60 percent of the cell. A lined cell without the gravel would provide similar benefits and protect against erosion and heaving.

The discharge channels work well under operational conditions and during flow measurements. During operation scale can develop around the mouth of the channel drain. There is a great deal of turbulence and aeration at the drain and periodic removal of the scale is required.

The flow measurement tank and drain system were adequate for setting and measuring all of the flow rates in the study. The flow rates measured have an estimated precision of no better than +/- 5%. Splashing in the tank and

irregular flow in the drain pipe contribute to flow reading error. Extending the tank inlet pipe to near the bottom of the tank would reduce the splashing.

The connecting channel and sediment pond both worked well and often improved the water quality over the reach. The sediment pond was full after approximately six months and was cleaned out with a backhoe. The material was very reducing and consisted of eroded soil cell and connecting channel sediment, scale and living and decaying bacteria.

The wetland distribution box allows good flow rate control and measurement. The weir plate and bypass gate combination allow independent control of the wetland. The box has filled with 12 to 18 inches of sediment, but this does not effect performance.

The wetland outlet dam provides fine adjustment of the wetland depth and discharge flow rate. It has performed well for a wooden structure and has not leaked.

The wetland has established itself quickly with little assistance since start up. Wetland vegetation grew to approximately 80 percent coverage over the growing season. Interior berms routed the water in desired pattern and increased wetland residence time. The amount organic material integrated into the wetland soil appears to be excessive. This high loading of organics resulted in decay and reducing conditions. There appears to be sufficient nutrients in the water to support aquatic plants without the additional organic amendments. A significant volunteer wetlands developed in the untreated bypass channel over the season with no soil amendments. To improve clayey soil conditions and encourage rapid plant development, straw mulch and manure amendments could be added. The amount used should be less than half the quantity used in this study.

During a strong, windy storm, a thick mat of oil accumulated near the mouths of the siphon tubes in the skimming pond. It reached a thickness of over

one inch, began to sink and was drawn into the siphon tubes. The next day the entire system was covered with a film of oil and numerous accumulations of thick crude oil were scattered throughout the system. The bacterial mats were gone. This may have been due to the storm or the oil. The system recovered quickly as the oil was washed away or degraded microbially. To prevent reoccurrence, a floating boom was installed around the siphon tubes. This, in combination with frequent pond skimming, has eliminated the problem.

5.2 General Character of the Pitchfork Effluent

Table 8 identifies the character of the untreated effluent over the course of the study. Included are the mean, high, low, range and standard deviation values for the thirteen sample dates.

The data indicate significant variability in the character of the water entering the treatment system. This is not surprising, considering the origin of the water and fluctuations in well field production. All of the constituents listed are typical to produced water, and are thus important to the assessment of system performance. Of primary concern to this particular site are radium 226 and toxicity.

Table 8 - General Character of the Untreated Pitchfork Effluent

Analytical Data						
Constituent	Mean Concentration	High Value	Low Value	Range	Standard Deviation	
potassium	131.8 (mg/l)	170 (mg/l)	112 (mg/l)	58 (mg/l)	13.2 (mg/l)	
sodium	307.8 (mg/l)	338 (mg/l)	298 (mg/l)	43 (mg/l)	10.42 (mg/l)	
chlorides	209.5 (mg/l)	221 (mg/l)	196 (mg/l)	25 (mg/l)	7.012 (mg/l)	
calcium	330.8 (mg/l)	380 (mg/l)	285 (mg/l)	95 (mg/l)	22.51 (mg/l)	
magnesium	110.7 (mg/l)	113 (mg/l)	108 (mg/l)	5 (mg/l)	1.498 (mg/l)	
carbonate	0 (mg/l)	0 (mg/l)	0 (mg/l)	0 (mg/l)	0 (mg/l)	
bicarbonate	1094 (mg/l)	1240 (mg/l)	929 (mg/l)	311 (mg/l)	83.94 (mg/l)	
radium 226	30.91 (pCi/l)	42.2 (pCi/l)	19.7 (pCi/l)	22.5 (pCi/l)	6.112 (pCi/l)	
sulfide	32.25 (mg/l)	48 (mg/l)	16.8 (mg/l)	31.2 (mg/l)	8.658 (mg/l)	
sulfate	892.5 (mg/l)	958 (mg/l)	823 (mg/l)	135 (mg/l)	41.94 (mg/l)	
benzene	26.46 (ug/l)	59 (ug/l)	17 (ug/l)	42 (ug/l)	12.18 (ug/l)	
toluene	48.23 (ug/l)	102 (ug/l)	27 (ug/l)	75 (ug/l)	21.85 (ug/l)	
ethylbenzene	17.45 (ug/l)	40 (ug/l)	9.9 (ug/l)	30.1 (ug/l)	8.388 (ug/l)	
xylene	36.08 (ug/l)	74 (ug/l)	21 (ug/l)	53 (ug/l)	15.45 (ug/l)	
total phenolics	0.131 (mg/l)	0.15 (mg/l)	0.13 (mg/l)	0.02 (mg/l)	0.007 (mg/l)	
TDS	2491 (mg/l)	2580 (mg/l)	2340 (mg/l)	240 (mg/l)	61.33 (mg/l)	
toxicity						
Ceriodaphnia	53.59 LC 50	not known	not known	not known	not known	
Fathead Minnow	61.56 LC 50	not known	not known	not known	not known	
Field Measurements						
Measurement	Mean Concentration	High Value	Low Value	Range	Standard Deviation	
temperature	30.54 deg C	35 deg C	22.5 deg C	12.5 deg C	3.739 deg C	
pH	7.2	7.5	6.7	0.8	0.236	
dissolved oxygen	0.569 (mg/l)	1.4 (mg/l)	0.1 (mg/l)	1.3 (mg/l)	0.541 (mg/l)	
redox	-122 mV	-79 mV	-182 mV	103 mV	33.36 mV	
conductivity	2697 umho/cm	3390 umho/cm	1450 umho/cm	1940 umho/cm	754 umho/cm	

5.3 Field Measurements and Analytical Results

Field measurements and analytical results for the study are given in Appendix B, Tables B1 - B8. The data are organized by measurement or constituent. Within this arrangement, each data table is sorted by sample date and includes the flow rate in BPD, the duration at that flow in hours or days and ambient temperature. When appropriate the abbreviations "eve" and "dusk" are used to identify sample times of 1:00 am and 5:00 pm, respectively. Each table is segregated into columns identified by their sample location, so the data may be tracked through the system. The units of measure used for each table are indicated at the top of the table.

Carbonate concentration was measured at each location on each sample date. All values were below detection limits and are not recorded in the tables. Though toxicity is important to the study from both a permit and assessment standpoint, it is not examined in detail for reasons that follow.

Few toxicity data were gathered during the study. Five sets of data exist with only three locations measured each time. On September 18, the effluent of the system failed acute toxicity tests on locations 1,5 and 6 for both Ceriodaphnia and Pimephales promelas. Location 4 passed on the Ceriodaphnia. On November 2, the effluent passed acute toxicity tests for both species at locations 2T, 4, and 5. However, the planar side of the system was shut down at this time, and no samples were performed on the untreated effluent as a control. Similarly, three subsequent tests performed with the full system operational lacked complete data for analysis. These samples taken on January 13, 17 and 23 also passed acute toxicity tests for both species at three locations. During one test, the untreated effluent also passed. During the other two tests no baseline

measurement for location 1 was established. The intermittent and incomplete nature of these data minimize their usefulness for system analysis.

Treatment efficiency for toxicity reduction is an elusive parameter to measure as a constituent. Treatment systems are not designed to treat toxicity, rather they are designed to treat the toxic components of the effluent (ie. there are no "toxicity filters"). Constituents believed to contribute to the toxicity of the Pitchfork effluent such as sulfide, BTEX components and total phenolics will be studied. The design criteria established will also focus on these constituents. For more on toxicity reduction see Caswell (1992).

Flow rates into and out of each cell were measured, but this data set is incomplete. Flow rate measurement of all the sample locations is a time consuming procedure and was omitted on most of the sampling dates. The data suggest that evaporation or seepage occurred across the treatment cells. However, no measurements were performed to assess evaporation or seepage directly. Flow rate increases of as much as 15 gallons per minute were observed. These increases are likely the result of measurement error.

5.4 Percent Change in Water Quality After Flow Through System Components

The change in field measurements and constituent concentrations through each system component was examined to assess the performance of each component. The percent change in reading or constituent concentration was calculated and tabulated for each reach between sample locations. This is not a useful approach for dissolved oxygen and redox, so net absolute change was calculated.

These data were then plotted on bar graphs to visually identify the most effective system components. A separate plot for each flow rate is provided for assessment of the ideal component/flow rate combination. These graphs are organized by field measurement or constituent, and include plots for 1000, 2000, 3000 and 4000 BPD on each page. System components are identified as "Reach Between Sample Locations" on the X-axis and "% Change" is on the Y-axis. The durations at each flow rate are identified with different fill patterns.

These graphs are given in Appendix B, Figures B1 - B21. The data tables for the graphs are located in Appendix B, Tables B9 - B17.

A summary of results for each graph follows. Elements examined in the summary include: the range of percent change; ranking the component performance; ranking the flow rates for best performance of components; identifying the influences of operating during the day or night; and an overall assessment of each constituent. When any of these elements is not addressed in a summary, it indicates that no trend is apparent.

Water temperature decreases ranged from 3 to 83 percent, with the largest occurring in the fall and winter. The greatest change occurred from 1T - 2T and 2P - 3P. The largest and most consistent changes occurred at 2000 BPD, with good results at 1000 BPD. The two largest temperature reductions occurred through the wetland.

pH increases ranged from 1 to 6 percent. The bypass channel and connecting channels both experienced substantial increases. The greatest change through the system occurred consistently from 1T - 2T. Slightly better than average pH increases occurred at 4000 BPD.

Conductivity was reduced by as much as 21 percent in some cases, but also increased occasionally by as much as 12 percent. The greatest decreases occurred from 1T - 2T and 1P - 2P. All parts of the system reduced conductivity

appreciably at 2000 BPD. The two gravel cells also performed well at 1000 BPD.

Dissolved oxygen increased from 4.2 to 9.7 mg/l across the entire system. It decreased through the connecting channel and wetland many times. The greatest increases occurred from 2P - 3P, with good results from 1T - 2T also. The rate of increase in dissolved oxygen decreased slightly with increased flow rates.

Redox increased from 117 to 305 mV across the entire system. Redox decreased across the wetland several times. The largest increases occurred from 2P - 3P and 1T - 2T and in the bypass channel. The net increase in redox decreased with increasing flow rate. The greatest increases occurred at 1000 and 2000 BPD.

The percent change in potassium concentrations ranged from a 23 percent decrease from 2P - 3P to an increase of 39 percent through the wetland. The greatest changes occurred at flows of 2000 and 4000 BPD and the smallest changes occurred at 3000 BPD. Every component is shown to increase or decrease the concentration at various times. Concentration decreases are most frequently observed at 2000 BPD.

The percent change in sodium concentrations ranged from a 15 percent decrease through the bypass channel to a 16 percent increase through the wetland. This graph follows the same trends as potassium.

Chloride concentrations increased 11 percent from 2P - 3P and decreased over 5 percent from 2P - 3P, in the connecting channel and across the wetland. The greatest reductions occurred from 2P - 3P and through the connecting channel. The greatest component increase also occurred from 2P - 3P however. The wetland reduced chloride over 5% at both 3000 BPD flows running for 30 and 56 day durations.

Calcium concentration decreased consistently through the system with a maximum reduction of 15 percent. The largest concentration reductions occurred from 1T - 2T, with good results also between 1P - 2P and 2P - 3P. The best results coincide with the 1000 BPD flow and the percent removal decreased as flow rate increased. The wetland performed best at night.

Bicarbonate follows nearly the same trends as calcium, with maximum bicarbonate reductions of 15 percent. The reach 1T - 2T had roughly twice the removal of the other surface flow cells at flows of 3000 and 4000 BPD. The wetland had the highest reductions during the night.

Radium 226 is removed less consistently than calcium or bicarbonate but is reduced many times by over 40 percent. The highest removals occurred at 4000 BPD in the evening during a severe storm. The wetland had consistently good removal at all flows. There was good performance from 1T - 2T at flows of 1000 and 2000 BPD. The most consistent removal by all components occurred at 1000 BPD.

Sulfide concentrations increased by as much as 100 percent through the wetland cell and decreased by as much as 75 percent from 1T - 2T. Removals of over 50 percent occurred consistently from 1T - 2T at all flows. Reaches 1P - 2P and 2P - 3P also performed well but at lower flows. The wetland consistently increased the sulfide concentration.

Sulfate concentrations increased consistently through all of the system components. Sulfate increases were on the order of 12 percent with a maximum increase of 22 percent. The lined gravel cells had the highest increases at 1000 BPD and the wetland had the highest increase at 4000 BPD.

All BTEX components behave very similarly. 100 percent removal is consistently achieved from 1T - 2T at 1000 BPD with roughly 90 percent removal at all other flows. Over 70 percent removal was achieved from 1P - 2P at 1000

and 2000 BPD flows. The only data available for the wetland showed 100 percent removal at 3000 BPD.

The total phenolics data are sparse, but shows fairly consistent removal by all components. The wetland achieved 100 percent removal at 1000 BPD. The removal of phenolics through the surface flow cells was inconsistent.

In general TDS concentration changed less than 2 percent. The wetland generally increased TDS. The largest increase was 15 percent and occurred through the wetland at a flow of 1000 BPD.

The magnesium concentration generally increased through all system components. The maximum increase was 13 percent. The largest increases occurred through the wetland at flows of 1000 and 4000 BPD.

The alkalinity data set is relatively small. However, the concentration is consistently reduced. The wetland had the greatest reduction at 4000 BPD. The surface flow cells performed well at all flows.

5.5 Performance Trends and Influences

Calcium, bicarbonate, radium, sulfide and hydrocarbon are constituents of primary concern in this study. The data analysis showed consistent reduction of these constituents in the treatment system. These constituents will be the focus of the remainder of this chapter. Though important constituents of produced water, potassium, sodium and chloride concentrations were not appreciably reduced.

The terraced, lined, gravel cell (1T - 2T); the planar, lined, gravel cell (1P - 2P); the planar, three percent grade soil cell (2P - 3P); and the wetland (4 - 5) showed the most consistent and/or most extreme removal of most constituents.

These components will be used for further evaluation of system performance and design criteria.

A series of graphical relationships was developed to examine potential influences on system performance. The variables selected for the assessment include: ambient air temperature, water temperature, pH, overall system maturity and wind and solar intensity. These variables were recorded for each sample set and can thus be compared to changes in constituent removal over the course of the study.

The examined variables are represented on the X-axis and percent change in the constituent or field measurement is represented on the Y-axis. Each variable is graphically represented for the three surface flow cells and wetland cell referred to above. The graphs are examined for increasing or decreasing trends in constituent data relative to the independent variable.

Ambient Temperature

Ambient temperature was plotted against water temperature, pH, redox, chlorides calcium and bicarbonate removal. These relationships are shown in Appendix B, Figure B22 - B28. The water temperature graph appeared to be the only plot affected by ambient temperature. The greatest decrease in water temperature occurred through the lined cells at an ambient temperature of 5 degrees Celsius. The temperature decrease is reduced as ambient temperature is increased. The soil cell and the wetland showed less of an effect.

Water Temperature

Water temperature was plotted against the change in pH and dissolved oxygen readings, and against the change in bicarbonate, radium and sulfide concentrations. These graphs are shown in Appendix B, Figures B29 - B33. The net change in dissolved oxygen increased through the soil cell as water temperature increased. It decreased through the wetland as water temperature increased. There is a slight trend toward increased radium removal with increased water temperature. This is most consistent through the planar lined cell and most extreme in the wetland. Sulfide removal generally increased through the soil cell with an increase in water temperature. Reliable trends could not be established for the rest of the data. However, the greatest removals for all constituents usually occurred at higher water temperatures.

pH Reading

The pH was plotted against the change in bicarbonate, radium 226 and sulfide concentrations. These graphs are shown in Appendix B, Figures B34 - B36. The soil cell indicated increased bicarbonate and sulfide removal with increased pH. Radium removals increased for all of the cells at increased pH, with the most consistent trend in the soil cell. The rest of the data are too scattered to identify any trends.

System Maturity

The system maturity, in consecutive days of operation, was plotted against the percent change in bicarbonate, radium 226 and sulfide concentrations. These graphs are shown in Appendix B, Figures B37 - B39. Each figure examines the

maturity on a scale from 0 to 200 days. No trends were identified by these plots. Interestingly however, the three surface flow cells all plotted similarly for each constituent.

Wind and Solar Intensity

A relative scale for wind and solar intensity was developed from field notes of the weather conditions on each sampling date. The scale is intended to show relative differences from date to date in the wind and solar conditions. The intensity data are not intended to represent actual measurements. Both wind and solar intensity is plotted for each cell type. Wind or solar intensity is represented on the X-axis and % change on the Y-axis. The estimations used for relative intensity data are defined in Appendix B, Table B18.

Intensity was plotted against the percent change in bicarbonate, radium 226 and sulfide concentrations. These graphs are shown in Appendix B, Figures B40 - B45. In general, the surface flow cells exhibited trends toward increasing bicarbonate and radium removal with increasing wind intensity. The wetland showed no removal trends for these constituents. The surface flow cells also exhibited trends toward increasing bicarbonate removal with increasing solar intensity. No trends were indicated for radium or sulfide. The most consistent trends are for increased removal of bicarbonate through the terraced cell with increased wind and solar intensities. No trends were identified for sulfide removal when compared to wind or solar intensity.

5.6 Daily Mass Removal of Constituents

The mass removal rates of constituents in the various system components were calculated. These data are presented in Appendix B, Tables B19 - B24. These tables were developed to consider the long term feasibility of similar treatment systems.

The data illustrates the potential need for periodic system maintenance and hazardous material safeguarding due to significant accumulation of removed constituents. The calcium data indicated maximum removals over 10 kg/day. The bicarbonate data indicate a range of removal from 3.2 to 162.8 kg/day. The radium data indicate removal rates frequently over 5 million pCi/day, with a maximum value of 23.7 million pCi/day.

The data also illustrate the need to consider the potentially significant releases of constituents into the atmosphere. The sulfide data indicate peak removal rates over 10 kg/day. A significant portion of the sulfide removal is believed to result from bacterial conversion to sulfate. Caswell (1992) discusses the sulfur cycle in detail. BTEX component data indicate peak removal rates from 8 to 30 g/day. Though the removal rates for these volatile compounds is often large, no data are available to determine the portion of removal attributed to microbial degradation.

5.7 Quality of Data

All the data to this point in the study have been treated as unique points, each the result of a variety of controlling variables and external influences. For this reason, the bulk of the data have not been statistically evaluated or averaged.

In the case of the sample location (1), the data were examined statistically to establish the variability of the effluent to be treated. Regression analysis and curve fitting will be used in the design criteria under defined assumptions.

Caswell (1992) performed an extensive QA/QC analysis to determine the validity of the data gathered in the study. In his analysis, he examined the spike and duplicate data provided by Energy Laboratories. He found the data to be within U. S. EPA standards for both accuracy and precision.

It is the opinion of the author that some measurement error may have resulted from disturbing bacteria and sediments while collecting samples. The bacterial mats are very fragile and sediments and scale particles are often loosely settled. These materials are easily disturbed and can become suspended in the effluent. Disturbance of these materials could not be easily avoided during sampling and occurred frequently. Mixing and suspension of these materials usually occurred to some degree. It is believed that inclusion of these suspended materials in samples may have lead to false concentration increases and variability in the data. If this proved to be true, it may explain some of the data that indicate a reintroduction of constituents and performance variability. This type of measurement error might be reduced by siphoning water samples from the cells.

Chapter 6

TREATMENT SYSTEM DESIGN CRITERIA

6.1 Assumptions and Concepts

Bicarbonate, radium 226, sulfide and total phenolics are the constituents considered in the design criteria. These constituents exhibited the best potential for removal and are all common to most produced water. BTEX components were removed successfully and are also common to produced water, but the higher volatility of these constituents makes them less persistent. It is believed that in most cases the BTEX components would be adequately removed prior to achieving removal levels required of the four constituents considered. For this reason design criteria for BTEX will not be addressed.

Design criteria are presented for a terraced, lined, gravel cell; planar, lined, gravel cell; 3 percent grade soil cell; and a wetland cell. These treatment cell types showed the most consistent constituent removal. The soil cell performed well, but is not a feasible design due to erosion and frost heaving. It is studied with the intent of modelling a more stable lined cell with no gravel layer. As such, the data should be used with caution as potential ion exchange with soil particles was not measured. If ion exchange occurred, the lined cell would not receive the benefit of this treatment mechanism.

A basic assumption fundamental to the analysis is that the treatment cells will provide a constant rate of constituent removal with performance variables held constant.

Performance variables include the elements examined in this study such as pH, temperature, flow rate and climate, as well as, others not yet identified. Performance variables are not well defined and require further study. The design criteria are intended to facilitate future study and implementation of these systems.

The design criteria are based on two assumptions: 1) future systems will operate as the system under study and will reduce constituents when performance variables are ideal; 2) increases in constituent concentrations in the data studied are a result of sampling error or non-ideal performance variables.

With these assumptions established, a fundamental relationship is supported by the data: the concentration of a particular constituent entering a treatment cell is proportional to the concentration of that constituent leaving the cell. This relationship is given in equation (1) as:

$$C_i = K_o * C_{out} \quad (1)$$

where: C_i = The constituent concentration entering a cell, (mass/volume)

C_{out} = the constituent concentration leaving a cell, (mass/volume)

K_o = a dimensionless constant representing constant
performance variables

$K_o < 1$ for constituent removal

$K_o = f(\text{pH, temperature, wind, solar, etc. and}$
flow rate/treatment surface area)

The net effect of performance variables (pH, temperature, etc.) will be considered constant and within a range facilitating constituent removal. Flow rate and treatment area will be considered variables. This assumption yields:

$$K_o = f \left(\frac{\text{FLOW RATE}}{\text{TREATMENT CELL AREA}} \right) * Z_o$$

where: Z_o represents the combined net effect of the performance variables

Subtracting C_{out} from both sides of equation (1) yields an expression defining C_{red} , the concentration reduction across a treatment cell.

$$C_{red} = C_I - C_{out} = K_o C_{out} - C_{out} = C_{out} (K_o - 1) = \left(\frac{C_I}{K_o} \right) * (K_o - 1)$$

$$= \left(\frac{C_I}{K_o} \right) * (K_o - 1) = C_I * \left(1 - \frac{1}{K_o} \right) \quad \text{let, } K_1 = \left(1 - \frac{1}{K_o} \right)$$

$$C_{red} = K_1 * C_I \quad (2)$$

where: $C_{red} = C_i - C_{out}$
 $K_1 = f(\text{treatment area/flow rate}) * Z_o$
 (dimensionless)

K_1 represents the concentration reduction across a cell divided by the concentration entering the cell, and is termed the reduction factor.

Multiplying flow rate by the concentration entering a cell yields the constituent mass loading into the cell. Equation (3) defines the relationship between C_{red} , the concentration reduction across a cell and ML, the constituent mass loading into the cell.

$$C_{red} = \left(\frac{FLOW RATE}{FLOW RATE} \right) * K_1 * C_i = \left(\frac{K_1}{FLOW RATE} \right) * (C_i * FLOW RATE)$$

$$C_{red} = K_2 * ML \tag{3}$$

where: ML = the constituent mass loading into a cell
 (mass/unit time)

$$K_2 = \left(\frac{K_1}{FLOW RATE} \right) \tag{4}$$

Equation (4) is used to determine treatment cell sizing at a given flow rate. K_2 represents the concentration reduction across a cell divided by the corresponding constituent mass loading, and is termed the removal factor.

By previous definition:

$$K_1 = f \left(\frac{TREATMENT\ AREA}{FLOW\ RATE} \right) * Z_o = f (R1) * Z_o$$

where R1 is termed the treatment ratio, and is defined as:

$$R1 = \left(\frac{TREATMENT\ AREA (sqft)}{FLOW\ RATE (BPD)} \right)$$

The removal factor, K_2 is then the link between constituent removal at a given mass loading rate, and required treatment area at a given flow rate. This is illustrated below.

$$\left(\frac{C_{red}}{ML} \right) = K_2 = \left(\frac{K_1}{FLOW\ RATE} \right) \rightarrow K_1 \propto R1 = \left(\frac{TREATMENT\ AREA (sqft)}{FLOW\ RATE (BPD)} \right)$$

6.2 Design Criteria

To present the data in form useful for design, the study data were manipulated and tabulated to yield concentration reductions and constituent mass loading into each cell. These data are organized by constituent, and given in Appendix C, Tables C1 and C2.

The tabulated data were then plotted to show the relationship defined in equation (3). The concentration reduction is plotted against the constituent mass loading for bicarbonate, radium 226, sulfide and total phenolics. When plotted, the data for each graph sorted into clusters grouped by treatment ratio, R1. The slope of this data, K_2 , the removal factor, was determined by linear regression of the data. Once the slope was determined, lines were constructed through the data, and represent the treatment ratios used in the study. These graphical relationships are given in Appendix C, Figures C1 - C10. Each figure includes graphs of the constant treatment ratios used in the study.

The treatment ratio, R1, is equal to the treatment area, in square feet, divided by the flow rate in barrels per day. Treatment ratios used in the study are defined below.

The surface flow cells cover 5000 square feet and yield:

R1	Flow Rate (BPD)
5	1000
2.5	2000
1.67	3000
1.25	4000

The wetland cell is approximately 33,000 square feet and yields:

R1	Flow Rate (BPD)
16.5	2000
8.25	4000
5.5	6000
4.13	8000

The treatment ratio plots provide the user with a quick reference of the range of treatment ratio required for various constituent concentration reductions at constituent mass loading rates.

The regression analysis used to fit these lines and determine K_2 , the removal factor, are given in Appendix C, Tables C3 - C6. The regression data are organized by constituent and sorted by cell type and flow rate. K_2 is given as "x coefficient" and the error in K_2 is given as "std err of coef." In most cases, the error is reasonable. In some cases, it is greater than 50 percent. The error in K_2 may be used by the designer to add a safety factor to K_2 . Safety factors will not be included in the design methodology. Data based on K_2 error greater than 50 percent was selectively omitted from the design criteria.

The removal factor data derived from the regressions were multiplied by their respective flow rates to yield reduction factors, K_1 . The corresponding treatment ratios, R1, were also calculated and tabulated. These data are given in Appendix C, Tables C7 - C10. The tables are organized by constituent and sorted by treatment cell type.

Treatment cell sizing criteria was developed by plotting the reduction factor, K_1 , against the corresponding treatment ratio, R1, data. These relationships are

given in Appendix C, Figures C11 - C20. The figures are organized by constituent and treatment cell type. Each curve defines the proportional relationship between reduction factor and treatment ratio. For the case of sulfide treatment using lined gravel cells, the reduction factor is inversely proportional to the treatment ratio. This indicates that the gravel creates more turbulence and provides better sulfide stripping when flows are relatively high and treatment areas are relatively small.

The treatment area required for a given reduction factor is determined by multiplying the treatment ratio by the flow rate to be treated.

$$\textit{Required Treatment Area (sqft)} = R1 * \textit{Flow Rate (BPD)}$$

This design procedure defines the cell area required to treat a given flow rate and mass loading for a desired concentration reduction. It does not define the width and length of the cell. Under theoretically ideal conditions, it would make no difference if a 2000 sqft cell was 20 feet wide and 100 feet long, or 100 feet wide and 20 feet long. The cell retention time and contact area would be the same based on the proportional relationship:

$$\textit{Flow Rate} = \textit{Velocity} * \textit{Cross-sectional Area}$$

However, in practice, frictional effects will have a significant influence on flow velocity and subsequent cross-sectional area. A reasonable approach for determining the width and length of a treatment cell is described and included in

the design procedure in section 6.3. It is based on the results determined in this study. Criteria for this approach include:

- the present surface flow cell length to width ratio is 2:1
- the present wetland cell length to width ratio is 19:1
- good constituent removal generally occurred at a flow rate of 2000 BPD in the surface flow cells and 4000 BPD in the wetland

6.3 Design Procedure

The design procedure is outlined in sequential order. The method is based on the assumptions, concepts and criteria of sections 6.1 and 6.2. The procedure is applicable to:

bicarbonate removal using a terraced, lined, 3 percent grade, gravel cell
a planar, lined, 3 percent grade, gravel cell
a planar, 3 percent grade, soil cell

radium 226 removal using a terraced, lined, 3 percent grade, gravel cell
a planar, lined, 3 percent grade, gravel cell
a constructed wetland cell

sulfide removal using a terraced, lined, 3 percent grade, gravel cell
a planar, lined, 3 percent grade, gravel cell
a planar, 3 percent grade, soil cell

total phenolics removal using a constructed wetland cell

The designer should first determine the type of cell to be used. The decision should be based on accommodating site topography and minimizing construction costs by implementing the smallest, most efficient design. Terraced cells require the most slope. Planar cells require less slope and wetland cells require no slope. A lined wetland cell or terraced cell would be the most costly to construct. Planar cells would be slightly less and unlined wetland cells would be the least costly. The most efficient design can only be determined by working through the design method for each cell type and determining the area required for each. The design procedure addresses only one cell type at a time.

1. Determine the constituent or combination of constituents to be removed.
2. Determine the daily flow rate in barrels per day (BPD).
3. Determine the required concentration reduction for the first constituent in (mg/l) or (pCi/l).
4. Calculate the daily mass loading of the first constituent in the units appropriate for Figures C1 - C10. (kg/day, uCi/day or g/day)
5. Calculate the removal factor, K_2 from:

$$K_2 = \left(\frac{C_{red}}{ML} \right)$$

6. Calculate the reduction factor, K_1 , from:

$$K_1 = K_2 * \text{FLOW RATE (BPD)}$$

7. Select the appropriate graph from Figures C11 - C20 for the constituent and cell type.
8. Record the treatment ratio, R_1 that corresponds to the calculated reduction factor, K_1 .
9. Multiply R_1 by the flow rate in BPD to determine the treatment area required.
10. Repeat steps 3 - 9 for each constituent.
11. Compare the required treatment area data. The constituent that is the most difficult to remove will have the largest area. Select this area for the system size. However, sulfide treatment design using lined gravel cells requires smaller treatment cell areas for better stripping. If sulfide is treated along with other constituents, using lined gravel cells, it is recommended that a separate sulfide stripping cell be constructed upstream of the other treatment cell.

Determination of the length to width ratio.

12. Divide the flow rate by 2000 BPD for surface flow cells and by 4000 for wetland cells.
13. Multiply this number by 50 feet for surface flow cells and by 35 feet for wetland cells. The result is the cell width.

14. Divide the cell width into the required treatment area to determine the cell length.
15. Verify at least a 2:1 length to width ratio for surface flow cells and a 19:1 length to width ratio for wetland cells. If the recommended length to width ratios are not achieved, reduce the width until the ratio is satisfied.

This procedure yields a reasonable estimate of treatment system area, cell length and cell width for a desired constituent concentration reduction at a given constituent mass loading and flow rate.

A design example is given in Appendix C, Figure C21. The example considers radium 226 removal from a hypothetical produced water using a 3% grade, terraced, lined gravel cell. The untreated effluent radium concentration is 10 pCi/l. The allowable discharge concentration is 5 pCi/l. The flow rate is 5,000 BPD. The resulting mass loading rate is 7.9 uCi/day radium. The results of the example call for a 50,000 sqft treatment area, 125 feet wide and 400 feet long. 16 one foot terraces and a seven percent site grade are required.

Chapter 7 CONCLUSIONS

7.1 System Integrity

The concepts governing the overall physical design of the system and components were sound. The system supported an environment for constituent removal, while performing under a variety of flow rates and ambient conditions. It provided adequate versatility for flow distribution and regulation. The system operated for eight months during the study without any component failures.

Improved performance and durability of nearly all the components could be achieved with some minor modifications in design or materials. These modifications are addressed by component in Section 5.1. Lining cells to prevent erosion, frost heaving and potential seepage is the most important recommended modification to future systems.

For long term operational systems, components should be constructed from more durable materials. Wooden structures should be replaced with steel and concrete structures. For temporary research facilities, the treated lumber design is adequate.

7.2 Produced Water Constituent Removal

The treatment system was successful at reducing bicarbonate, radium 226, sulfide and hydrocarbon concentrations. Little success was realized with potassium, sodium, chloride and magnesium. The following summarizes the removal percentages:

<u>Constituent</u>	<u>Maximum Removal:</u>	<u>**Average Removal:</u>
bicarbonate	15 %	6 %
radium 226	64 %	21 %
sulfide	77 %	39 %
BTEX	100 %	82 %
total phenolics	100 %	31 %

** average removal percent based on removal data only

The system components, ranked by best overall performance to worst overall performance, are: (1) terraced, lined, gravel cell; (2) planar, lined, gravel cell; (3) planar, 3 percent grade, soil cell; (4) planar, 2 percent grade, soil cell. The wetland performance is highly constituent specific. It provided good treatment of hydrocarbons and radium 226.

In general, treatment efficiency decreased as flow rate increased. The best constituent removal usually occurred at flows of 1000 and 2000 BPD over the 5000 square foot surface flow cells, and 2000 and 4000 BPD over the 33,000 square foot wetland cell. The decrease in constituent removal efficiency, with flow rate increase, tends to be constituent specific.

7.3 Performance Influences and Trends

The study results indicate that many performance influences and variables are present. These influences can greatly affect system performance and at times, actually increase constituent concentrations across the system. Water temperature, pH and wind and solar intensity were identified in this study as influencing system performance. Many performance variables were not studied or are not well defined. Those affecting biological processes are likely the most significant.

Future systems and studies should be designed to better isolate and quantify performance influences and variables. It is suggested that external variables such as weather conditions and solar intensity be accurately monitored. As positive influences are identified, it may be useful to consider a batch treatment process under ideal conditions.

7.4 Design Criteria

The design method presented here provides a reasonable approach to the design of future systems. Design criteria is included for bicarbonate, radium 226, sulfide and total phenolics removal. The method determines the required system size based on desired constituent concentration reductions at given flow rates and mass loading rates. They do not define well the most efficient length to width ratio of a treatment cell, though guidelines are included in the design method.

The design method should be used with some caution and allowances for performance variability should be made. The design criteria are based on several assumptions and conditions that may lead to error. These include: the criteria

were developed solely from the data showing constituent removal; it is assumed that concentration increases are the result of sampling error; future systems are assumed to perform as well as this system; often only a few data points were available to develop design graphs; it is assumed that the system is fully mature, though this cannot be assessed after operating only eight months under many different flow rates. It is likely that the wetland in particular is still in its early stages of development.

7.5 Feasibility of Treatment Method

Constructed surface flow and wetland systems provide a reasonable means of produced water treatment using available technology and materials. These systems are relatively inexpensive to build and operate and require little maintenance and supervision. They have been shown in this study to remove constituents of concern from produced water. Larger and more efficient systems of this type would likely improve water quality to the extent necessary for permitted surface discharge of the effluent.

Periodic removal of accumulated material and final site closure will be required of these systems. The mass removal data discussed in Section 5.6, indicate that a successful system may accumulate significant quantities of waste material in the treatment cells. Treatment cells will require periodic removal and disposal of this material during operation and before closure. Final closure will include the removal of system components and reclamation of the site. Costs of these operating and closure activities should be estimated and considered during the planning process.

Health and safety considerations for operating personnel and wildlife, as well as, air quality issues must be considered before implementing these systems. The mass removal data indicate substantial accumulations of radium in the treatment cells and substantial releases of sulfide and BTEX components into the atmosphere. It may be prohibitively expensive to safely handle and dispose of waste materials. The risks associated with exposure to these materials has not been studied here. Until these matters of waste disposal and risk have been addressed, these systems should not be deemed acceptable.

Wildlife protection should also be considered and included in the design of these systems. Surface flow cells provide no habitat and should be fenced and possibly netted. Wetlands provide excellent habitat, but as a treatment facility, raise the question: "Should wildlife be permitted in an environment that concentrates radium and degrades hydrocarbons?" Wildlife officials and experts should be consulted over these issues before developing these systems.

REFERENCES CITED

- Brus, Kathy. Personal Conversation. 29 Jan 1992.
- Caswell, Peter C. "Contaminant removal and toxicity reduction in a pilot scale surface flow/wetland system for the treatment of oilfield produced water." Thesis: Colorado School of Mines, 1992.
- Chen, A. S. C., et al. 1991. Removal of oil, grease and suspended solids from produced water with ceramic crossflow microfiltration. SPE Prod. Engineering 6 (2): pp.131-136.
- Cohen, Ronald. Personal Conversation. November 1990.
- Corbitt, Robert A. ed. Standard Handbook of Environmental Engineering. New York: McGraw-Hill, 1990.
- Cowan, Jack C. and Donald J. Weintritt, 1976. Water-Formed Scale Deposits. Houston, TX: Gulf Pub. Co.
- Crist, Dennis R. "Brine management practices in Ohio." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Emerick, John. Personal Conversation. November, 1990.
- Haney, P. D. 1954. Theoretical Principles of Aeration. J. of American Waterworks Assn. 46: p.353.
- Heilshorn, Elyse D. 1990. "Removing VOCs from Contaminated Water". Chemical Engineering 98 (3): pp. 152-158.
- Hostomsky, J. and A. G. Jones. 1990. Calcium carbonate crystallization, agglomeration and form during continuous precipitation from solution. J. of Physics 24 (2): pp.165-170.

- Kok, S., A. Zaidi and R. Soloman. 1989. Total dissolved solids removal from water produced during the in situ recovery of heavy oil and bitumen. The J. of Canadian Petroleum Technology 28 (1): pp.100-105.
- Ostroff, A. G. Introduction to Oilfield Water Technology. 2nd ed. Houston, TX: Nat'l Assoc. of Corrosion Engineers, 1979.
- Perry, Charles W. and Kenneth Gigliello. "An EPA perspective on current RCRA enforcement trends and their application to oil and gas production wastes." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Pietri, Alan. Personal Conversation. 29 January 1992.
- Simmons, Brad F. Telephone conversation. 6 May 1991.
- Subramonian, Suresh, Dennis Clifford and Winston Vijeswarapu. 1990. Evaluating ion exchange for removing radium from groundwater. J - American Water Works Assn. 82 (5): pp.61-70.
- Tchobanoglous, George and Edward D. Schroeder. Water Quality. Reading, MA: Addison-Wesley, 1985.
- Van Sickel, Virginia and C. G. Groat. "Oil field brines: another problem for Louisiana's coastal wetlands." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Wagner, John F. "Toxicity and radium 226 in produced water - Wyoming's regulatory approach." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Wagner, John F. Telephone Conversation. 20 Nov 1991.
- Xyla, Aglaia G., Efthimios K. Giannimaras and Petros G. Koutsoukos. 1991. The precipitation of calcium carbonate in aqueous solutions. Colloids and Surfaces 53 (3/4): pp.241-255.

SELECTED BIBLIOGRAPHY

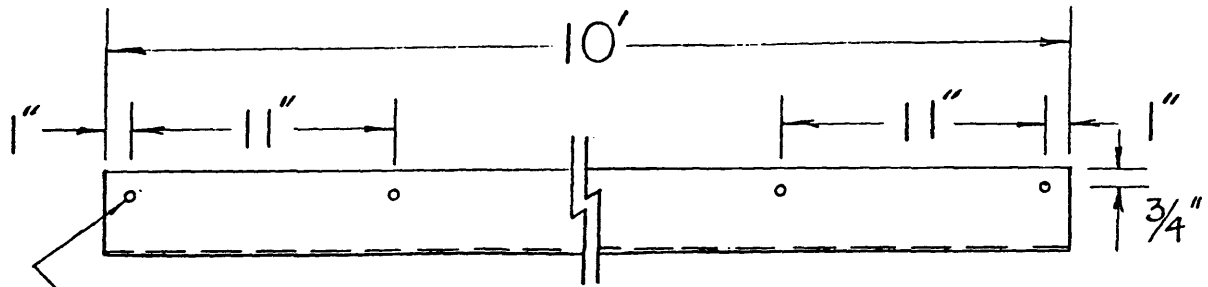
- Bos, M. G. ed. Discharge Measurement Structures. Wageningen, The Netherlands: ILRI, 1976.
- Chapman, David T. and Jerry Grammas. 1989. Management and analysis of data from petroleum refinery wastewater treatment plants. Wat. Pol. resrch. J. of Canada 24 (3): pp.391-409.
- Chapman, Peter M. 1989. Toxicity measurement and reduction procedures (Biomonitoring and TRE Programs). Wat. Pol. Resrch J. of Canada 24 (3): pp.425-434.
- Crume, Richard V., et al. 1990. Risk analysis on air emissions from ground water aeration. Resrch J. of the Wat. Pol. Control Fed. 62 (2): pp.119-123.
- Davison, Maggie. Letter from Wyoming DEQ to Marathon Oil Company. 3 Feb. 1989.
- Deuel, L. E. Jr. "Evaluation of limiting constituents suggested for land disposal of exploration and production wastes." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Dold, P. L. 1989. Current practice for treatment of petroleum refinery wastewater and toxics removal. Wat. Pol. Resrch J. of Canada 24 (3): pp. 364-381.
- Ervine, Dr. Alan. "Two phase flow in hydraulic structures." Lecture series presented to the Bureau of Reclamation. July 1985.
- Fang, C. S. and Sok-Leng Khor. 1989. "Reduction of Volatile Organic Compounds in Aqueous Solutions Through Air Stripping and Gas-Phase Carbon Adsorption". Environmental Progress 8 (4): pp.270-278.

- Farnand, Brian A. and Thomas A. Krug. 1989. Oil removal from oilfield-produced water by cross flow ultrafiltration. The J. of Canadian Petroleum Technology 28 (6): pp.18-24.
- Hall, Robert W. "Environmental consequences of mismanagement of wastes from oil and gas exploration, development, and production." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Johnson, Perry L., et al. "Gas transfer at hydraulic structures." Task Committee on Gas Transfer at Hydraulic Structures. ASCE.
- Kiser, S. C., M. J. Wilson and L. M. Bazeley. "Oil field disposal practices in Western Kern County, California." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Lamarche, Phillippe and Ronald L. Droste. 1989. "Air Stripping Mass Transfer Correlations for Volatile Organics". J. of American Water Works Association 81 (1): pp. 78-89.
- Li, K. Y. and K. J. Hsiao. 1991. "How to Optimize an Air Stripper". Chemical Engineering 98 (7): pp. 114-118.
- Mangelson, Kenneth A. and Richard P. Lauch. 1990. Removing and disposing of radium from well water. J. - American Water Works Assn. 82 (6): pp.72-76.
- Mendelssohn, Irving A., Kathryn M. Flynn and Brian L. Wilsey. 1990. The relationship between produced water discharges, and plant biomass and species composition, in three Louisiana marshes. Oil and Chemical Pollution 7 (4): pp.317-335.
- Miller, H. T. and E. D. Bruce. "Pathway exposure and the identification of waste disposal options for petroleum production wastes containing naturally occurring radioactive materials." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.

- Myers, Julian M. and Michael J. Barnhart. "Pilot bioremediation of petroleum contaminated soil." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Nirmalakhandan, N., W. Jang and R. E. Speece. 1990. "Counter-Current Cascade Air Stripping for Removal of Low Volatile Organic Contaminants". Water Research 24 (5): pp. 615-623.
- Nutt, Stephen G. 1989. Optimization and control petroleum refinery wastewater treatment systems - status, trends and needs. Wat. Pol. Resrch J. of Canada 24 (3): pp. 463-477.
- Patton, Dr. Charles C. Oilfield Water Systems. 2nd ed. Norman, OK: Cambell Petroleum Series, 1977.
- Rabalais, Nancy N., Jay C. Means and Donald F. Boesch. "Fate and effects of produced water discharges in coastal environments." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Schmidt, Ernst and Shilee Jaeger. "PRS treatment and reuse of oilfield wastewaters." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Simmons, Brad F. "The treatment and disposal of wastewaters produced with coalbed methane by reverse osmosis." Thesis: Colorado School of Mines, 1991.
- Simms, K., S. Kok and A. Zaidi. "Alternative processes for the removal of oil from oilfield brines." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Smyth, I. C. and M. T. Thew. "The use of hydrocyclones in the treatment of oil contaminated water systems." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.

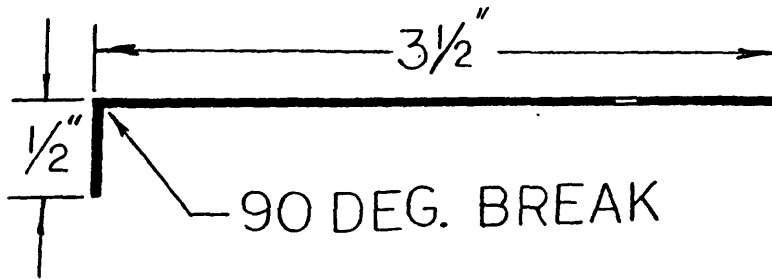
- St. Pe, Kerry M., et al. "An assessment of produced water impacts to low-energy, brackish water systems in southeast Louisiana: A project summary." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Stilwell, C. T. "Area waste management plan for drilling and production operations." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Subra, Wilma A. "Unsuccessful oilfield waste disposal techniques in Vermilion Parish, Louisiana." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- United States Dept. of the Interior. "Air-Water Flow in Hydraulic Structures." Water Resources technical publication, engineering monograph No. 41.
- Valentine, Richard L., Karen M. Spangler and John Meyer. 1990. Removing radium by adding preformed hydrous manganese oxides. J - American Water Works Assn. 82 (2): pp.66-71.
- Vickers, D. Troy. "Disposal practices for waste waters from coalbed methane extraction in the Black Warrior Basin, Alabama." Proceedings of The First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. 10-13 Sept. 1990. New Orleans, LA.
- Ward, Robert C. and Jim C. Loftis. 1989. Monitoring systems for water quality. Crit. Rev. in Env. Control 19 (2): pp.101-117.
- Wood, Dianne F., et al. 1990. "Air Stripping of Volatile Hydrophobic Compounds Using Packed Crisscross Flow Cascades". Environmental Progress 9 (1): pp. 24-29.
- Wyoming DEQ. Marathon Oil Company, NPDES permit No. WY-0026590. "Authorization to discharge under the National Pollutant Discharge Elimination System." 1989.

APPENDIX A
FABRICATION DRAWINGS



TOP VIEW NTS

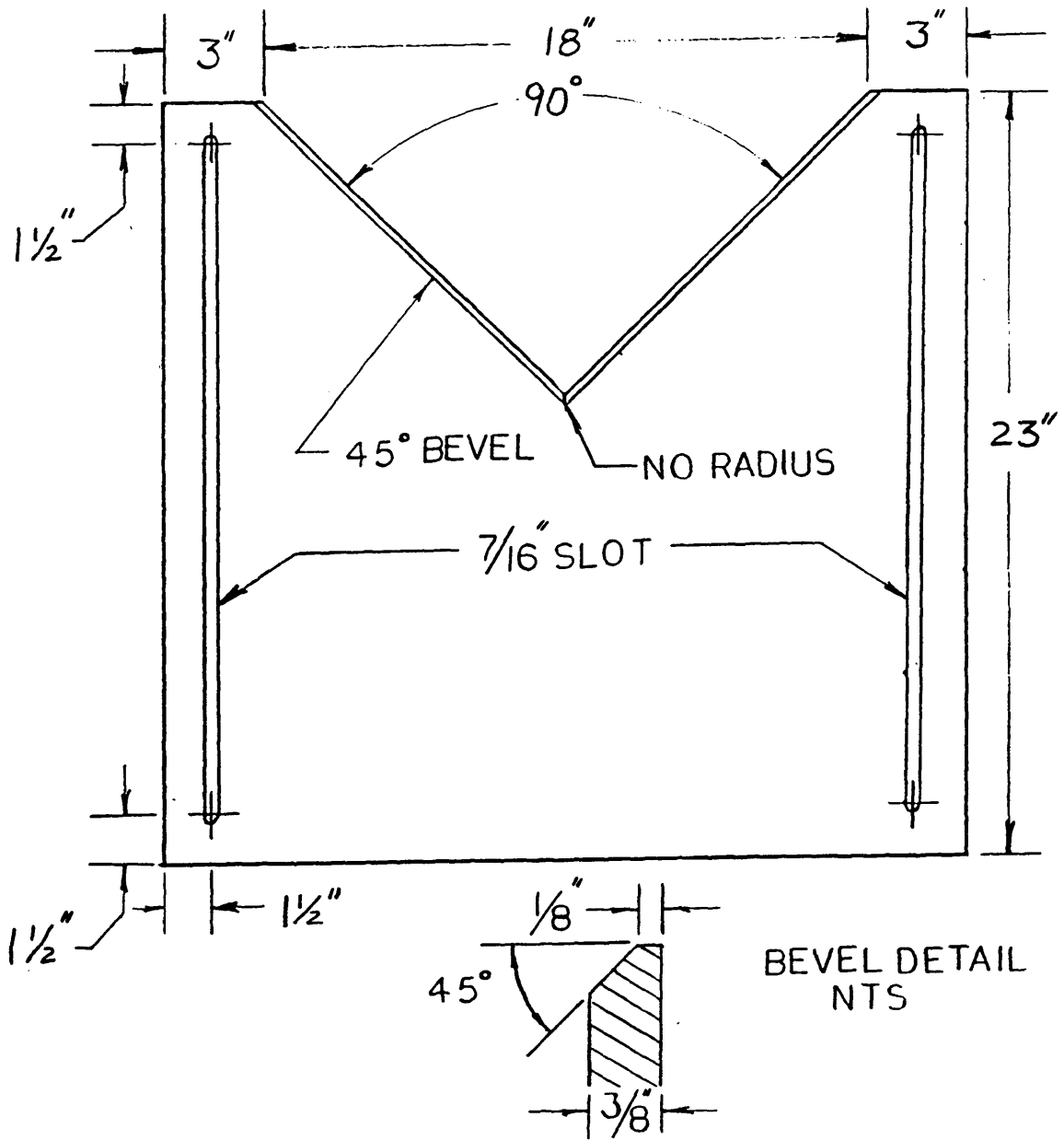
1/8" PUNCH 12" CENTERS
EXCEPT AS INDICATED



SIDE CROSS-SEC. NTS

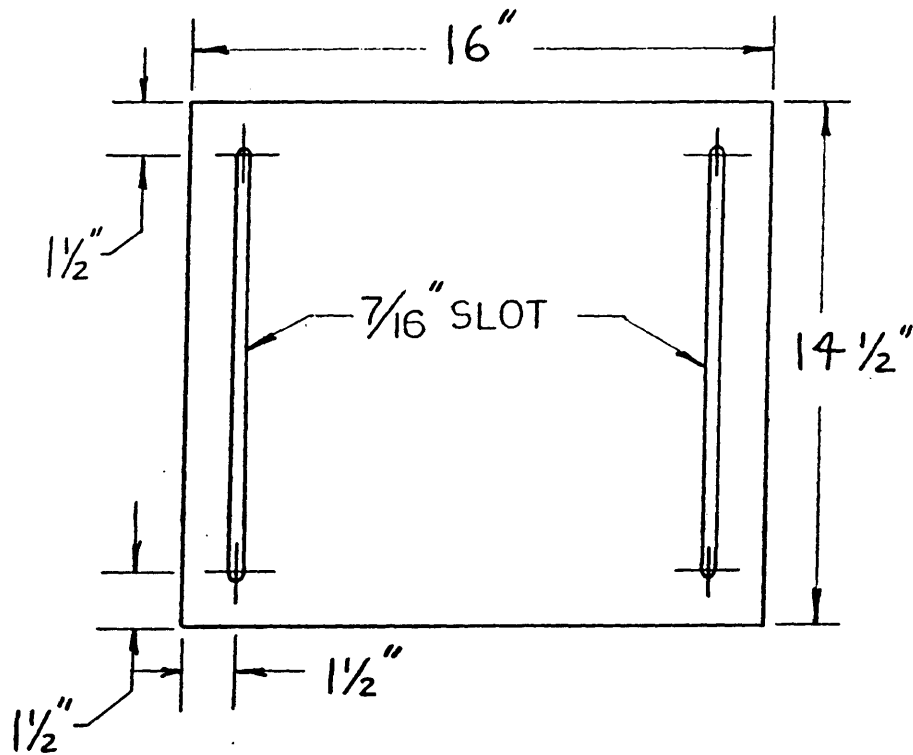
PART: DRIP EDGE
MAT'L: 24 GA. SS MILL FINISH
10 REQUIRED
DANIEL GELB - CSM

Figure A1 - Terrace drip edge



PART: V-NOTCH WEIR PLATE
MATERIAL: 3/8" UHMWPE

Figure A2 - V-notch weir plate

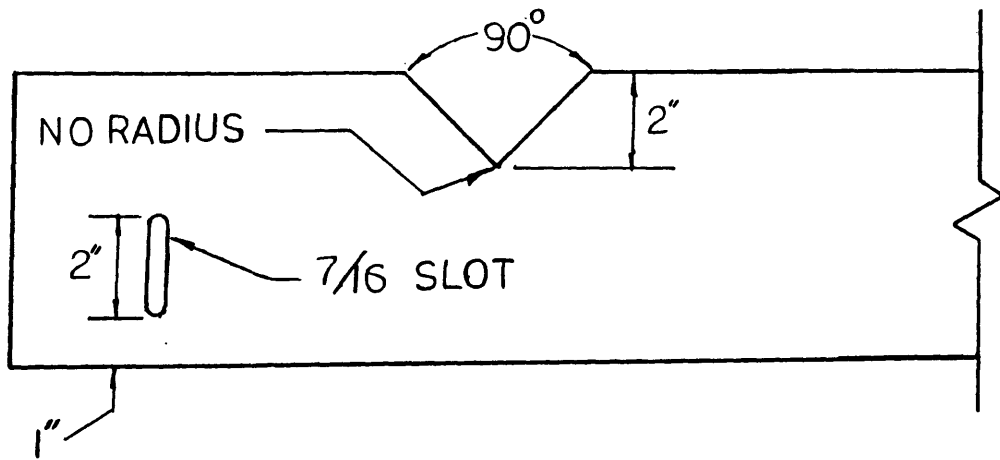
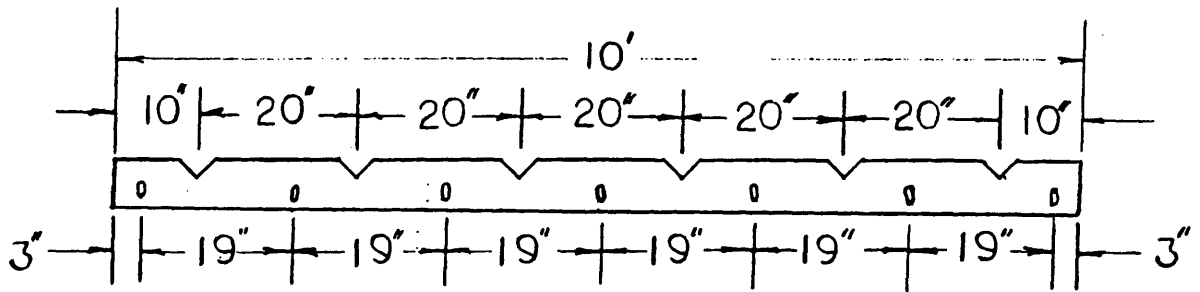


PART: CHECK DAM 1 REQUIRED

MATERIAL: $\frac{3}{8}$ " UHMWPE

DANIEL GELB-CSM $\frac{3}{16}$ SCALE

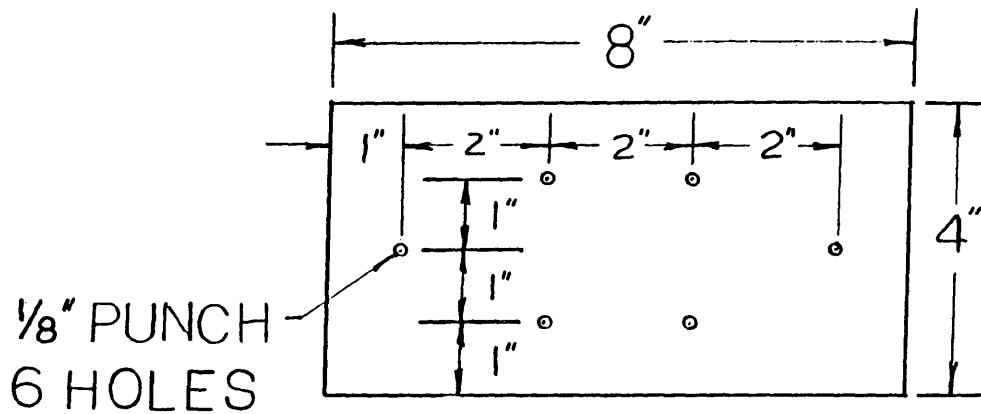
Figure A3 - Adjustable spillway



SLOT AND V-NOTCH DETAIL

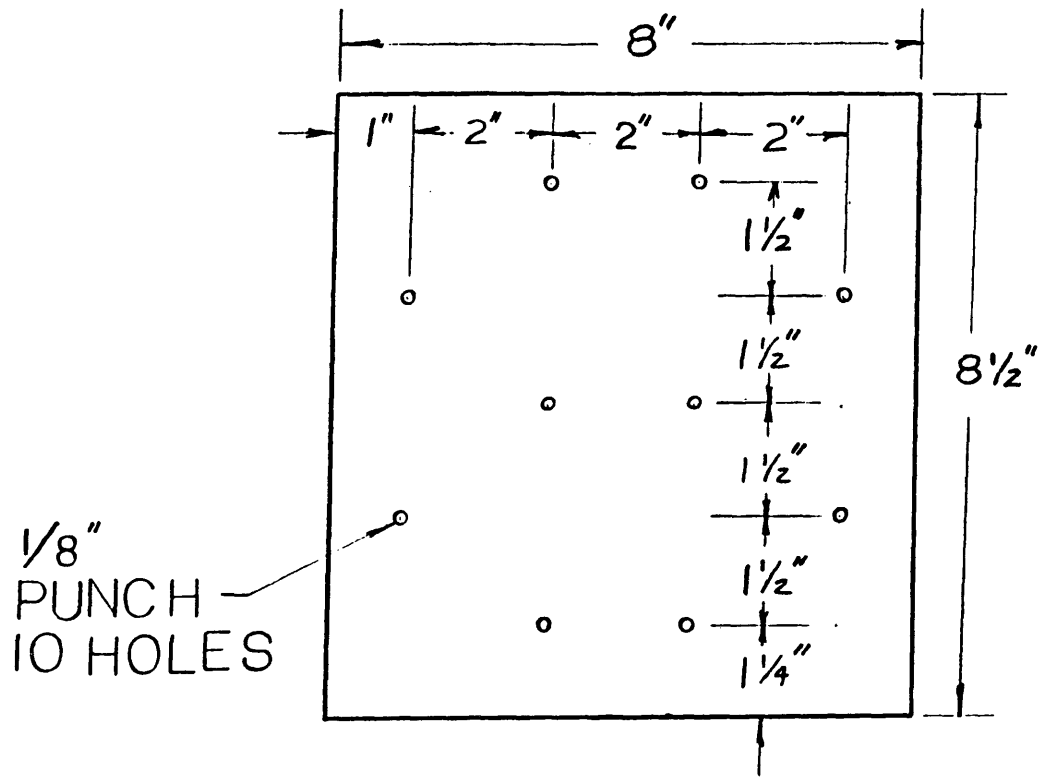
PART: V-NOTCH WEIR PLATE
MATERIAL: 3/8" UHMWPE
10 PCS REQUIRED
DANIEL GELB - CSM

Figure A4 - Adjustable weir strip



PART: UNION PLATE
MATERIAL: 24GA. GALV. STL.
20 PCS. REQUIRED
DANIEL GELB - CSM $\frac{3}{8}$ SCALE

Figure A5 - Channel union plate 1



PART: UNION PLATE
MATERIAL: 24GA. GALV. STL.
36 PCS. REQUIRED
DANIEL GELB - CSM $\frac{3}{8}$ SCALE

Figure A6 - Channel union plate 2

APPENDIX B
RESULTS

Table B1 - Field Measurements: Flow Rate, Water Temperature and pH

Measurement: Flow Rate (GPM)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/30/91	1000	N/A	26.0	304.1	304.1	29.3	24.5	24.0	31.6	28.6	26.0	47.8	43.5
08/02/91	2000	N/A	17.5	241.0	241.0	60.0	52.0	50.0	64.0	63.0	57.0	112.0	105.0
08/08/91	2000	N/A	14.0	247.0	247.0	55.0	63.0	63.0	63.0	63.0	55.0	128.0	120.0
07/25/91	3000	N/A	18.3	194.8	194.8	83.9	78.9	91.6	86.3	91.6	87.0	183.0	163.0
08/05/91	4000	N/A	23.0	127.0	127.0	113.0	109.0	113.0	125.0	125.0	128.0	***	***

*** Wetland Shut-in

Measurement: Water Temperature (deg C)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	32.0	28.0	32.0	27.3	26.5	32.0	29.0	27.0	26.5	18.0
07/26/91	4000	24 hr	16.0	31.0	23.0	31.5	29.0	28.0	31.5	29.5	28.0	23.0	16.0
07/30/91	1000	48 hr	26.0	32.0	30.0	31.0	24.0	24.5	32.0	26.5	26.0	24.0	19.0
07/31/91	1000	72 hr	26.5	33.0	31.0	33.0	27.5	26.5	27.0	27.5	27.0	25.5	20.0
08/02/91	2000	48 hr	17.5	33.0	30.5	32.5	22.5	22.5	32.5	28.0	22.5	22.5	16.0
08/02/91	2000	60 hr eve	14.0	35.0	30.0	35.0	20.0	18.0	35.0	25.0	19.0	18.0	19.0
08/03/91	2000	72 hr	16.0	34.0	32.0	34.0	28.0	27.0	34.0	29.0	27.0	27.0	17.0
08/05/91	4000	48 hr	23.0	34.0	30.0	34.0	29.0	27.5	34.0	31.5	27.5	17.5	20.0
08/05/91	4000	60 hr eve	16.0	33.5	28.0	33.5	19.5	18.0	33.5	25.0	18.0	16.0	15.5
08/08/91	2000	30 day	14.0	28.0	25.0	28.0	19.0	17.5	28.0	22.0	18.0	16.5	14.0
11/02/91	3000	56 day	-10.0	28.0	22.5	26.0	16.5	15.0	28.0	23.0	16.0	15.0	6.5
01/13/92	4000	71 d dusk	-4.0	27.0	20.0	27.0	21.0	15.0	27.0	21.0	16.0	15.0	9.0
01/17/92	2000	72 hr	-5.0	24.5	20.0	24.0	10.5	7.0	24.0	15.0	9.0	8.0	1.5
01/23/92	1000	120 hr	5.0	22.5	19.0	22.5	8.0	6.0	22.5	11.0	7.0	6.0	1.0

Measurement: pH				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	7.1	7.9	7.4	7.8	7.9	7.4	7.7	7.8	8.0	6.1
07/26/91	4000	24 hr	16.0	7.2	7.4	7.3	7.5	7.6	7.3	7.5	7.6	7.5	7.5
07/30/91	1000	48 hr	26.0	7.3	7.9	7.6	7.8	7.9	7.7	7.8	7.9	7.9	8.1
07/31/91	1000	72 hr	26.5	7.1	7.7	7.3	7.6	7.7	7.5	7.6	7.7	7.9	7.8
08/02/91	2000	48 hr	17.5	7.1	7.6	7.2	7.6	7.6	7.3	7.5	7.6	7.7	7.7
08/02/91	2000	60 hr eve	14.0	7.7	7.8	7.7	7.8	7.9	7.7	7.8	7.8	8.0	7.9
08/03/91	2000	72 hr	16.0	7.4	7.8	7.3	7.3	7.4	7.4	7.4	7.4	7.7	7.7
08/05/91	4000	48 hr	23.0	7.1	7.8	7.4	7.6	7.7	7.4	7.6	7.7	7.8	7.9
08/05/91	4000	60 hr eve	16.0	7.5	7.8	7.5	7.7	7.9	7.5	7.8	7.8	7.9	7.9
08/08/91	2000	30 day	14.0	6.9	7.3	6.9	7.1	7.2	7.0	7.1	7.2	7.3	7.3
11/02/91	3000	56 day	-10.0	6.7	7.1	6.7	6.8	7.0	6.7	6.9	7.0	7.1	7.1
01/13/92	4000	71 d dusk	-4.0	7.2	7.8	7.2	7.3	7.5	7.3	7.4	7.5	7.5	7.6
01/17/92	2000	72 hr	-5.0	7.2	7.4	7.2	7.3	7.4	7.2	7.3	7.4	7.4	7.5
01/23/92	1000	120 hr	5.0	7.3	7.4	7.2	7.3	7.4	7.2	7.3	7.4	7.4	7.4
01/17/92	2000	72 hr	-5.0	7.2	7.4	7.2	7.3	7.4	7.2	7.3	7.4	7.4	7.5
01/23/92	1000	120 hr	5.0	7.3	7.4	7.2	7.3	7.4	7.2	7.3	7.4	7.4	7.4

Table B2 - Field Measurements: Conductivity, Dissolved Oxygen and Redox

Measurement: Conductivity (micro-mhos)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	3390	3250	3200	3200	3200	3200	3290	3175	3150	2775
07/26/91	4000	24 hr	18.0	3150	2995	3150	3150	3200	3150	3200	3200	2990	2560
07/30/91	1000	48 hr	26.0	3125	3225	3275	3000	3000	2975	3025	2990	2925	2750
07/31/91	1000	72 hr	26.5	3325	3250	3175	2975	2975	3325	3025	2950	2900	2700
08/02/91	2000	48 hr	17.5	3350	3175	3150	2950	2950	3325	3025	2950	2825	2350
08/02/91	2000	60 hr eve	14.0	3400	3100	3275	2600	2400	3350	2800	2450	2425	2450
08/03/91	2000	72 hr	18.0	3025	3225	2975	2975	2950	3375	3025	2925	2900	2525
08/05/91	4000	48 hr	23.0	3300	3175	2700	3025	3000	3300	3150	3000	2525	2600
08/05/91	4000	60 hr eve	16.0				NO DATA DUE TO HAIL STORM						
09/08/91	2000	30 day	14.0	2525	2325	2525	2575	2200	2525	2350	2175	2125	1925
11/02/91	3000	56 day	-10.0	1450	1600	1600	1600	1600	1550	1700	1600	1575	1350
01/13/92	4000	71 d dusk	-4.0	1800	1725	1875	1825	1725	1925	1850	1700	1875	1550
01/17/92	2000	72 hr	-5.0	1800	1700	1825	1600	1475	1875	1625	1475	1425	1325
01/23/92	1000	120 hr	5.0	1825	1725	1975	1575	1500	1950	1600	1500	1475	1425

Measurement: Dissolved Oxygen (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	0.1	6.2	0.3	5.8	6.2	0.2	3.4	6.0	5.5	6.0
07/26/91	4000	24 hr	18.0	0.1	4.8	0.2	5.2	5.2	0.2	3.8	5.3	4.3	4.4
07/30/91	1000	48 hr	26.0	0.1	3.8	0.1	4.3	9.2	0.1	0.2	9.2	6.3	4.9
07/31/91	1000	72 hr	26.5	0.2	3.8	0.1	4.4	8.2	0.1	0.1	9.4	6.7	5.2
08/02/91	2000	48 hr	17.5	0.2	4.5	0.5	5.4	7.2	0.5	2.5	8.4	6.2	5.0
08/02/91	2000	60 hr eve	14.0	0.2	3.2	0.2	3.1	5.2	0.2	0.6	3.8	5.2	5.9
08/03/91	2000	72 hr	16.0	0.2	3.3	0.2	4.8	8.7	0.2	0.2	7.8	5.9	5.9
08/05/91	4000	48 hr	23.0	0.1	3.8	0.1	5.1	7.0	0.1	0.1	7.1	6.7	6.5
08/05/91	4000	60 hr eve	16.0				NO DATA DUE TO HAIL STORM						
09/08/91	2000	30 day	14.0	1.3	3.1	0.8	2.8	4.1	0.7	0.8	2.9	4.1	5.1
11/02/91	3000	56 day	-10.0	1.1	2.4	1.3	3.9	5.8	1.3	1.3	4.7	5.3	7.9
01/13/92	4000	71 d dusk	-4.0	1.4	4.3	1.2	2.2	3.8	1.2	1.2	3.0	4.8	8.3
01/17/92	2000	72 hr	-5.0	1.0	5.4	0.8	8.8	8.7	1.0	4.1	7.9	8.6	10.8
01/23/92	1000	120 hr	5.0	1.4	5.9	1.3	7.6	8.5	1.3	7.5	8.1	8.8	10.4

Measurement: Redox (mV)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	-145	132	-120	22	70	-120	-24	32	118	38
07/26/91	4000	24 hr	18.0	-80	172	-110	22	66	-101	-30	35	178	12
07/30/91	1000	48 hr	26.0	-79	151	-102	79	172	-105	-92	122	174	191
07/31/91	1000	72 hr	26.5	-91	152	-104	55	172	-104	-78	150	174	129
08/02/91	2000	48 hr	17.5	-84	135	-108	74	131	-115	-48	70	147	134
08/02/91	2000	60 hr eve	14.0	-88	63	-129	-42	8	-129	-100	-35	39	108
08/03/91	2000	72 hr	16.0	-101	72	-133	36	121	-128	-66	74	132	105
08/05/91	4000	48 hr	23.0	-86	84	-129	-6	79	-134	-90	16	148	158
08/05/91	4000	60 hr eve	16.0	-127	-18	-162	-97	-59	-168	-129	-79	107	48
09/08/91	2000	30 day	14.0	-154	76	-184	10	24	-184	-180	34	68	115
11/02/91	3000	56 day	-10.0	-163	-11	-183	-45	45	-203	-194	10	38	108
01/13/92	4000	71 d dusk	-4.0	-182	38	-204	-122	-68	-199	-193	-65	-39	107
01/17/92	2000	72 hr	-5.0	-144	67	-177	28	68	-192	-38	68	73	118
01/23/92	1000	120 hr	5.0	-156	74	-172	86	90	-184	77	100	106	127

Table B3 - Analytical Data: Potassium, Sodium and Chloride

Constituent: Potassium (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	120	128	120	124	129	120	133	136	125	125
07/30/91	1000	48 hr	26.0	131	NT	131	142	130	131	135	126	133	145
07/31/91	1000	72 hr	26.5	135	NT	135	141	147	135	136	142	140	149
08/02/91	2000	48 hr	17.5	170	107	170	145	138	170	133	123	108	108
08/02/91	2000	60 hr eve	14.0	132	97	132	128	129	132	139	107	134	110
08/03/91	2000	72 hr	16.0	130	103	130	136	126	130	120	146	131	95
08/05/91	4000	48 hr	23.0	132	119	132	117	132	132	99	134	120	167
08/05/91	4000	60 hr eve	16.0	131	131	131	123	128	131	114	133	111	153
08/08/91	2000	30 day	14.0	120	129	120	127	135	120	118	130	120	116
11/02/91	3000	56 day	-10.0	112	108	112	108	108	NT	NT	NT	111	112
01/13/92	4000	71 d dusk	-4.0	142	122	142	139	144	142	159	150	163	148
01/17/92	2000	72 hr	-5.0	128	139	128	144	136	128	125	148	124	116
01/24/92	1000	120 hr	5.0	130	131	130	130	134	130	145	122	138	159

Constituent: Sodium (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	300	308	300	308	309	300	310	310	311	310
07/30/91	1000	48 hr	26.0	304	NT	304	325	322	304	312	311	315	333
07/31/91	1000	72 hr	26.5	311	NT	311	321	328	311	313	325	326	337
08/02/91	2000	48 hr	17.5	339	288	339	309	304	339	319	301	300	300
08/02/91	2000	60 hr eve	14.0	309	284	309	303	316	309	310	302	314	303
08/03/91	2000	72 hr	16.0	308	288	308	317	318	308	296	320	308	284
08/05/91	4000	48 hr	23.0	309	310	309	304	313	309	293	316	308	354
08/05/91	4000	60 hr eve	16.0	309	314	309	313	315	309	305	315	305	353
08/08/91	2000	30 day	14.0	301	308	301	307	315	301	306	310	291	291
11/02/91	3000	56 day	-10.0	296	296	296	291	292	NT	NT	NT	294	285
01/13/92	4000	71 d dusk	-4.0	315	287	315	314	322	315	333	327	328	310
01/17/92	2000	72 hr	-5.0	299	314	299	318	312	299	308	309	302	297
01/24/92	1000	120 hr	5.0	302	304	302	309	311	302	315	306	309	323

Constituent: Chloride (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	214	218	214	215	215	214	212	220	213	202
07/30/91	1000	48 hr	26.0	214	NT	214	228	225	214	220	224	228	237
07/31/91	1000	72 hr	26.5	215	NT	215	225	218	215	225	228	225	239
08/02/91	2000	48 hr	17.5	221	208	221	213	215	221	215	201	214	211
08/02/91	2000	60 hr eve	14.0	212	201	212	210	206	212	215	210	203	217
08/03/91	2000	72 hr	16.0	211	197	211	214	213	211	211	235	213	214
08/05/91	4000	48 hr	23.0	219	220	219	214	228	219	216	223	217	234
08/05/91	4000	60 hr eve	16.0	208	221	208	222	222	208	218	217	221	233
08/08/91	2000	30 day	14.0	201	223	201	205	221	201	201	223	203	209
11/02/91	3000	56 day	-10.0	204	204	204	200	204	NT	NT	NT	205	192
01/13/92	4000	71 d dusk	-4.0	204	209	204	206	200	204	205	208	208	205
01/17/92	2000	72 hr	-5.0	196	206	196	203	206	196	206	202	205	202
01/24/92	1000	120 hr	5.0	205	210	205	212	210	205	216	208	209	216

NT = no test

Table B4 - Analytical Data: Calcium, Bicarbonate and Radium 226

Constituent: Calcium (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	345	328	345	325	312	345	321	307	314	322
07/30/91	1000	48 hr	26.0	333	NT	333	284	275	333	299	270	270	271
07/31/91	1000	72 hr	26.5	328	NT	328	283	268	328	297	257	257	267
08/02/91	2000	48 hr	17.5	265	328	265	298	291	265	314	279	280	308
08/02/91	2000	60 hr eve	14.0	310	328	310	311	322	310	315	302	312	277
08/03/91	2000	72 hr	16.0	329	335	329	299	293	329	301	280	280	309
08/05/91	4000	48 hr	23.0	330	328	330	308	301	330	318	298	294	284
08/05/91	4000	60 hr eve	16.0	326	327	326	313	324	326	308	306	312	280
08/08/91	2000	30 day	14.0	349	347	349	325	320	349	344	323	314	299
11/02/91	3000	56 day	-10.0	360	359	360	341	343	NT	NT	NT	341	323
01/13/92	4000	71 d dusk	-4.0	347	340	347	331	310	347	312	315	309	284
01/17/92	2000	72 hr	-5.0	340	327	340	298	304	340	319	310	299	295
01/24/92	1000	120 hr	5	338	329	338	308	295	338	316	304	294	292

Constituent: Bicarbonate (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	1100	1050	1100	1040	1020	1100	1060	1020	997	1070
07/30/91	1000	48 hr	26.0	1050	NT	1050	896	841	1050	968	848	839	883
07/31/91	1000	72 hr	26.5	1050	NT	1050	889	824	1050	953	810	798	852
08/02/91	2000	48 hr	17.5	929	1040	929	960	920	929	1010	908	887	1020
08/02/91	2000	60 hr eve	14.0	977	1050	977	1060	1050	977	1060	1010	1020	864
08/03/91	2000	72 hr	16.0	1030	1070	1030	936	925	1030	995	892	889	944
08/05/91	4000	48 hr	23.0	1060	1040	1060	997	959	1060	1010	965	945	952
08/05/91	4000	60 hr eve	16.0	1030	1050	1030	1050	1090	1030	1010	1040	1050	922
08/08/91	2000	30 day	14.0	1200	1120	1200	1120	1040	1200	1140	1070	997	991
11/02/91	3000	56 day	-10.0	1240	1150	1240	1120	1070	NT	NT	NT	1080	1050
01/13/92	4000	71 d dusk	-4.0	1230	1120	1230	1140	1080	1230	1150	1110	1100	989
01/17/92	2000	72 hr	-5.0	1140	1100	1140	1040	1020	1140	1070	1040	1020	1000
01/24/92	1000	120 hr	5.0	1180	1100	1180	1040	983	1180	1060	1020	994	1000

Constituent: Radium 226 (pCi/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	28.3	34.6	28.3	36.9	25.3	28.3	28.5	25.8	29.0	18.7
07/30/91	1000	48 hr	26.0	27.6	NT	27.8	19.5	20.9	27.8	22.1	20.4	15.4	9.6
07/31/91	1000	72 hr	26.5	34.1	NT	34.1	18.7	20.4	34.1	24.1	20.5	16.8	12.3
08/02/91	2000	48 hr	17.5	42.2	31.4	42.2	25.4	25.3	42.2	26.7	26.3	20.6	15.8
08/02/91	2000	60 hr eve	14.0	30.7	29.5	30.7	23.4	23.5	30.7	29.2	23.5	27.3	14.0
08/03/91	2000	72 hr	16.0	35.4	36.9	35.4	26.7	25.6	35.4	25.1	20.7	21.8	15.4
08/05/91	4000	48 hr	23.0	33.8	33.3	33.8	31.3	27.8	33.8	34.0	24.4	30.9	12.3
08/05/91	4000	60 hr eve	16.0	33.6	8.0	33.6	12.0	21.6	33.6	24.0	16.0	10.4	13.1
08/08/91	2000	30 day	14.0	19.7	28.9	19.7	21.9	21.8	19.7	25.0	25.0	25.7	18.5
11/02/91	3000	56 day	-10.0	25.8	28.1	25.8	21.8	27.8	NT	NT	NT	30.2	29.5
01/13/92	4000	71 d dusk	-4.0	39.9	37.5	39.9	38.0	36.2	39.9	37.6	34.4	36.9	33.7
01/17/92	2000	72 hr	-5.0	25.4	24.6	25.4	22.5	29.1	25.4	25.9	21.9	24.2	22.2
01/24/92	1000	120 hr	5.0	25.3	22.4	25.3	27.0	24.7	25.3	27.6	26.3	25.3	23.9

NT = no test

Table B5 - Analytical Data: Sulfide and Sulfate

Constituent: Sulfide (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	22.4	7.2	22.4	7.2	7.2	22.4	10.4	5.6	11.2	8.0
07/30/91	1000	48 hr	26.0	24.8	NT	24.8	20.0	12.8	24.8	31.2	7.2	6.4	8.0
07/31/91	1000	72 hr	26.5	28.0	NT	28.0	8.8	10.4	28.0	14.4	6.4	9.6	10.4
08/02/91	2000	48 hr	17.5	29.6	16.0	29.6	8.8	8.8	29.6	30.4	10.4	12.0	14.4
08/02/91	2000	60 hr eve	14.0	48.0	23.2	48.0	12.0	16.0	48.0	24.8	11.2	11.2	14.4
08/03/91	2000	72 hr	16.0	29.6	26.4	29.6	10.4	14.4	29.6	11.2	10.4	23.2	22.4
08/05/91	4000	48 hr	23.0	43.2	11.2	43.2	12.0	10.4	43.2	19.2	14.4	10.4	11.2
08/05/91	4000	60 hr eve	16.0	33.6	8.0	33.6	12.0	21.6	33.6	24.0	16.0	10.4	11.2
09/08/91	2000	30 day	14.0	42.4	15.2	42.4	18.4	15.2	42.4	24.8	15.2	14.4	12.0
11/02/91	3000	56 day	-10.0	26.0	13.6	28.0	7.2	6.4	NT	NT	NT	6.4	12.8
01/13/92	4000	71 d dusk	-4.0	40.0	21.6	40.0	20.8	20.8	40.0	26.4	21.6	19.2	21.6
01/17/92	2000	72 hr	-5.0	32.8	17.6	32.8	21.6	17.6	32.8	20.8	17.6	17.6	21.6
01/24/92	1000	120 hr	5.0	16.8	10.4	16.8	13.6	11.2	16.8	12.0	15.2	4.8	9.6

Constituent: Sulfate (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	937	948	937	940	937	937	920	959	928	851
07/30/91	1000	48 hr	26.0	939	NT	939	966	990	939	955	961	1010	1050
07/31/91	1000	72 hr	26.5	910	NT	910	998	942	910	982	992	991	1070
08/02/91	2000	48 hr	17.5	908	913	908	933	941	908	955	880	926	900
08/02/91	2000	60 hr eve	14.0	906	901	906	897	876	906	923	888	859	973
08/03/91	2000	72 hr	16.0	923	859	923	831	945	923	914	1010	922	893
08/05/91	4000	48 hr	23.0	958	961	958	918	992	958	918	964	926	1030
08/05/91	4000	60 hr eve	16.0	903	966	903	925	920	903	924	901	910	1110
09/08/91	2000	30 day	14.0	845	949	845	899	946	845	843	942	866	876
11/02/91	3000	56 day	-10.0	839	916	839	895	915	NT	NT	NT	919	849
01/13/92	4000	71 d dusk	-4.0	851	901	851	875	861	851	886	899	891	898
01/17/92	2000	72 hr	-5.0	861	915	861	885	902	861	894	890	892	879
01/24/92	1000	120 hr	5.0	823	875	823	924	920	823	908	915	915	890

NT = no test

Table B6 - Analytical Data: Benzene, Toluene and Ethylbenzene

Constituent: Benzene (ug/l)

Date	Flow BPD	Duration	Amb T (C)	1,1T/P	6	2T	2P	4	5
07/25/91	3000	30 day	18.3	21.0	1.5	3.0	NT	0.97	<0.50
07/30/91	1000	48 hr	26.0	17.0	NT	<0.50	5.3	<0.50	NT
07/31/91	1000	72 hr	26.5	17.0	NT	<0.50	4.8	<0.50	NT
08/02/91	2000	48 hr	17.5	24.0	NT	0.7	7.1	<0.50	NT
08/02/91	2000	60 hr eve	14.0	28.0	NT	2.4	8.3	0.94	NT
08/03/91	2000	72 hr	16.0	29.0	NT	1.8	8.4	<0.50	NT
08/05/91	4000	48 hr	23.0	27.0	NT	1.3	12.0	<0.50	NT
08/05/91	4000	60 hr eve	16.0	25.0	NT	1.7	13.0	<0.50	NT
09/08/91	2000	30 day	14.0	59.0	8.7	3.2	23.0	<0.50	NT
11/02/91	3000	56 day	-10.0	52.0	8.9	13.0	NT	5.60	NT
01/13/92	4000	71 d dusk	-4.0	23.0	2.1	5.2	11.0	2.5	NT
01/17/92	2000	72 hr	-5.0	21.0	3.0	2.9	7.4	1.1	NT
01/24/92	1000	120 hr	5.0	27.0	5.9	2.4	11.0	0.5	NT

Constituent: Toluene (ug/l)

Date	Flow BPD	Duration	Amb T (C)	1,1T/P	6	2T	2P	4	5
07/25/91	3000	30 day	18.3	37.0	2.0	4.7	NT	1.20	<0.50
07/30/91	1000	48 hr	26.0	27.0	NT	<0.50	6.2	<0.50	NT
07/31/91	1000	72 hr	26.5	27.0	NT	<0.50	5.6	<0.50	NT
08/02/91	2000	48 hr	17.5	44.0	NT	1.3	9.4	<0.50	NT
08/02/91	2000	60 hr eve	14.0	48.0	NT	3.9	13.0	1.70	NT
08/03/91	2000	72 hr	16.0	51.0	NT	3.9	13.0	<0.50	NT
08/05/91	4000	48 hr	23.0	48.0	NT	1.9	16.0	<0.50	NT
08/05/91	4000	60 hr eve	16.0	44.0	NT	3.0	19.0	<0.50	NT
09/08/91	2000	30 day	14.0	102.0	13.0	4.8	36.0	<0.50	NT
11/02/91	3000	56 day	-10.0	90.0	15.0	24.0	NT	9.7	NT
01/13/92	4000	71 d dusk	-4.0	37.0	3.0	6.5	18.0	3.8	NT
01/17/92	2000	72 hr	-5.0	38.0	4.8	4.3	9.5	1.5	NT
01/24/92	1000	120 hr	5.0	36.0	6.1	2.1	7.5	0.9	NT

Constituent: Ethylbenzene (ug/l)

Date	Flow BPD	Duration	Amb T (C)	1,1T/P	6	2T	2P	4	5
07/25/91	3000	30 day	18.3	13.0	0.91	2.2	NT	0.60	<0.50
07/30/91	1000	48 hr	26.0	10.0	NT	<0.50	3.5	<0.50	NT
07/31/91	1000	72 hr	26.5	9.9	NT	<0.50	3.0	<0.50	NT
08/02/91	2000	48 hr	17.5	15.0	NT	<0.50	3.7	<0.50	NT
08/02/91	2000	60 hr eve	14.0	16.0	NT	1.3	5.6	<0.50	NT
08/03/91	2000	72 hr	16.0	17.0	NT	1.1	5.3	<0.50	NT
08/05/91	4000	48 hr	23.0	16.0	NT	1.8	7.8	<0.50	NT
08/05/91	4000	60 hr eve	16.0	15.0	NT	2.2	8.0	<0.50	NT
09/08/91	2000	30 day	14.0	40.0	NT	2.3	13.0	<0.50	NT
11/02/91	3000	56 day	-10.0	32.0	5.9	9.5	NT	9.7	NT
01/13/92	4000	71 d dusk	-4.0	15.0	1.4	3.6	6.8	1.8	NT
01/17/92	2000	72 hr	-5.0	12.0	1.9	1.8	3.7	0.7	NT
01/24/92	1000	120 hr	5.0	14.0	2.4	1.2	4.2	<0.50	NT

NT = no test

Table B7 - Analytical Data: Xylenes and Total Phenolics

Constituent: Xylenes (ug/l)

Date	Flow BPD	Duration	Amb T (C)	1,1T/P	6	2T	2P	4	5
07/25/91	3000	30 day	18.3	28.0	3.4	4.7	NT	1.1	<1.0
07/30/91	1000	48 hr	28.0	21.0	NT	<1.0	8.0	<1.0	NT
07/31/91	1000	72 hr	28.5	21.0	NT	<1.0	8.5	<1.0	NT
08/02/91	2000	48 hr	17.5	32.0	NT	1.5	9.2	<0.01	NT
08/02/91	2000	60 hr eve	14.0	37.0	NT	3.1	12.0	1.2	NT
08/03/91	2000	72 hr	18.0	31.0	NT	3.1	13.0	<0.01	NT
08/05/91	4000	48 hr	23.0	38.0	NT	5.0	19.0	<1.0	NT
08/05/91	4000	60 hr eve	18.0	38.0	NT	6.1	20.0	<1.0	NT
09/08/91	2000	30 day	14.0	74.0	12.0	5.9	30.0	2.1	NT
11/02/91	3000	56 day	-10.0	68.0	13.0	21.0	NT	11.0	NT
01/13/92	4000	71 d dusk	-4.0	32.0	3.1	8.4	17.0	3.8	NT
01/17/92	2000	72 hr	-5.0	28.0	4.8	5.2	9.3	1.8	NT
01/24/92	1000	120 hr	5.0	25.0	4.5	1.8	5.3	1.0	NT

Constituent: Total Phenolics (mg/l)

Date	Flow BPD	Duration	Amb T (C)	1,1T/P	6	2T	2P	4	5
07/25/91	3000	30 day	18.3	0.13	0.07	0.11	NT	0.04	0.04
07/30/91	1000	48 hr	28.0	*0.13	NT	NT	NT	0.03	0.01
07/31/91	1000	72 hr	28.5	*0.13	NT	NT	NT	0.04	0.00
08/02/91	2000	48 hr	17.5	*0.13	0.10	NT	NT	0.05	0.08
08/02/91	2000	60 hr eve	14.0	*0.13	0.08	NT	NT	0.10	0.06
08/03/91	2000	72 hr	18.0	*0.13	0.07	NT	NT	0.08	0.07
09/08/91	2000	30 day	14.0	0.13	0.10	0.13	0.15	0.09	0.08
11/02/91	3000	56 day	-10.0	0.15	0.10	0.14	NT	0.12	0.07
01/13/92	4000	71 d dusk	-4.0	*0.13	0.10	NT	NT	0.11	0.10
01/17/92	2000	72 hr	-5.0	0.13	0.13	NT	NT	0.12	0.12
01/24/92	1000	120 hr	5.0	0.12	0.11	NT	NT	0.09	0.09

*NT = no test, ** denotes estimated value

Table B8 - Analytical Data: TDS, Magnesium and Alkalinity

Constituent: Total Dissolved Solids @ 180 deg C (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	2500	2520	2500	2500	2500	2500	2510	2480	2470	2510
07/30/91	1000	48 hr	26.0	2500	NT	2500	2450	2420	2500	2450	2400	2400	2540
07/31/91	1000	72 hr	26.5	2480	NT	2480	2450	2440	2480	2450	2380	2400	2770
08/02/91	2000	48 hr	17.5	2340	2520	2340	2440	2430	2340	2450	2670	2400	2480
08/02/91	2000	60 hr eve	14.0	2420	2490	2420	2480	2480	2420	2480	2420	2450	2470
08/03/91	2000	72 hr	16.0	2480	2520	2480	2430	2440	2480	2440	2420	2410	2480
08/05/91	4000	48 hr	23.0	2480	2510	2480	2480	2450	2480	2450	2370	2430	2600
08/05/91	4000	60 hr eve	16.0	2450	2510	2450	2480	2500	2450	2440	2440	2440	2620
08/08/91	2000	30 day	14.0	2480	2510	2480	2450	2410	2480	2500	2410	2350	2220
11/02/91	3000	56 day	-10.0	2580	2600	2580	2540	2560	NT	NT	NT	2570	2510
01/13/92	4000	71 d dusk	-4.0	2570	2570	2570	2530	2500	2570	2540	2520	2510	2470
01/17/92	2000	72 hr	-5.0	2540	2510	2540	2480	2480	2540	2480	2500	2470	2420
01/24/92	1000	120 hr	5.0	2540	2560	2540	2510	2470	2540	2530	2510	2480	2480

Constituent: Magnesium (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
07/25/91	3000	30 day	18.3	109	112	109	111	111	109	111	111	111	113
07/30/91	1000	48 hr	26.0	108	NT	108	113	112	108	110	109	110	118
07/31/91	1000	72 hr	26.5	111	NT	111	112	114	111	111	112	113	119
08/02/91	2000	48 hr	17.5	112	109	112	108	109	112	111	109	112	113
08/02/91	2000	60 hr eve	14.0	110	109	110	110	114	110	110	112	111	114
08/03/91	2000	72 hr	16.0	110	110	110	111	113	110	108	112	111	113
08/05/91	4000	48 hr	23.0	111	113	111	112	111	111	111	112	112	125
08/05/91	4000	60 hr eve	16.0	110	112	110	113	114	110	112	112	114	129
08/08/91	2000	30 day	14.0	109	111	109	109	111	109	111	110	104	105
11/02/91	3000	56 day	-10.0	112	113	112	110	111	NT	NT	NT	111	110
01/13/92	4000	71 d dusk	-4.0	113	115	113	113	115	113	117	115	115	115
01/17/92	2000	72 hr	-5.0	113	114	113	112	116	113	116	116	114	116
01/24/92	1000	120 hr	5.0	111	113	111	116	116	111	116	116	113	117

Constituent: Total Alkalinity as CaCO3 (mg/l)				Sample Location									
Date	Flow BPD	Duration	Amb T (C)	1	6	1T	2T	3T	1P	2P	3P	4	5
08/05/91	4000	48 hr	23.0	870	851	870	817	786	870	828	791	774	780
08/05/91	4000	60 hr eve	16.0	846	860	846	860	892	846	827	849	859	755
09/08/91	2000	30 day	14.0	985	921	985	919	850	985	934	878	817	812
11/02/91	3000	56 day	-10.0	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	1010	914	1010	831	885	1010	945	909	902	811
01/17/92	2000	72 hr	-5.0	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
01/24/92	1000	120 hr	5.0	964	905	964	849	806	964	881	834	815	823

NT = no test

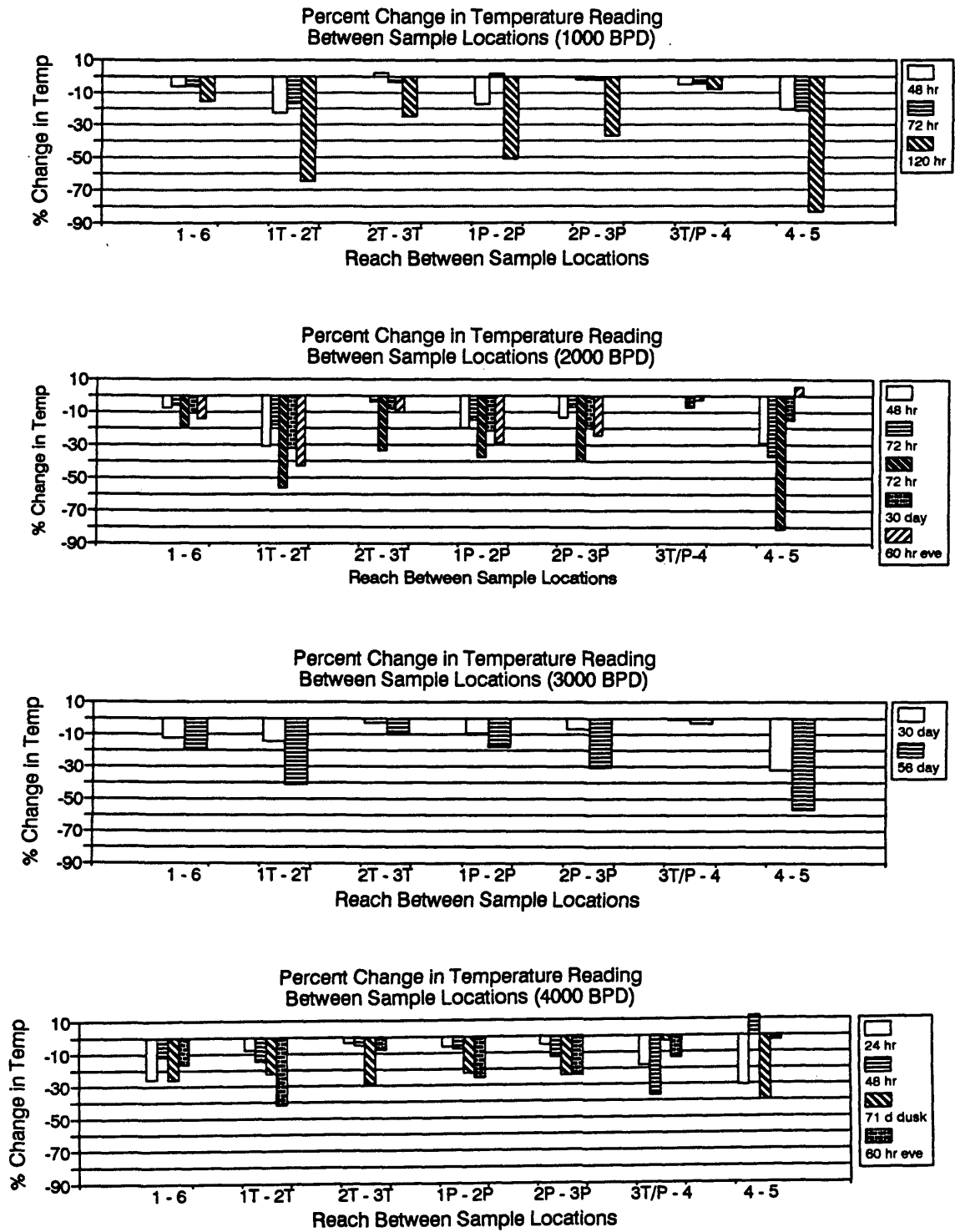


Figure B1 - Percent Change in Water Temperature Between Sample Locations

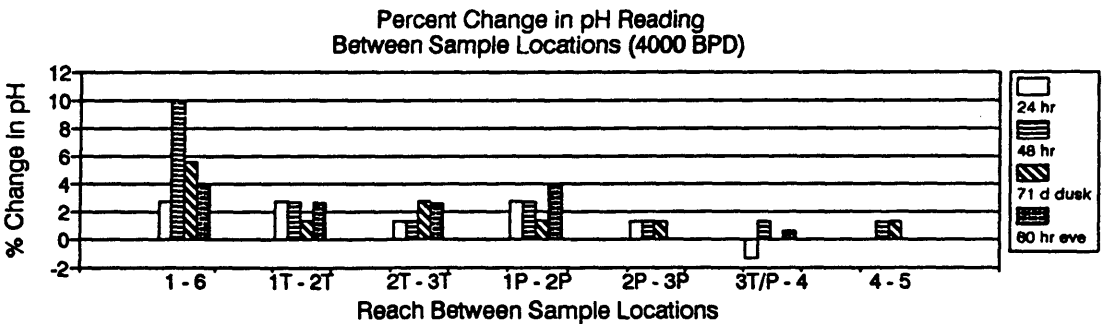
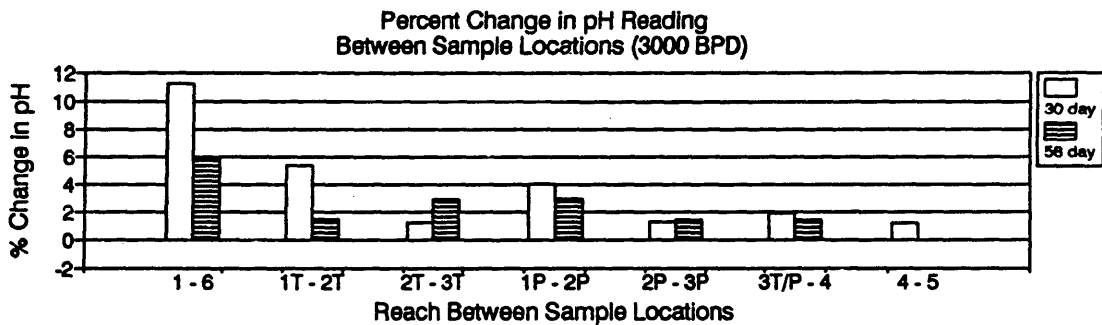
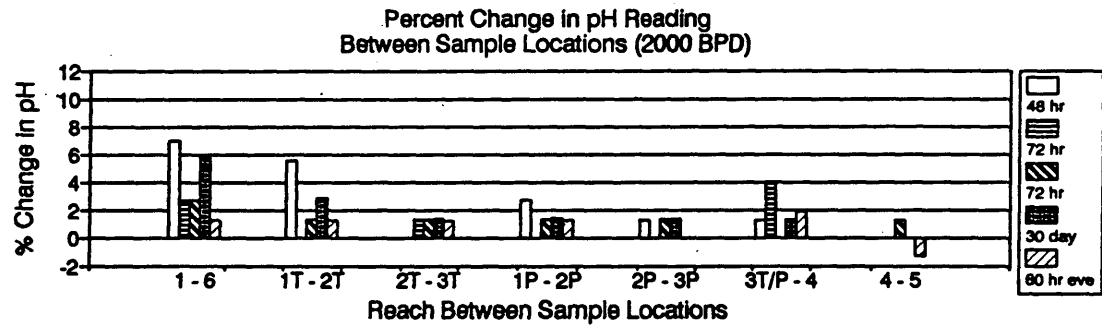
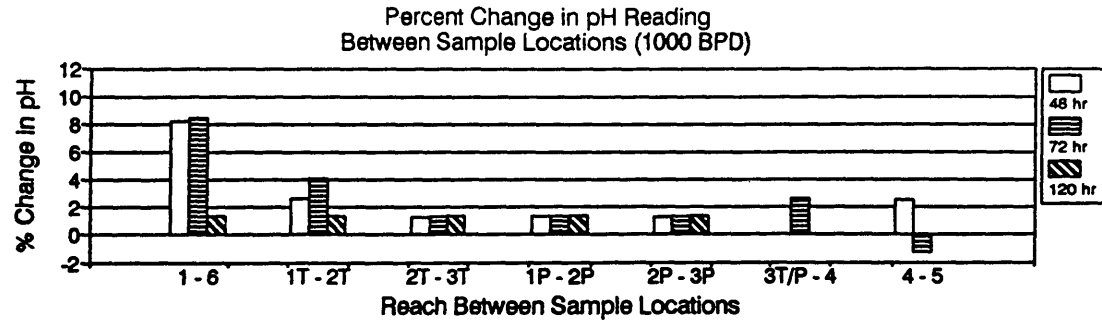


Figure B2 - Percent Change in pH Between Sample Locations

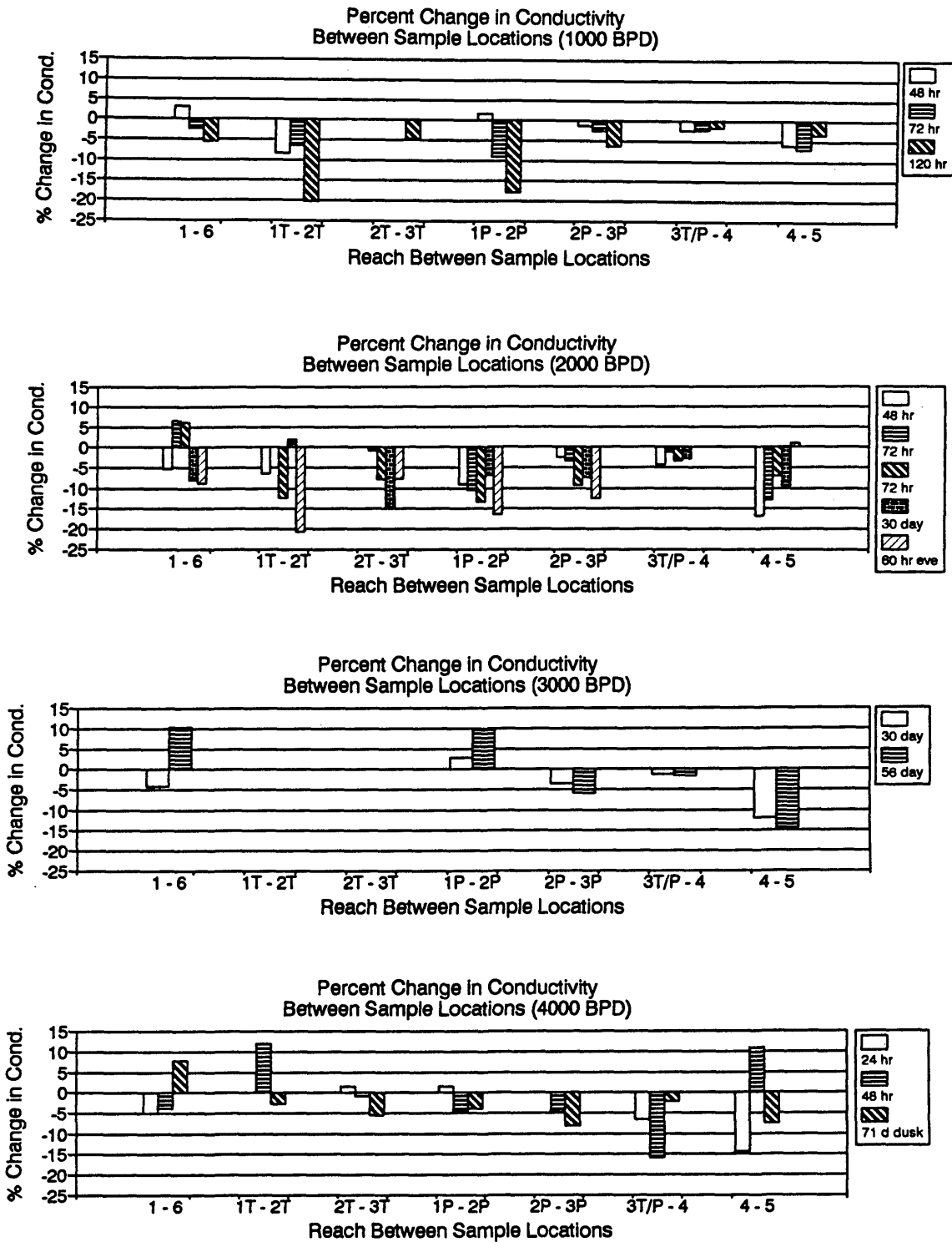


Figure B3 - Percent Change in Conductivity Between Sample Locations

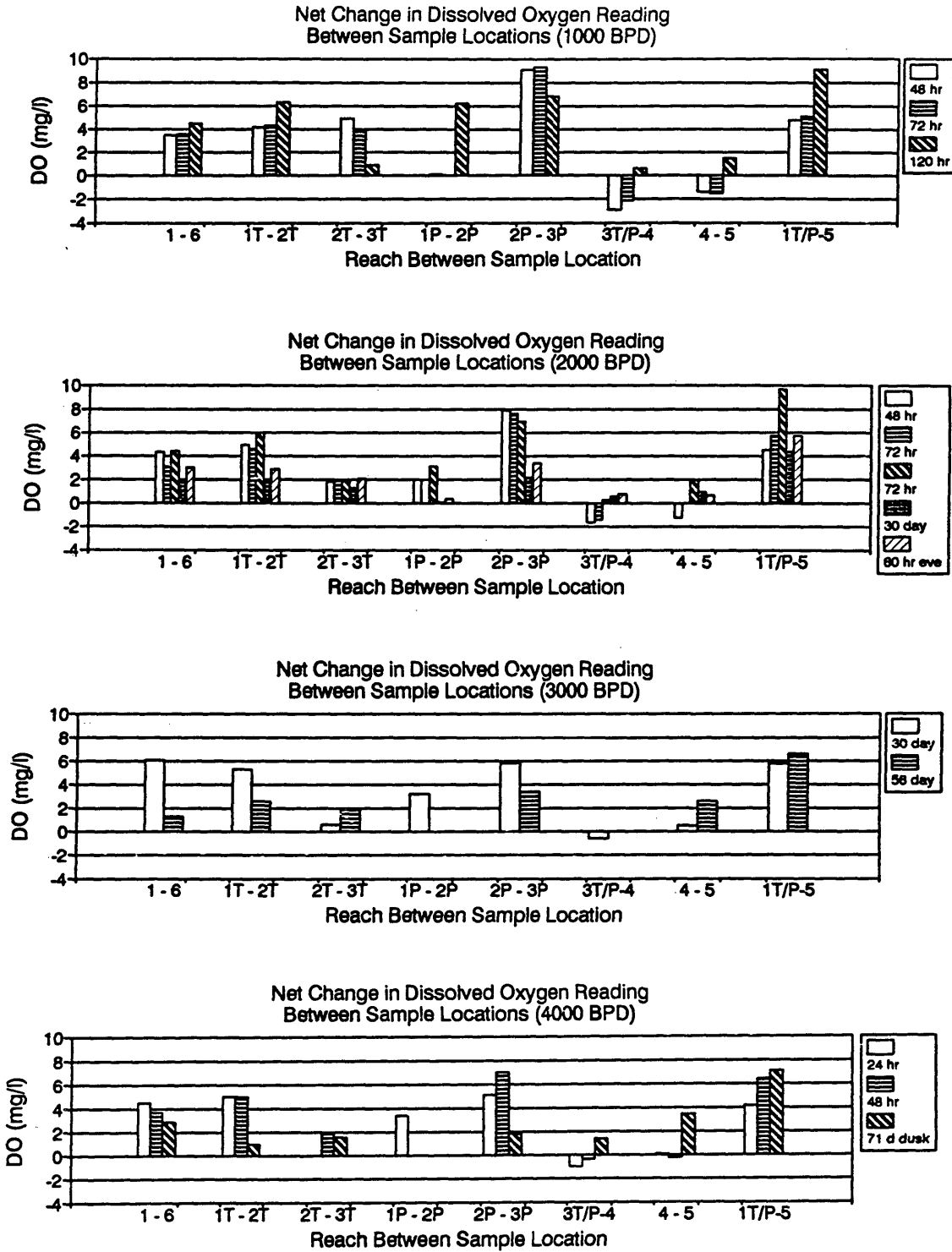


Figure B4 - Net Change in Dissolved Oxygen Between Sample Locations

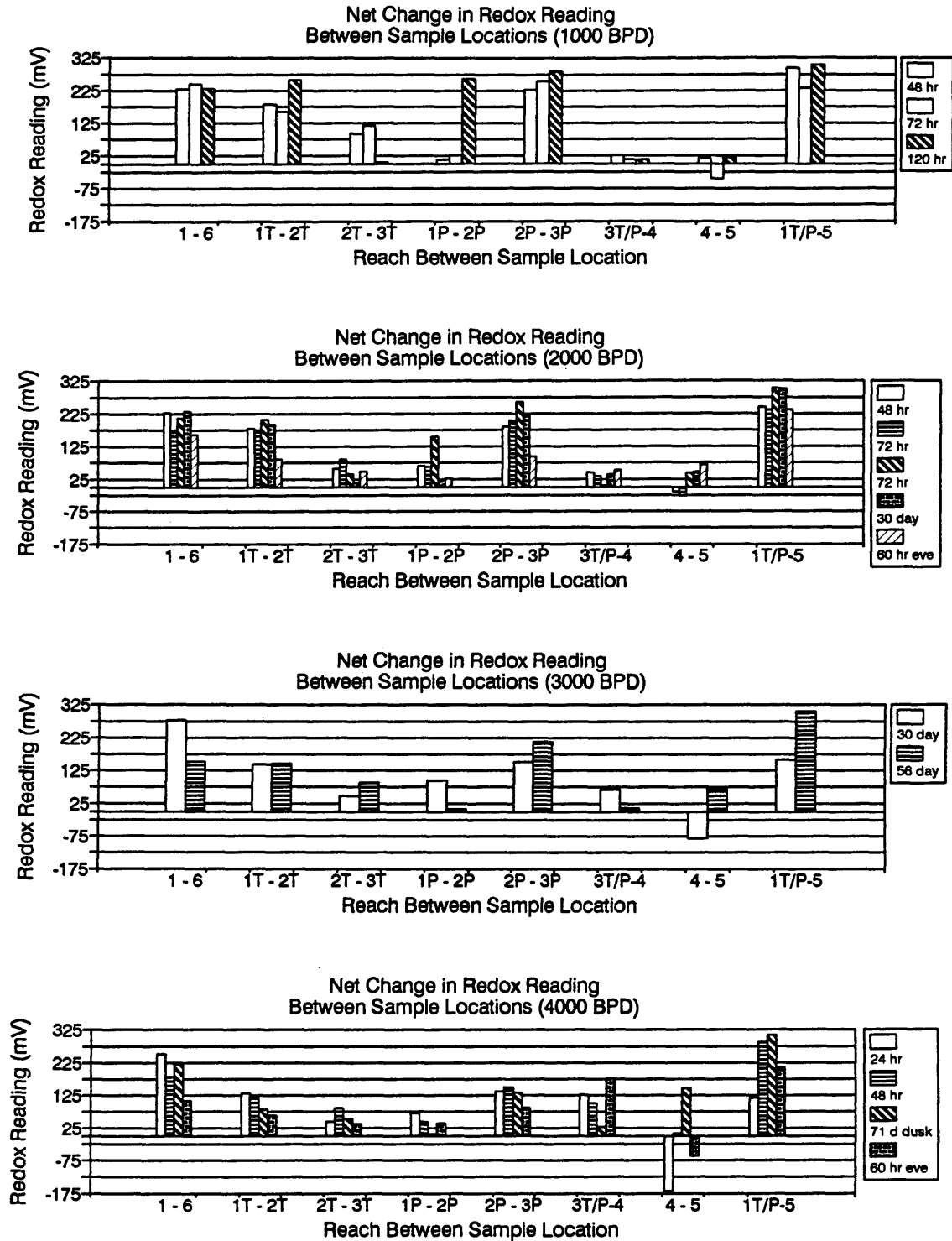


Figure B5 - Net Change in Redox Between Sample Locations

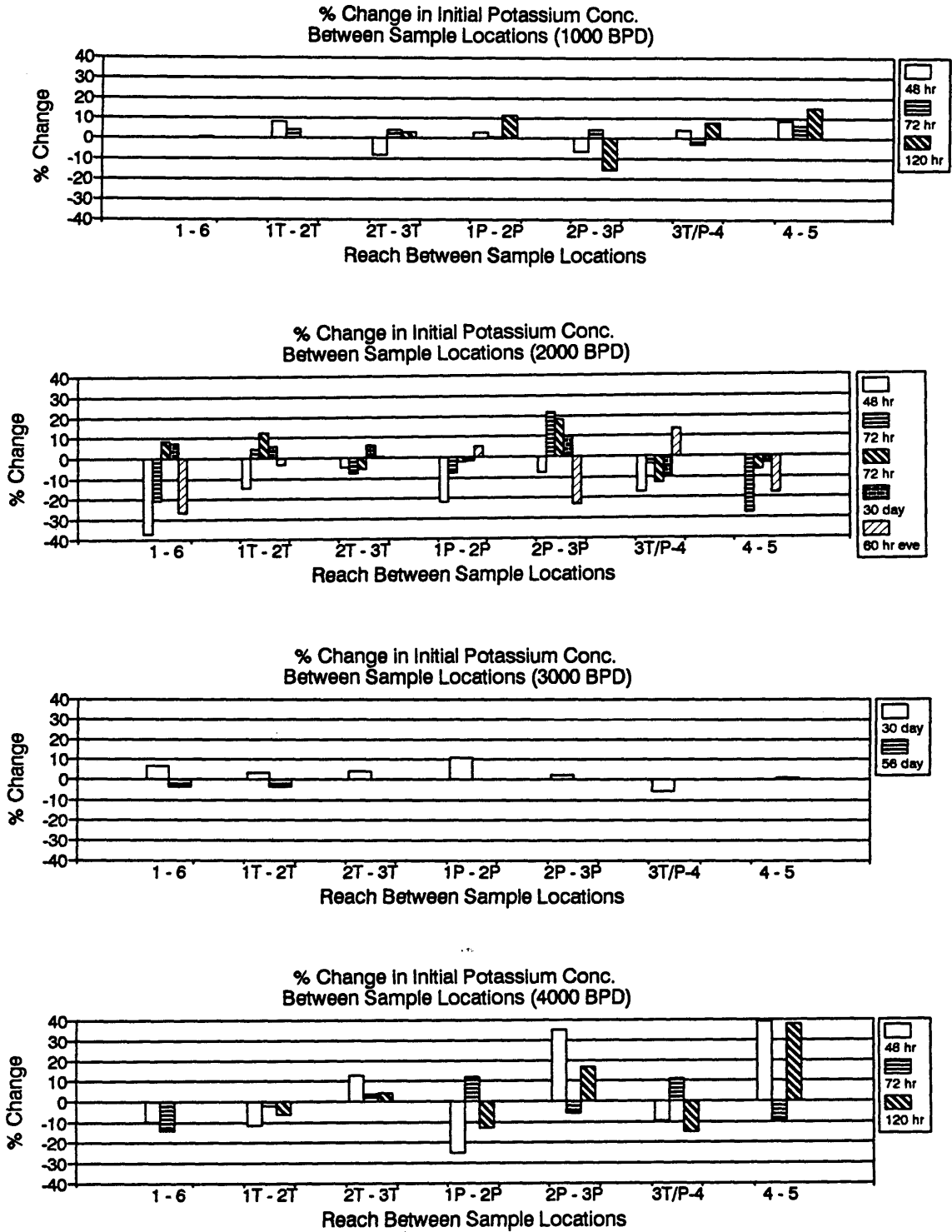


Figure B6 - Percent Change in Potassium Conc. Between Sample Locations

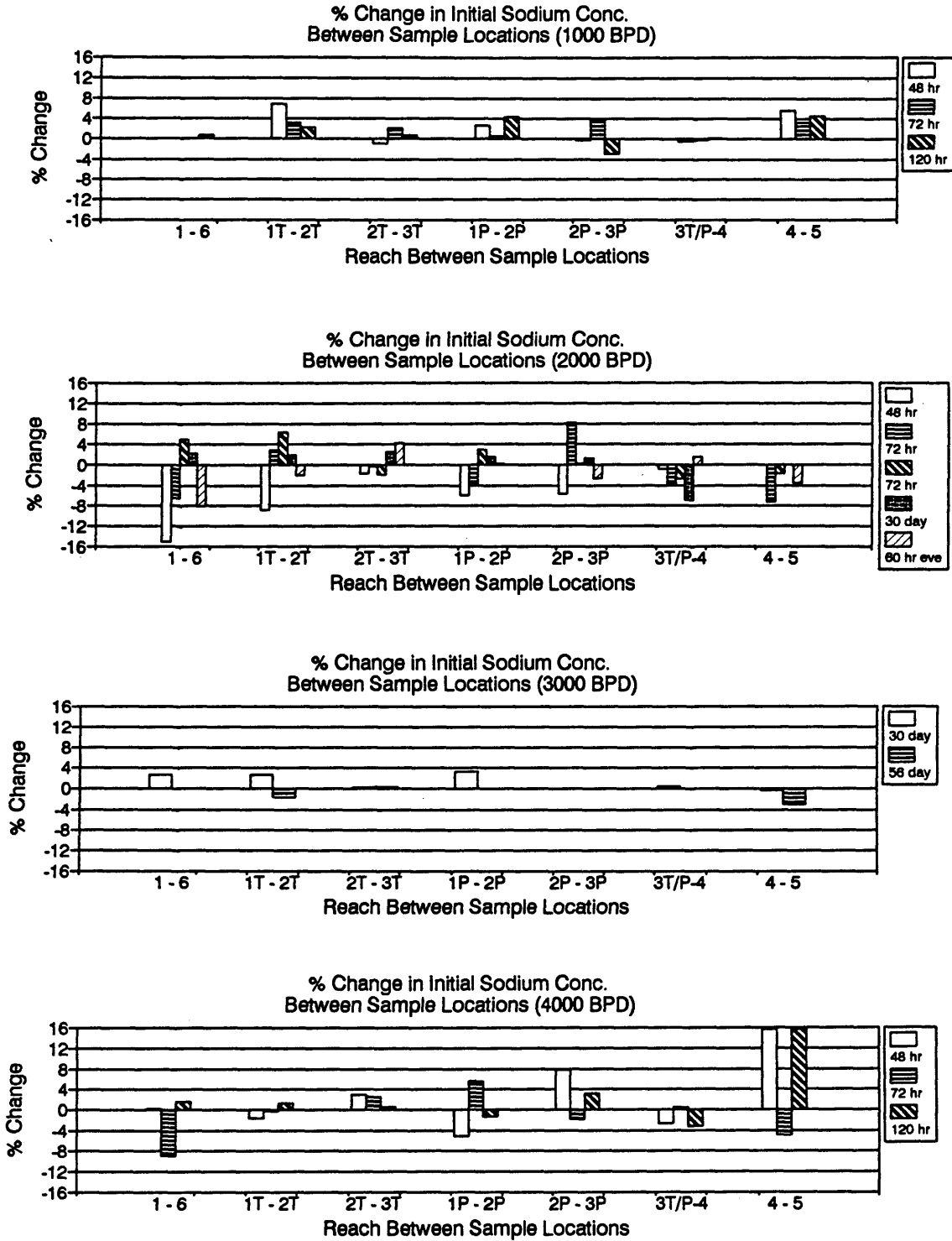


Figure B7 - Percent Change in Sodium Conc. Between Sample Locations

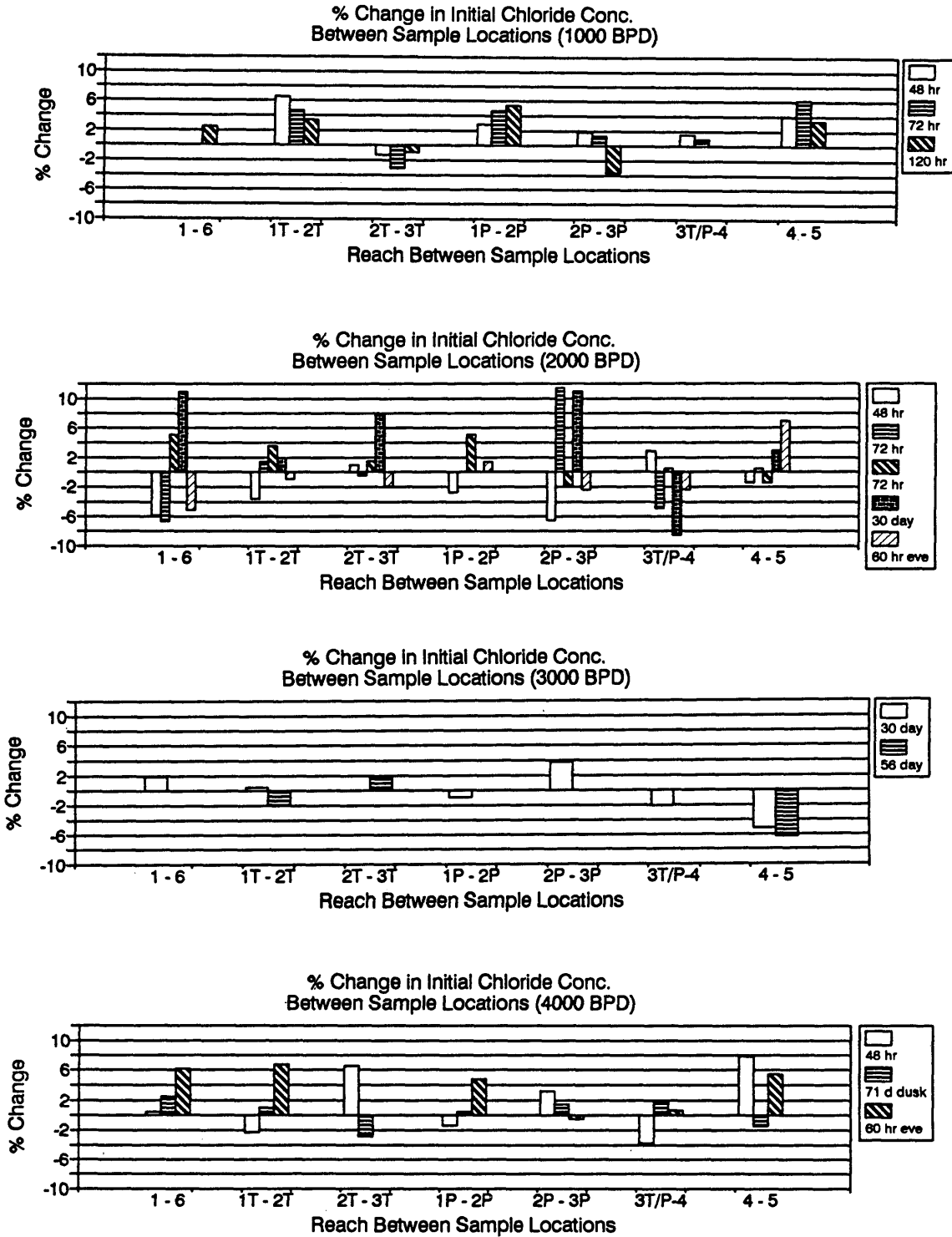


Figure B8 - Percent Change in Chloride Conc. Between Sample Locations

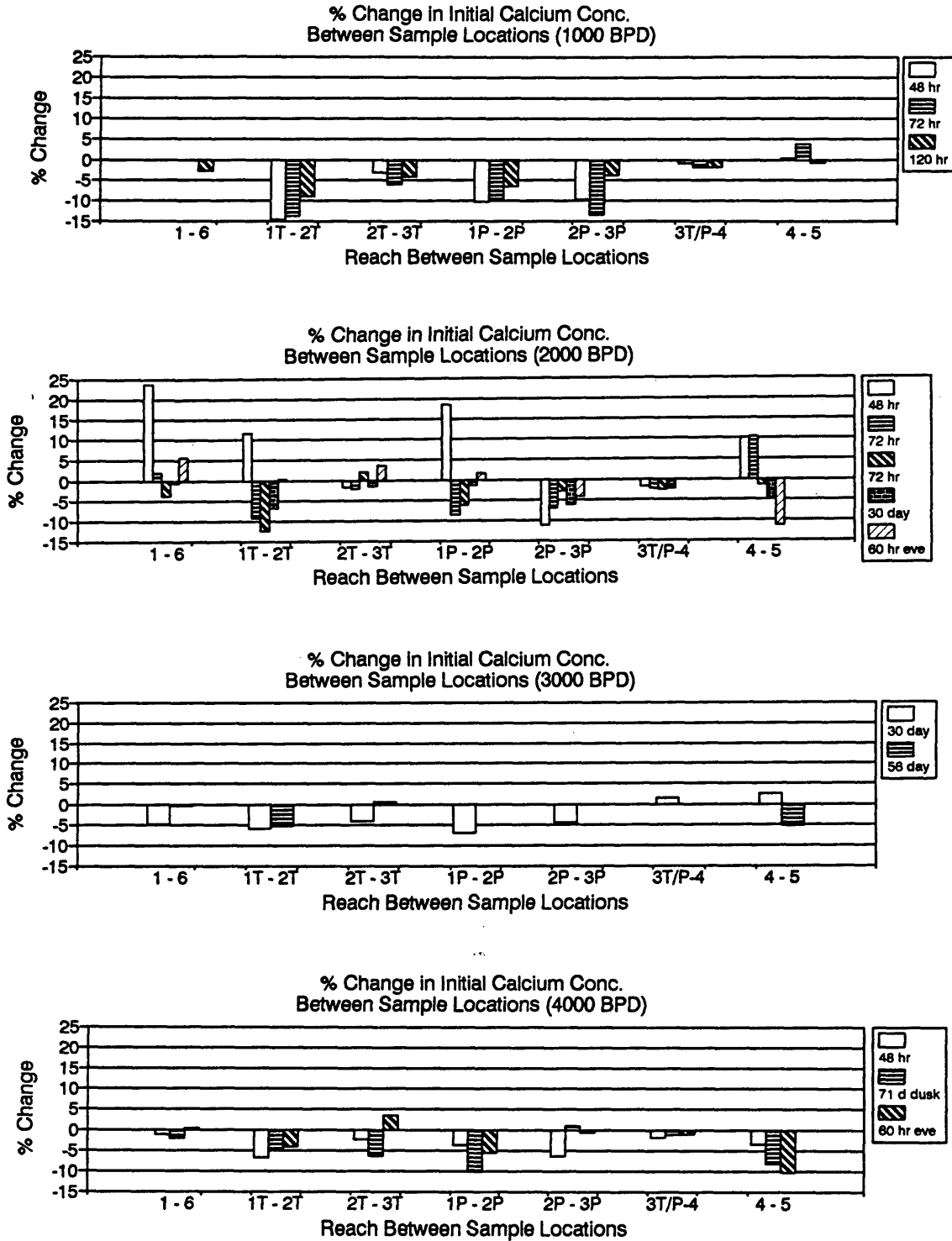


Figure B9 - Percent Change in Calcium Conc. Between Sample Locations

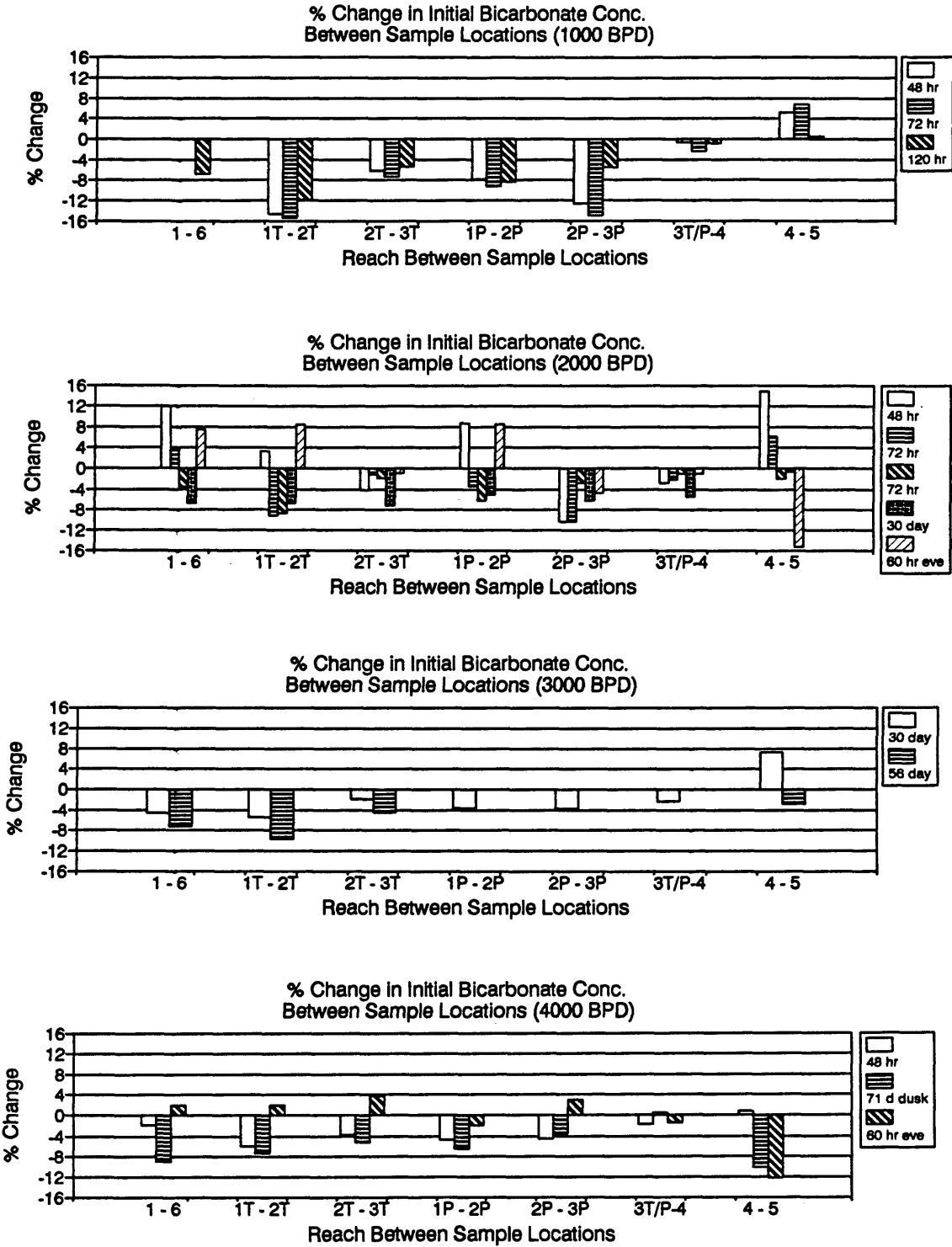


Figure B10 - Percent Change in Bicarbonate Conc. Between Sample Locations

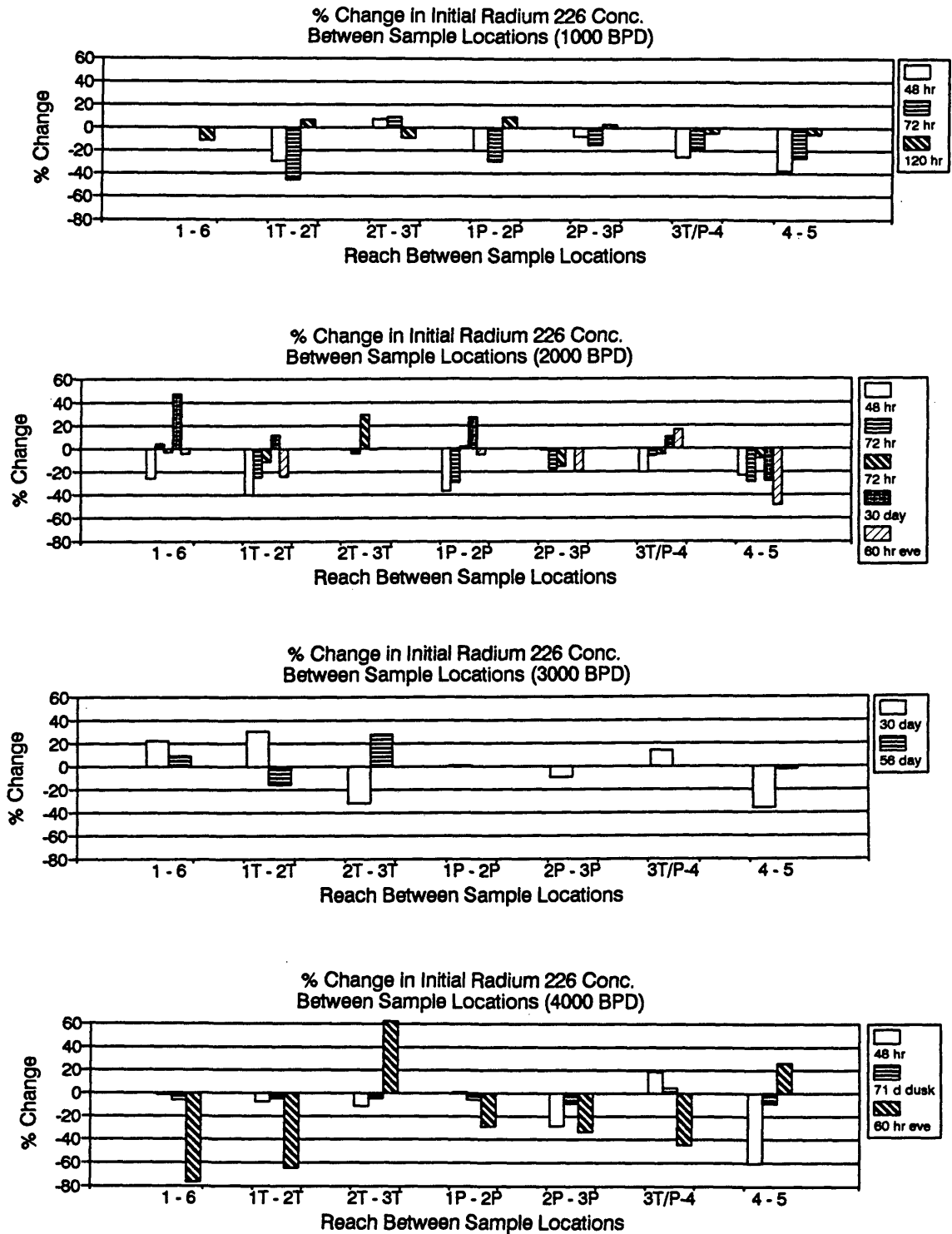


Figure B11 - Percent Change in Radium 226 Conc. Between Sample Locations

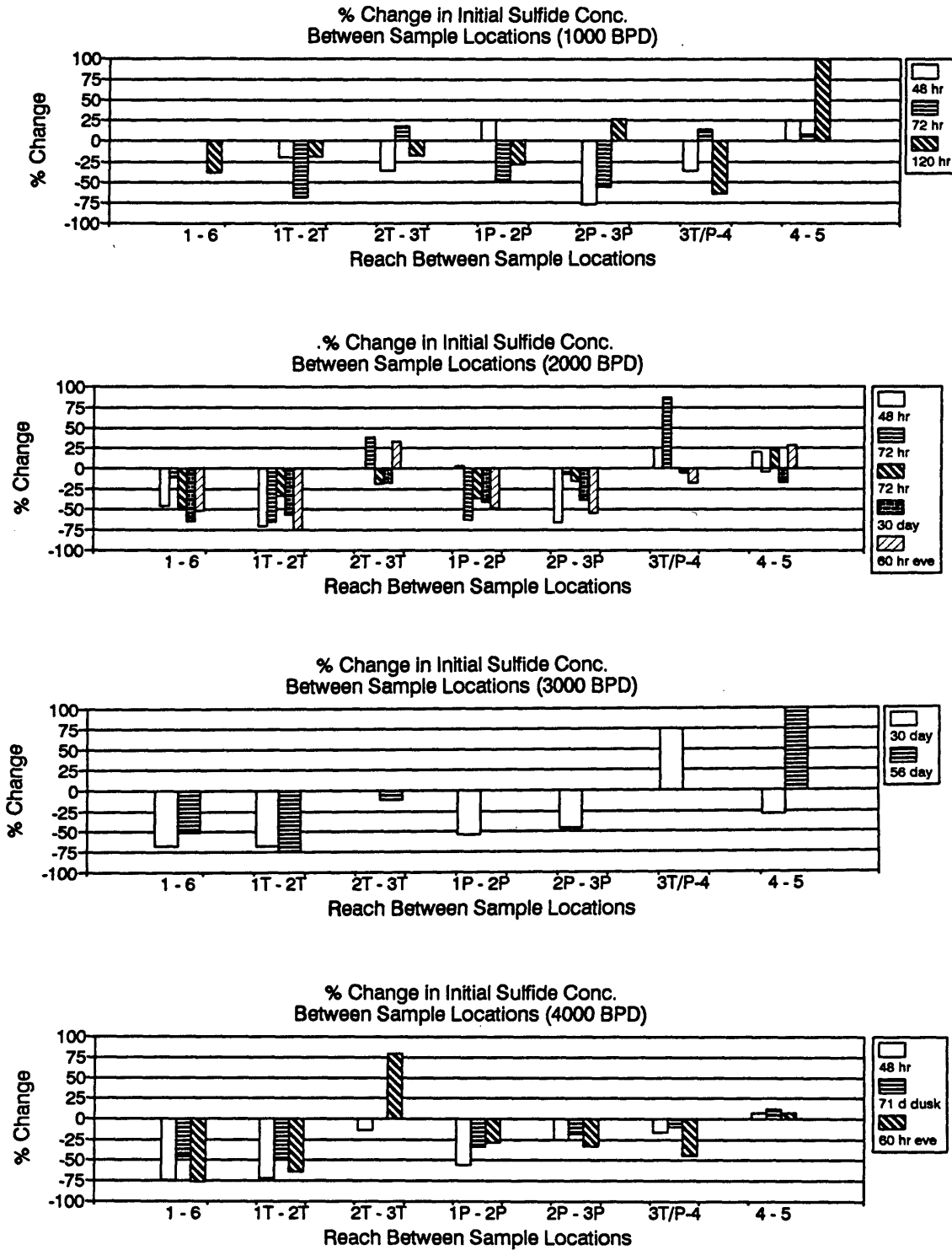


Figure B12 - Percent Change in Sulfide Conc. Between Sample Locations

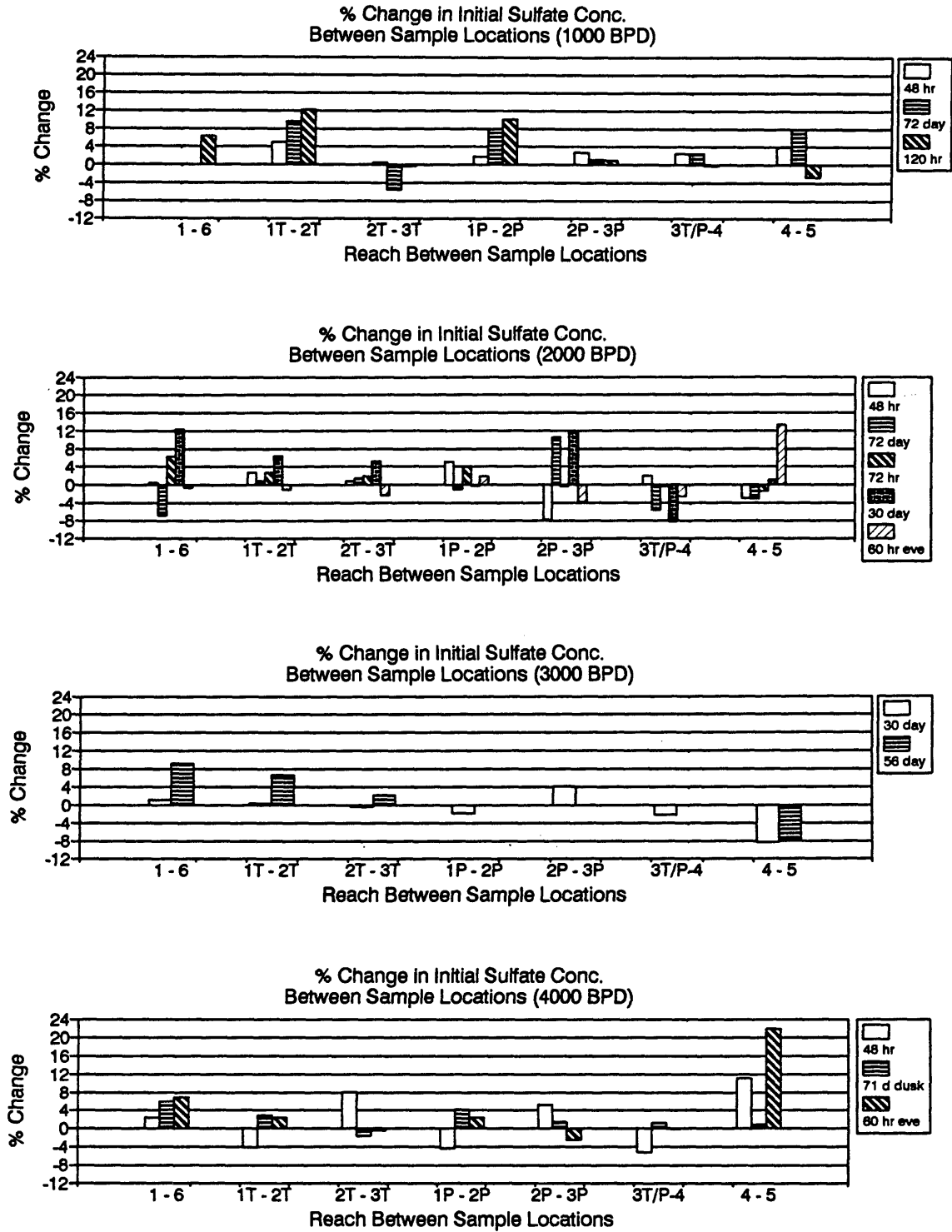


Figure B13 - Percent Change in Sulfate Conc. Between Sample Locations

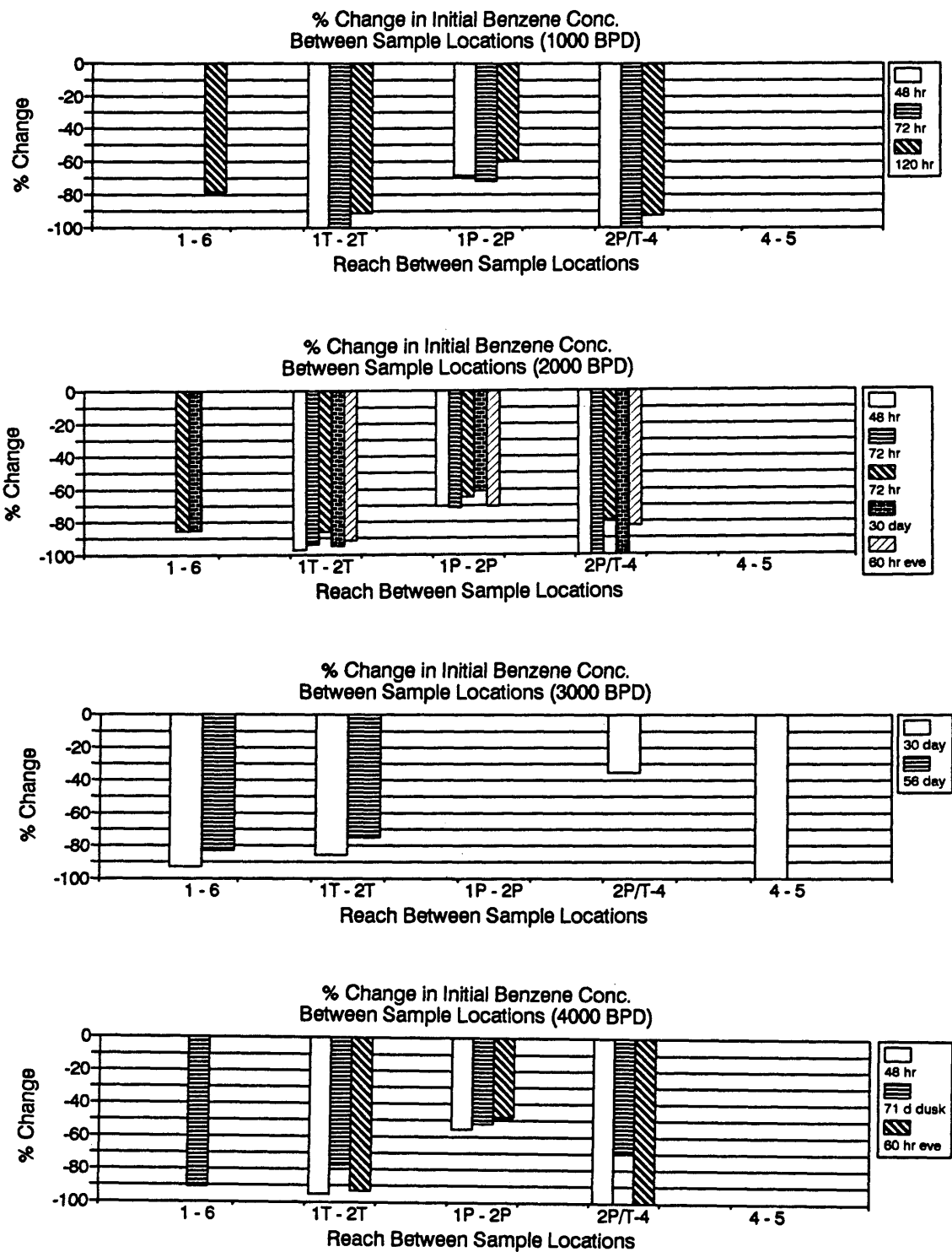


Figure B14 - Percent Change in Benzene Conc. Between Sample Locations

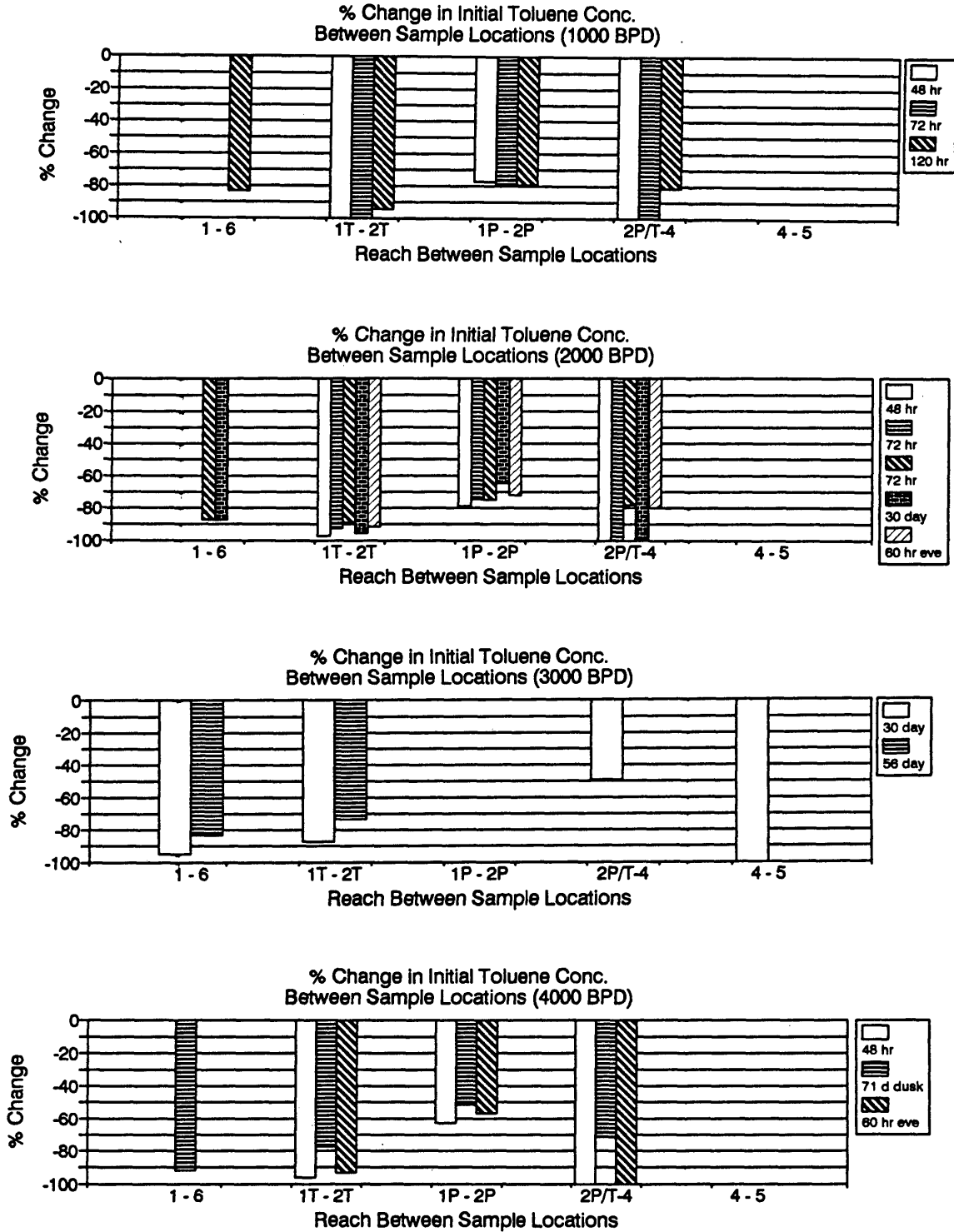


Figure B15 - Percent Change in Toluene Conc. Between Sample Locations

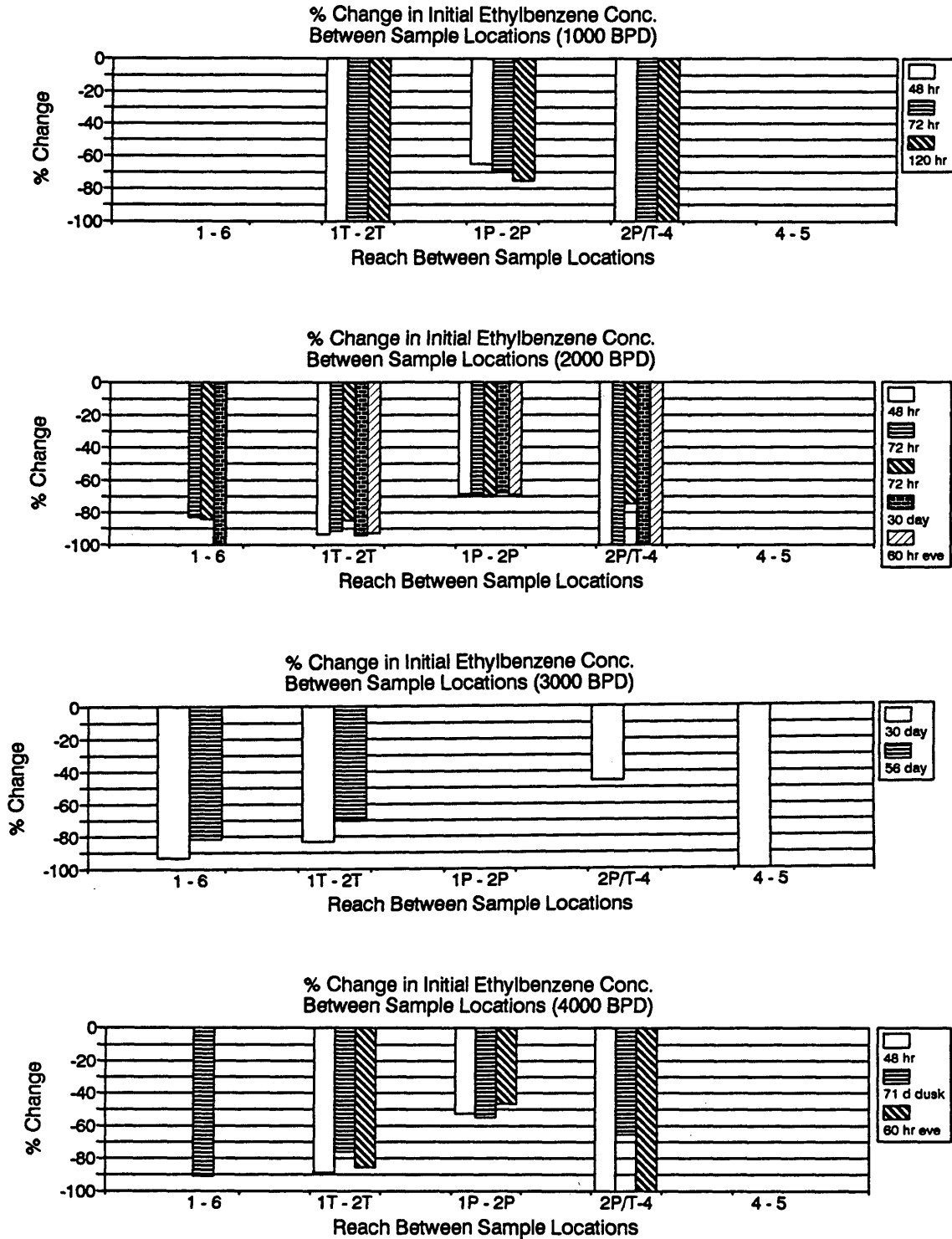


Figure B16 - Percent Change in Ethylbenzene Conc. Between Sample Locations

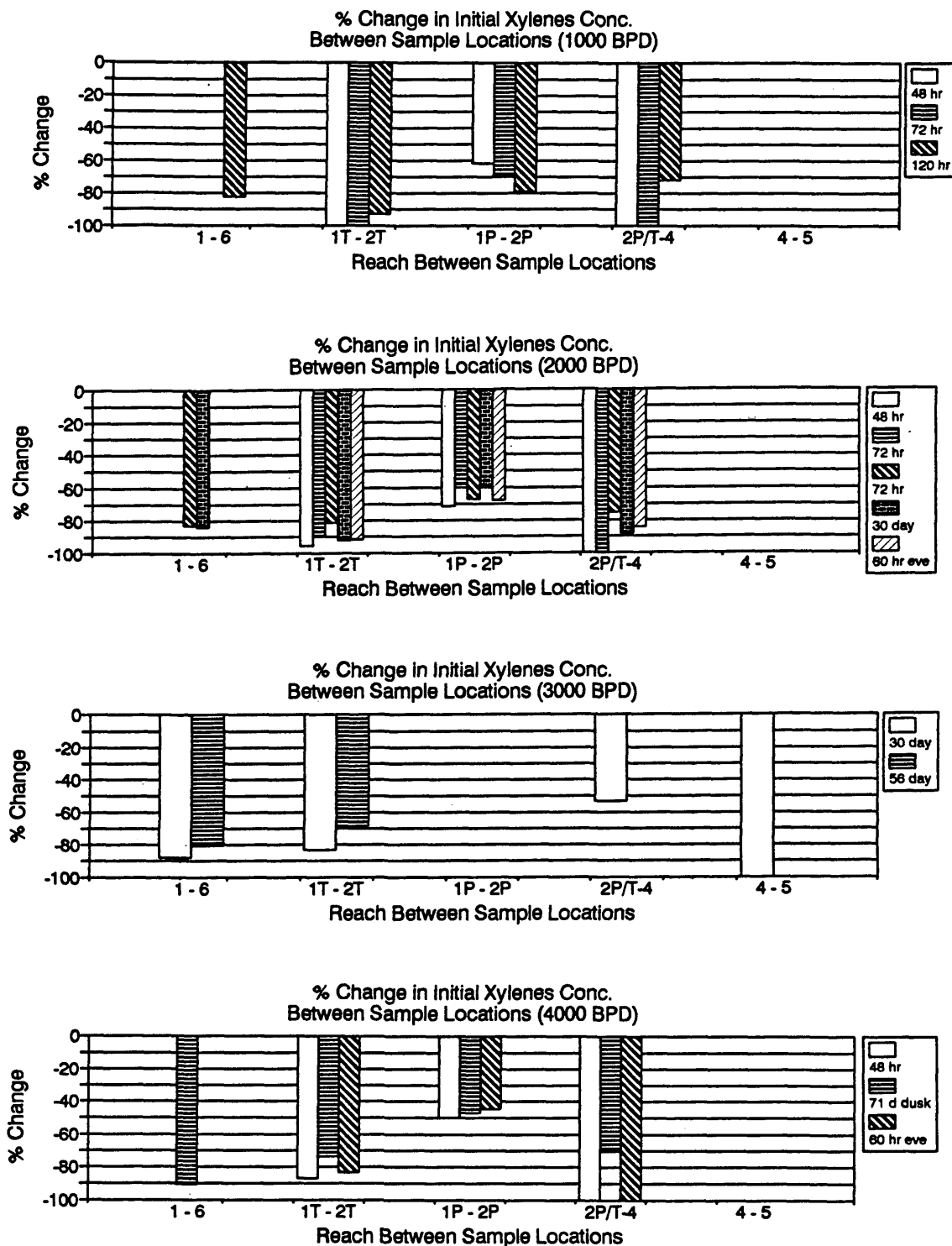


Figure B17 - Percent Change in Xylenes Conc. Between Sample Locations

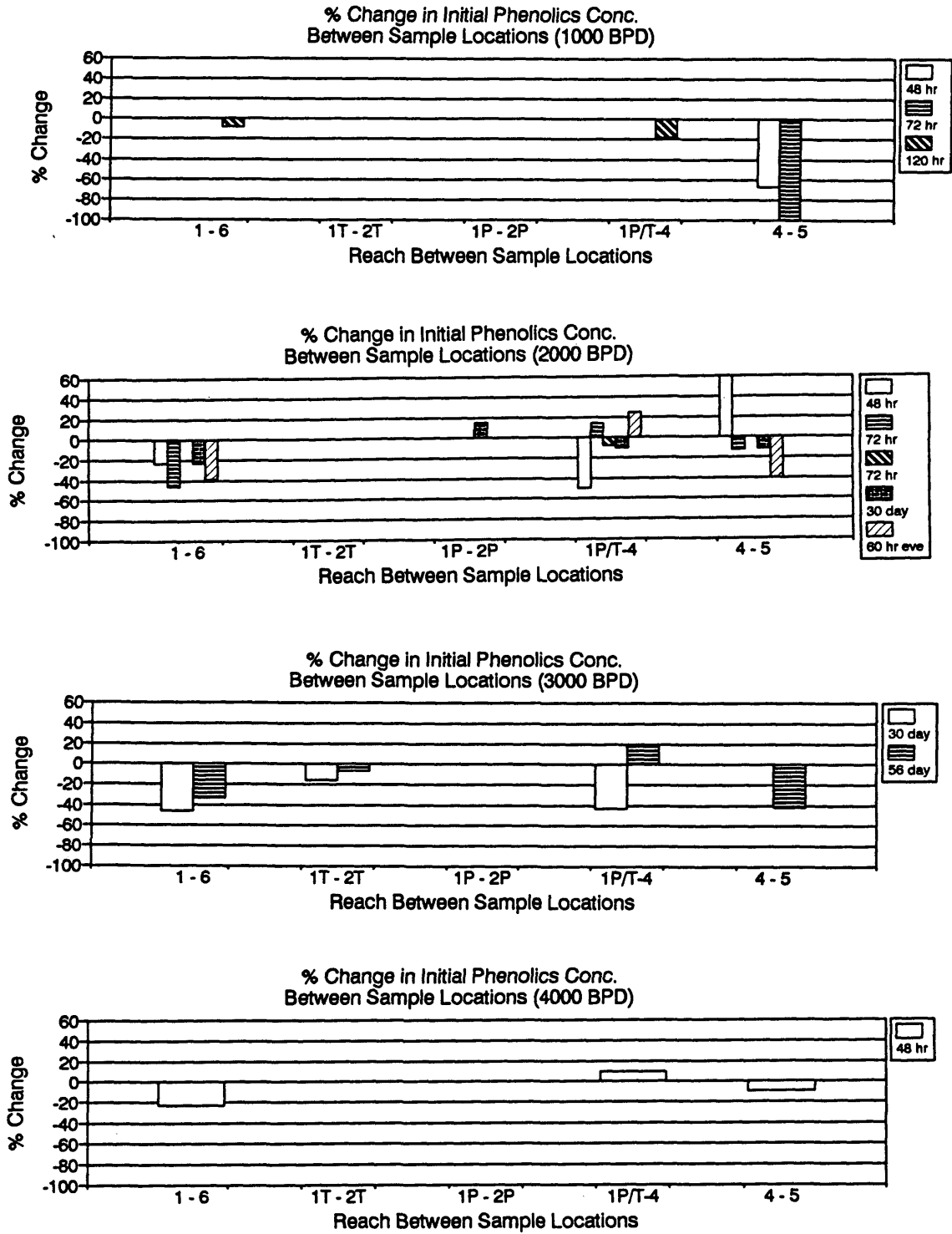


Figure B18 - Percent Change in Total Phenolics Conc. Between Sample Locations

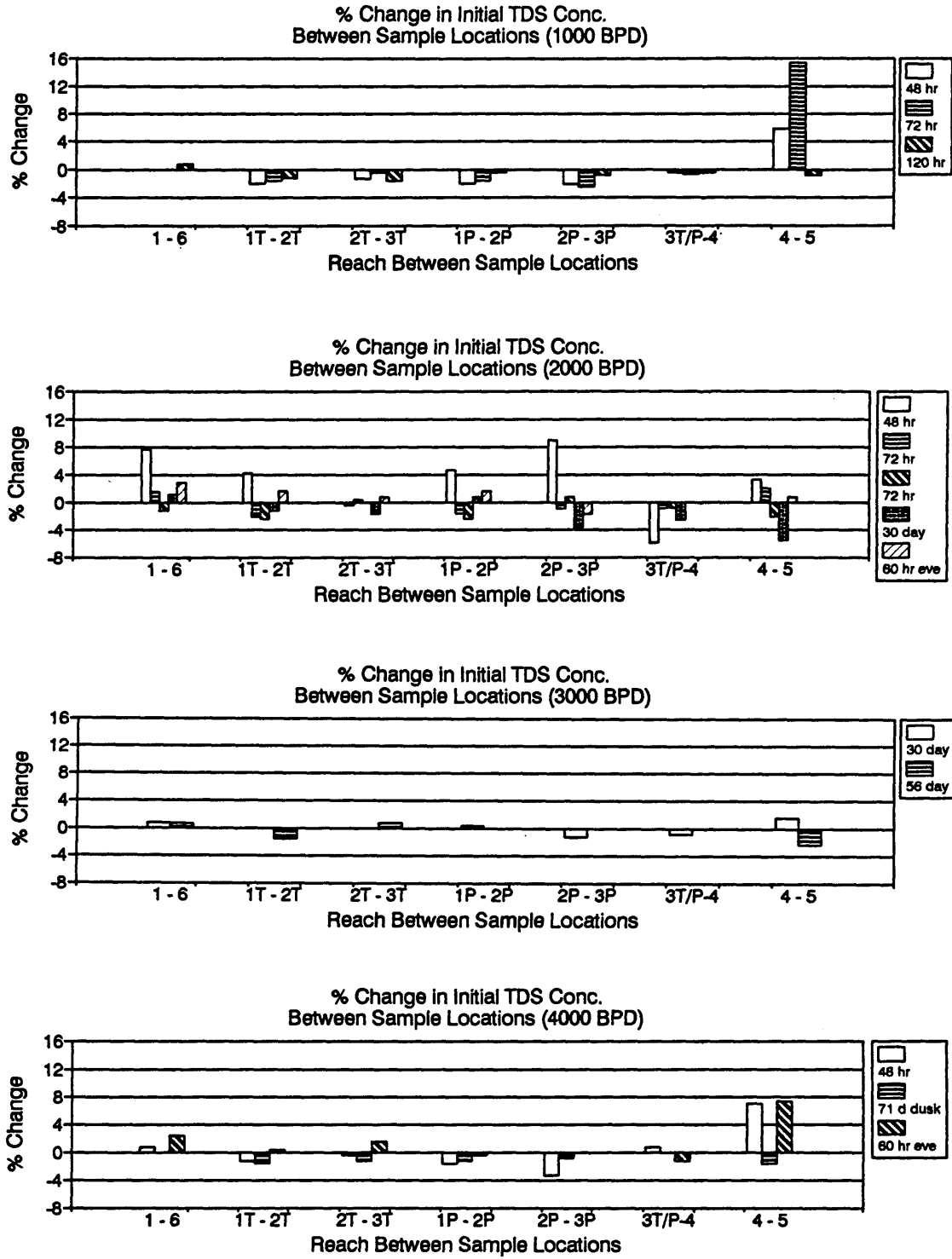


Figure B19 - Percent Change in TDS Conc. Between Sample Locations

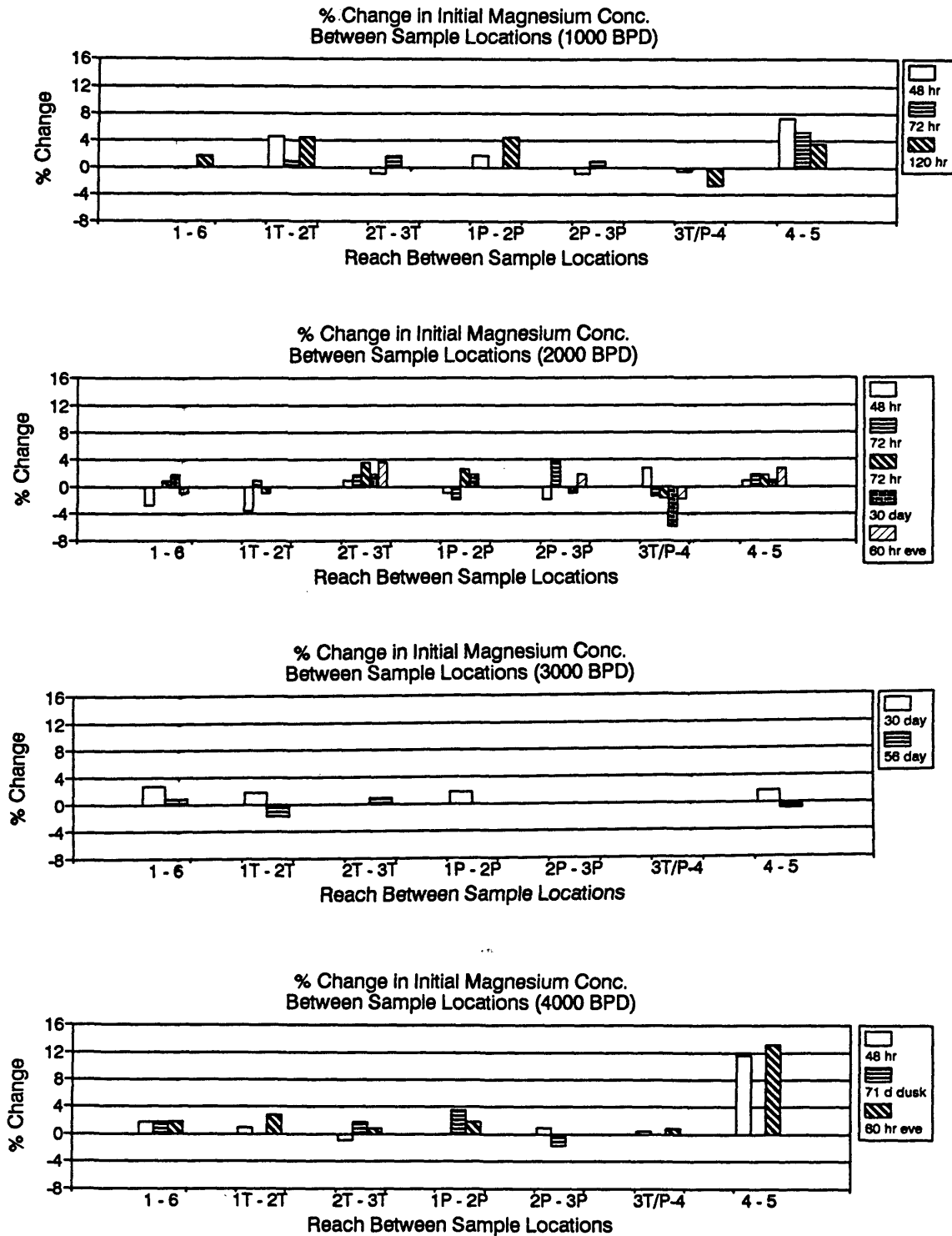


Figure B20 - Percent Change in Magnesium Conc. Between Sample Locations

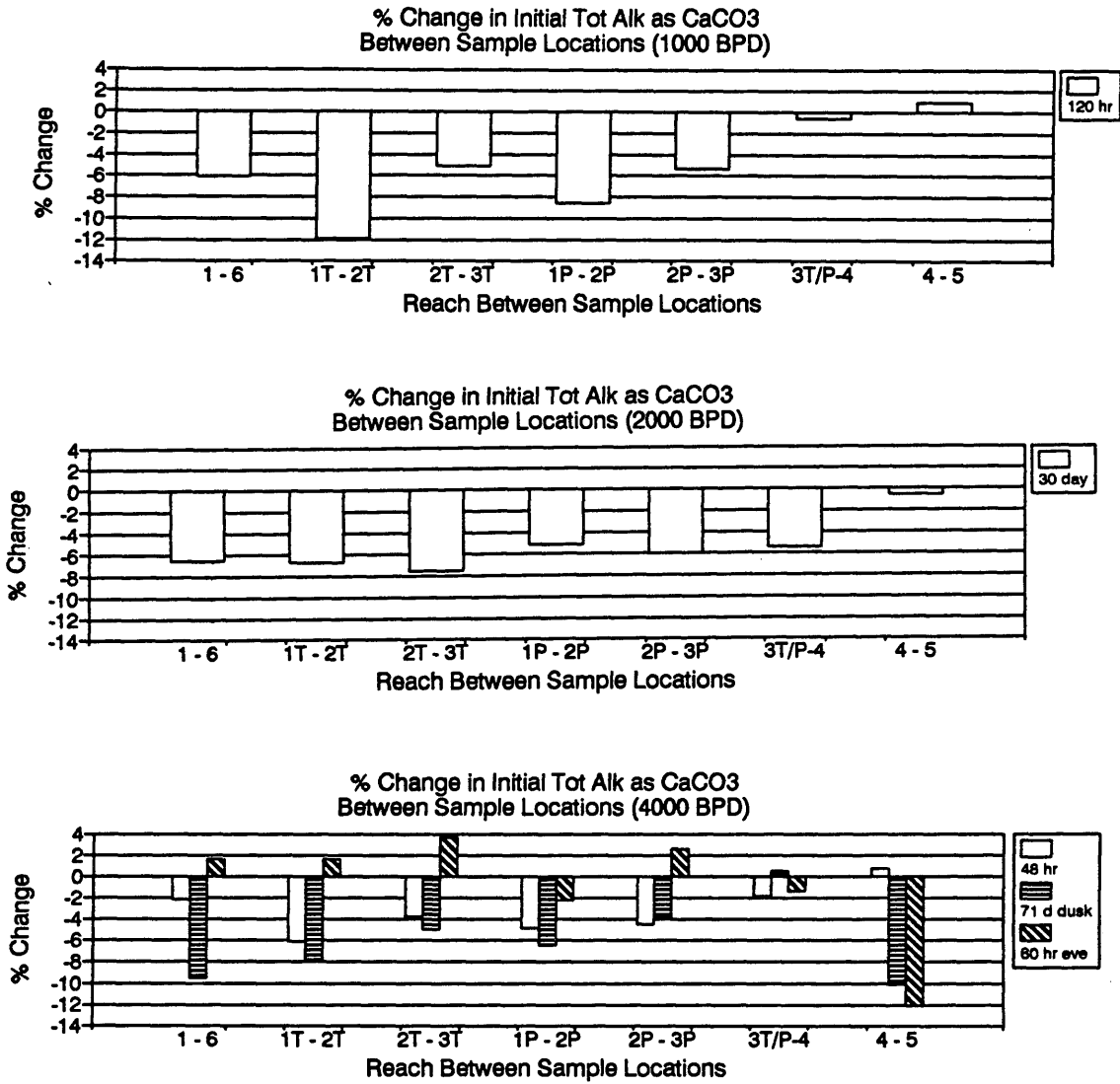


Figure B21 - Percent Change in Alkalinity Conc. Between Sample Locations

Table B9 - Percent Change in Flow Rate, Water Temperature and pH

Measurement: Flow Rate (GPM)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/30/91	1000	N/A	26.0	0	-16	-2	-9	-9	81	-9
08/02/91	2000	N/A	17.5	0	-13	-4	-2	-10	109	-6
09/08/91	2000	N/A	14.0	0	15	0	0	-13	117	-6
07/25/91	3000	N/A	18.3	0	-6	18	6	-5	105	0
08/05/91	4000	N/A	23.0	0	-4	4	0	2	***	***

*** Wetland Shut-In

Measurement: Water Temperature (deg C)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	-13	-15	-3	-9	-7	-1	-32
07/26/91	4000	24 hr	16.0	-26	-8	-3	-6	-5	-18	-30
07/30/91	1000	48 hr	26.0	-6	-23	2	-17	-2	-5	-21
07/31/91	1000	72 hr	26.5	-6	-17	-4	2	-2	-5	-22
08/02/91	2000	48 hr	17.5	-8	-31	0	-20	-13	0	-28
08/02/91	2000	60 hr eve	14.0	-14	-43	-10	-29	-24	-3	6
08/03/91	2000	72 hr	16.0	-6	-18	-4	-15	-7	0	-37
08/05/91	4000	48 hr	23.0	-12	-15	-5	-7	-13	-36	14
08/05/91	4000	60 hr eve	16.0	-16	-42	-8	-25	-24	-14	-3
09/08/91	2000	30 day	14.0	-11	-32	-8	-21	-18	-7	-15
11/02/91	3000	56 day	-10.0	-20	-41	-9	-18	-30	-3	-57
01/14/92	4000	71 d dusk	-4.0	-26	-22	-29	-22	-24	-3	-40
01/18/92	2000	72 hr	-5.0	-18	-56	-33	-38	-40	0	-61
01/24/92	1000	120 hr	5.0	-16	-64	-25	-51	-36	-8	-63

Measurement: pH				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	11	5	1	4	1	2	1
07/26/91	4000	24 hr	16.0	3	3	1	3	1	-1	0
07/30/91	1000	48 hr	26.0	8	3	1	1	1	0	3
07/31/91	1000	72 hr	26.5	8	4	1	1	1	3	-1
08/02/91	2000	48 hr	17.5	7	6	0	3	1	1	0
08/02/91	2000	60 hr eve	14.0	1	1	1	1	0	2	-1
08/03/91	2000	72 hr	16.0	3	0	1	0	0	4	0
08/05/91	4000	48 hr	23.0	10	3	1	3	1	1	1
08/05/91	4000	60 hr eve	16.0	4	3	3	4	0	1	0
09/08/91	2000	30 day	14.0	6	3	1	1	1	1	0
11/02/91	3000	56 day	-10.0	6	1	3	3	1	1	0
01/14/92	4000	71 d dusk	-4.0	6	1	3	1	1	0	1
01/18/92	2000	72 hr	-5.0	3	1	1	1	1	0	1
01/24/92	1000	120 hr	5.0	1	1	1	1	1	0	0

Table B10 - Percent Change in Conductivity

Measurement: Conductivity (micro-mhos)				Sample Location							
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5	
07/25/91	3000	30 day	18.3	-4	0	0	3	-3	-1	-12	
07/26/91	4000	24 hr	18.0	-5	0	2	2	0	-7	-14	
07/30/91	1000	48 hr	28.0	3	-8	0	2	-1	-2	-6	
07/31/91	1000	72 hr	28.5	-2	-6	0	-9	-2	-2	-7	
08/02/91	2000	48 hr	17.5	-5	-6	0	-9	-2	-4	-17	
08/02/91	2000	60 hr eve	14.0	-9	-21	-8	-16	-13	0	1	
08/03/91	2000	72 hr	18.0	7	0	-1	-10	-3	-1	-13	
08/05/91	4000	48 hr	23.0	-4	12	-1	-5	-5	-16	11	
08/05/91	4000	60 hr eve	18.0	NO DATA DUE TO HAIL STORM							
09/08/91	2000	30 day	14.0	-8	2	-15	-7	-7	-3	-8	
11/02/91	3000	56 day	-10.0	10	0	0	10	-6	-2	-14	
01/14/92	4000	71 d dusk	-4.0	8	-3	-5	-4	-8	-2	-7	
01/18/92	2000	72 hr	-5.0	6	-12	-8	-13	-9	-3	-7	
01/24/92	1000	120 hr	5.0	-5	-20	-5	-18	-6	-2	-3	

Table B11 - Net Change in Redox and Dissolved Oxygen

Measurement: Redox (mV)				Sample Location							
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5	1T/P-5
07/25/91	3000	30 day	18.3	277	142	48	98	152	68	-81	158
07/28/91	4000	24 hr	18.0	251	132	44	71	138	127	-168	117
07/30/91	1000	48 hr	26.0	230	181	83	13	228	27	17	294
07/31/91	1000	72 hr	26.5	243	159	118	28	254	13	-45	233
08/02/91	2000	48 hr	17.5	229	180	57	68	184	47	-13	244
08/02/91	2000	60 hr eve	14.0	181	87	50	28	94	53	69	237
08/03/91	2000	72 hr	18.0	173	169	85	83	202	34	-27	235
08/05/91	4000	48 hr	23.0	180	123	85	44	150	100	8	287
08/05/91	4000	60 hr eve	18.0	109	85	38	39	88	178	-82	210
09/08/91	2000	30 day	14.0	230	194	14	24	217	39	48	299
11/02/91	3000	56 day	-10.0	152	148	90	9	213	11	70	305
01/14/91	4000	71 d dusk	-4.0	220	83	54	7	135	27	148	309
01/18/91	2000	72 hr	-5.0	211	205	40	154	280	5	44	302
01/24/91	1000	120 hr	5.0	230	258	5	281	284	13	19	305

Measurement: Dissolved Oxygen (mg/l)				Sample Location							
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5	1T/P-5
07/25/91	3000	30 day	18.3	6.1	5.3	0.6	3.2	5.8	-0.6	0.5	5.8
07/28/91	4000	24 hr	18.0	4.5	5.0	0.0	3.4	5.1	-1.0	0.1	4.2
07/30/91	1000	48 hr	26.0	3.5	4.2	4.9	0.1	8.1	-2.9	-1.4	4.8
07/31/91	1000	72 hr	26.5	3.8	4.3	3.8	0.0	9.3	-2.1	-1.5	5.1
08/02/91	2000	48 hr	17.5	4.3	4.9	1.8	2.0	7.9	-1.8	-1.2	4.5
08/02/91	2000	60 hr eve	14.0	3.0	2.9	2.1	0.4	3.4	0.8	0.7	5.7
08/03/91	2000	72 hr	18.0	3.1	4.8	1.9	0.0	7.6	-1.3	0.0	5.7
08/05/91	4000	48 hr	23.0	3.7	5.0	1.9	0.0	7.0	-0.3	-0.2	6.4
08/05/91	4000	60 hr eve	18.0								
09/08/91	2000	30 day	14.0	1.8	2.0	1.3	0.1	2.2	0.6	1.0	4.4
11/02/91	3000	56 day	-10.0	1.3	2.8	1.9	0.0	3.4	0.0	2.8	6.8
01/13/92	4000	71 d dusk	-4.0	2.9	1.0	1.8	0.0	1.8	1.4	3.5	7.1
01/17/92	2000	72 hr	-5.0	4.4	6.0	1.9	3.1	6.9	0.3	2.0	9.7
01/23/92	1000	120 hr	5.0	4.5	6.3	0.9	6.2	6.8	0.6	1.5	9.1

Table B12 - Percent Change in Potassium, Sodium, and Chloride Concentration

Constituent: Potassium (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	7	3	4	11	2	-6	0
07/30/91	1000	48 hr	26.0	NT	8	-8	3	-7	4	9
07/31/91	1000	72 hr	26.5	NT	4	4	1	4	-3	6
08/02/91	2000	48 hr	17.5	-37	-15	-5	-22	-8	-17	0
08/02/91	2000	60 hr eve	14.0	-27	-3	1	5	-23	14	-18
08/03/91	2000	72 hr	16.0	-21	5	-7	-8	22	-4	-27
08/05/91	4000	48 hr	23.0	-10	-11	13	-25	35	-10	39
08/05/91	4000	60 hr eve	16.0	0	-6	4	-13	17	-15	38
08/08/91	2000	30 day	14.0	8	6	6	-2	10	-9	-3
11/02/91	3000	56 day	-10.0	-4	-4	0	NT	NT	NT	1
01/13/92	4000	71 d dusk	-4.0	-14	-2	4	12	-6	11	-9
01/17/92	2000	72 hr	-5.0	9	13	-6	-2	18	-13	-6
01/24/92	1000	120 hr	5.0	1	0	3	12	-16	8	15

Constituent: Sodium (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	3	3	0	3	0	0	-0
07/30/91	1000	48 hr	26.0	NT	7	-1	3	-0	-0	6
07/31/91	1000	72 hr	26.5	NT	3	2	1	4	-0	3
08/02/91	2000	48 hr	17.5	-15	-9	-2	-6	-6	-1	0
08/02/91	2000	60 hr eve	14.0	-8	-2	4	0	-3	2	-4
08/03/91	2000	72 hr	16.0	-6	3	-0	-4	8	-4	-7
08/05/91	4000	48 hr	23.0	0	-2	3	-5	8	-3	16
08/05/91	4000	60 hr eve	16.0	2	1	1	-1	3	-3	16
08/08/91	2000	30 day	14.0	2	2	3	2	1	-7	0
11/02/91	3000	56 day	-10.0	0	-2	0	NT	NT	NT	-3
01/13/92	4000	71 d dusk	-4.0	-9	-0	3	6	-2	0	-5
01/17/92	2000	72 hr	-5.0	5	6	-2	3	0	-3	-2
01/24/92	1000	120 hr	5.0	1	2	1	4	-3	0	5

Constituent: Chloride (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	2	0	0	-1	4	-2	-5
07/30/91	1000	48 hr	26.0	NT	7	-1	3	2	2	4
07/31/91	1000	72 hr	26.5	NT	5	-3	5	1	1	6
08/02/91	2000	48 hr	17.5	-6	-4	1	-3	-7	3	-1
08/02/91	2000	60 hr eve	14.0	-5	-1	-2	1	-2	-2	7
08/03/91	2000	72 hr	16.0	-7	1	-0	0	11	-5	0
08/05/91	4000	48 hr	23.0	0	-2	7	-1	3	-4	8
08/05/91	4000	60 hr eve	16.0	6	7	0	5	-0	1	5
08/08/91	2000	30 day	14.0	11	2	8	0	11	-9	3
11/02/91	3000	56 day	-10.0	0	-2	2	NT	NT	NT	-6
01/13/92	4000	71 d dusk	-4.0	2	1	-3	0	1	2	-1
01/17/92	2000	72 hr	-5.0	5	4	1	5	-2	0	-1
01/24/92	1000	120 hr	5.0	2	3	-1	5	-4	0	3

NT = no test

Table B13 - Percent Change in Calcium, Bicarbonate and Radium 226 Conc.

Constituent: Calcium (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	-5	-6	-4	-7	-4	1	3
07/30/91	1000	48 hr	26.0	NT	-15	-3	-10	-10	-1	0
07/31/91	1000	72 hr	26.5	NT	-14	-6	-9	-13	-2	4
08/02/91	2000	48 hr	17.5	24	12	-2	18	-11	-2	10
08/02/91	2000	60 hr eve	14.0	6	0	4	2	-4	0	-11
08/03/91	2000	72 hr	16.0	2	-9	-2	-9	-7	-2	10
08/05/91	4000	48 hr	23.0	-1	-7	-2	-4	-6	-2	-3
08/05/91	4000	60 hr eve	16.0	0	-4	4	-6	-1	-1	-10
09/08/91	2000	30 day	14.0	-1	-7	-2	-1	-6	-2	-5
11/02/91	3000	56 day	-10.0	-0	-5	1	NT	NT	NT	-5
01/13/92	4000	71 d dusk	-4.0	-2	-5	-6	-10	1	-1	-8
01/17/92	2000	72 hr	-5.0	-4	-12	2	-6	-3	-3	-1
01/24/92	1000	120 hr	5.0	-3	-9	-4	-7	-4	-2	-1

Constituent: Bicarbonate (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	-5	-5	-2	-4	-4	-2	7
07/30/91	1000	48 hr	26.0	NT	-15	-6	-6	-13	-1	5
07/31/91	1000	72 hr	26.5	NT	-15	-7	-9	-15	-2	7
08/02/91	2000	48 hr	17.5	12	3	-4	9	-10	-3	15
08/02/91	2000	60 hr eve	14.0	7	8	-1	8	-5	-1	-15
08/03/91	2000	72 hr	16.0	4	-9	-1	-3	-10	-2	6
08/05/91	4000	48 hr	23.0	-2	-6	-4	-5	-4	-2	1
08/05/91	4000	60 hr eve	16.0	2	2	4	-2	3	-1	-12
09/08/91	2000	30 day	14.0	-7	-7	-7	-5	-6	-5	-1
11/02/91	3000	56 day	-10.0	-7	-10	-4	NT	NT	NT	-3
01/13/92	4000	71 d dusk	-4.0	-9	-7	-5	-7	-3	0	-10
01/17/92	2000	72 hr	-5.0	-4	-6	-2	-6	-3	-1	-2
01/24/92	1000	120 hr	5.0	-7	-12	-5	-6	-6	-1	1

Constituent: Radium 226 (pCi/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	22	30	-31	1	-9	14	-36
07/30/91	1000	48 hr	26.0	NT	-29	7	-20	-8	-25	-36
07/31/91	1000	72 hr	26.5	NT	-45	9	-29	-15	-18	-27
08/02/91	2000	48 hr	17.5	-26	-40	-0	-37	-1	-20	-23
08/02/91	2000	60 hr eve	14.0	-4	-24	0	-5	-20	16	-49
08/03/91	2000	72 hr	16.0	4	-25	-4	-29	-18	-7	-29
08/05/91	4000	48 hr	23.0	-1	-7	-11	1	-28	18	-60
08/05/91	4000	60 hr eve	16.0	-76	-64	60	-29	-33	-45	26
09/08/91	2000	30 day	14.0	47	11	-0	27	0	10	-28
11/02/91	3000	56 day	-10.0	9	-16	28	NT	NT	NT	-2
01/13/92	4000	71 d dusk	-4.0	-6	-5	-5	-6	-9	5	-9
01/17/92	2000	72 hr	-5.0	-3	-11	29	2	-15	-5	-8
01/24/92	1000	120 hr	5.0	-11	7	-9	9	3	-5	-6

NT* = no test

Table B14 - Percent Change in Sulfide and Sulfate Conc.

Constituent: Sulfide (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 8	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	-88	-68	0	-54	-46	75	-29
07/30/91	1000	48 hr	26.0	NT	-19	-36	26	-77	-36	25
07/31/91	1000	72 hr	26.5	NT	-69	18	-49	-56	14	8
08/02/91	2000	48 hr	17.5	-46	-70	0	3	-66	25	20
08/02/91	2000	60 hr eve	14.0	-52	-75	33	-48	-55	-18	29
08/03/91	2000	72 hr	18.0	-11	-65	36	-62	-7	87	-3
08/05/91	4000	48 hr	23.0	-74	-72	-13	-56	-25	-16	8
08/05/91	4000	60 hr eve	18.0	-78	-64	80	-29	-33	-45	6
08/08/91	2000	30 day	14.0	-64	-57	-17	-42	-39	-5	-17
11/02/91	3000	56 day	-10.0	-51	-74	-11	NT	NT	NT	100
01/13/92	4000	71 d dusk	-4.0	-46	-48	0	-34	-18	-9	13
01/17/92	2000	72 hr	-5.0	-46	-34	-19	-37	-15	0	23
01/24/92	1000	120 hr	5.0	-36	-19	-18	-29	27	-64	100

Constituent: Sulfate (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 8	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	1	0	-0	-2	4	-2	-8
07/30/91	1000	48 hr	26.0	NT	5	0	2	3	2	4
07/31/91	1000	72 hr	26.5	NT	10	-6	8	1	2	8
08/02/91	2000	48 hr	17.5	1	3	1	5	-8	2	-3
08/02/91	2000	60 hr eve	14.0	-1	-1	-2	2	-4	-3	13
08/03/91	2000	72 hr	18.0	-7	1	2	-1	11	-6	-3
08/05/91	4000	48 hr	23.0	2	-4	8	-4	5	-5	11
08/05/91	4000	60 hr eve	18.0	7	2	-1	2	-2	-0	22
08/08/91	2000	30 day	14.0	12	6	5	-0	12	-8	1
11/02/91	3000	56 day	-10.0	9	7	2	NT	NT	NT	-8
01/13/92	4000	71 d dusk	-4.0	6	3	-2	4	1	1	1
01/17/92	2000	72 hr	-5.0	6	3	2	4	-0	-0	-1
01/24/92	1000	120 hr	5.0	6	12	-0	10	1	-0	-3

NT* = no test

Table B15 - Percent Change in Benzene, Toluene and Ethylbenzene Conc.

Constituent: Benzene (ug/l)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	1P - 2P	2P/T-4	4 - 5
07/25/91	3000	30 day	18.3	-93	-88	NT	-35	-100
07/30/91	1000	48 hr	26.0	NT	-100	-69	-100	NT
07/31/91	1000	72 hr	26.5	NT	-100	-72	-100	NT
08/02/91	2000	48 hr	17.5	NT	-97	-70	-100	NT
08/02/91	2000	60 hr eve	14.0	NT	-91	-70	-82	NT
08/03/91	2000	72 hr	16.0	NT	-94	-71	-100	NT
08/05/91	4000	48 hr	23.0	NT	-95	-58	-100	NT
08/05/91	4000	60 hr eve	16.0	NT	-93	-48	-100	NT
09/08/91	2000	30 day	14.0	-85	-95	-61	-100	NT
11/02/91	3000	56 day	-10.0	-83	-75	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	-91	-77	-52	-69	NT
01/17/92	2000	72 hr	-5.0	-86	-86	-65	-79	NT
01/24/92	1000	120 hr	5.0	-78	-91	-59	-83	NT

Constituent: Toluene (ug/l)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	1P - 2P	2P/T-4	4 - 5
07/25/91	3000	30 day	18.3	-95	-87	NT	-49	-100
07/30/91	1000	48 hr	26.0	NT	-100	-77	-100	NT
07/31/91	1000	72 hr	26.5	NT	-100	-79	-100	NT
08/02/91	2000	48 hr	17.5	NT	-97	-79	-100	NT
08/02/91	2000	60 hr eve	14.0	NT	-92	-72	-80	NT
08/03/91	2000	72 hr	16.0	NT	-92	-75	-100	NT
08/05/91	4000	48 hr	23.0	NT	-96	-83	-100	NT
08/05/91	4000	60 hr eve	16.0	NT	-93	-57	-100	NT
09/08/91	2000	30 day	14.0	-87	-95	-85	-100	NT
11/02/91	3000	56 day	-10.0	-83	-73	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	-92	-77	-51	-71	NT
01/17/92	2000	72 hr	-5.0	-87	-89	-75	-78	NT
01/24/92	1000	120 hr	5.0	-83	-84	-79	-81	NT

Constituent: Ethylbenzene (ug/l)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	1P - 2P	2P/T-4	4 - 5
07/25/91	3000	30 day	18.3	-93	-83	NT	-45	-100
07/30/91	1000	48 hr	26.0	NT	-100	-65	-100	NT
07/31/91	1000	72 hr	26.5	NT	-100	-70	-100	NT
08/02/91	2000	48 hr	17.5	NT	-100	-75	-100	NT
08/02/91	2000	60 hr eve	14.0	NT	-83	-69	-100	NT
08/03/91	2000	72 hr	16.0	NT	-84	-69	-100	NT
08/05/91	4000	48 hr	23.0	NT	-89	-53	-100	NT
08/05/91	4000	60 hr eve	16.0	NT	-85	-47	-100	NT
09/08/91	2000	30 day	14.0	-100	-84	-68	-100	NT
11/02/91	3000	56 day	-10.0	-82	-70	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	-91	-78	-55	-85	NT
01/17/92	2000	72 hr	-5.0	-84	-85	-69	-75	NT
01/17/92	2000	72 hr	5.0	-83	-91	-70	-100	NT

NT* = no test

Table B16 - Percent Change in Xylenes and Total Phenolics Conc.

Constituent: Xylenes (ug/l)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	1P - 2P	2P/T-4	4 - 5
07/25/91	3000	30 day	18.3	-88	-83	NT	-53	-100
07/30/91	1000	48 hr	26.0	NT	-100	-62	-100	NT
07/31/91	1000	72 hr	26.5	NT	-100	-69	-100	NT
08/02/91	2000	48 hr	17.5	NT	-95	-71	-100	NT
08/02/91	2000	60 hr eve	14.0	NT	-92	-68	-84	NT
08/03/91	2000	72 hr	16.0	NT	-90	-58	-100	NT
08/05/91	4000	48 hr	23.0	NT	-87	-50	-100	NT
08/05/91	4000	60 hr eve	16.0	NT	-83	-44	-100	NT
08/08/91	2000	30 day	14.0	-84	-92	-59	-88	NT
11/02/91	3000	56 day	-10.0	-90	-68	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	-90	-74	-47	-70	NT
01/17/92	2000	72 hr	-5.0	-83	-81	-67	-75	NT
01/24/92	1000	120 hr	5.0	-82	-93	-79	-72	NT

Constituent: Total Phenolics (mg/l)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	1P - 2P	1P/T-4	4 - 5
07/25/91	3000	30 day	18.3	-46	-15	NT	-43	0
07/30/91	1000	48 hr	26.0	NT	NT	NT	ERR	-67 *
07/31/91	1000	72 hr	26.5	NT	NT	NT	ERR	-100 *
08/02/91	2000	48 hr	17.5	-23	NT	NT	-50	60 *
08/02/91	2000	60 hr eve	14.0	-38	NT	NT	25	-40 *
08/03/91	2000	72 hr	16.0	-46	NT	NT	14	-12 *
08/08/91	2000	30 day	14.0	-23	0	15	-10	-11
11/02/91	3000	56 day	-10.0	-33	-7	NT	20	-42
01/13/92	4000	71 d dusk	-4.0	-23	NT	NT	10	-9 *
01/17/92	2000	72 hr	-5.0	0	NT	NT	-8	0
01/24/92	1000	120 hr	5.0	-6	NT	NT	-18	0

NT* = no test, *** data in this row is based on estimated inflow concentration

Table B17 - Percent Change in TDS, Magnesium and Alkalinity Conc.

Constituent: Total Dissolved Solids @ 180 deg C (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	1	0	0	0	-1	-1	2
07/30/91	1000	48 hr	26.0	NT	-2	-1	-2	-2	-0	6
07/31/91	1000	72 hr	26.5	NT	-2	-0	-2	-2	-1	15
08/02/91	2000	48 hr	17.5	8	4	-0	5	8	-8	3
08/02/91	2000	60 hr eve	14.0	3	2	1	2	-2	0	1
08/03/91	2000	72 hr	16.0	2	-2	0	-2	-1	-1	2
08/05/91	4000	48 hr	23.0	1	-1	-0	-2	-3	1	7
08/05/91	4000	60 hr eve	16.0	2	0	2	-0	0	-1	7
08/08/91	2000	30 day	14.0	1	-1	-2	1	-4	-2	-8
11/02/91	3000	56 day	-10.0	1	-2	1	NT	NT	NT	-2
01/13/92	4000	71 d dusk	-4.0	0	-2	-1	-1	-1	0	-2
01/17/92	2000	72 hr	-5.0	-1	-2	0	-2	1	-1	-2
01/24/92	1000	120 hr	5.0	1	-1	-2	-0	-1	-0	-1

Constituent: Magnesium (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
07/25/91	3000	30 day	18.3	3	2	0	2	0	0	2
07/30/91	1000	48 hr	26.0	NT	5	-1	2	-1	-0	7
07/31/91	1000	72 hr	26.5	NT	1	2	0	1	0	5
08/02/91	2000	48 hr	17.5	-3	-4	1	-1	-2	3	1
08/02/91	2000	60 hr eve	14.0	-1	0	4	0	2	-2	3
08/03/91	2000	72 hr	16.0	0	1	2	-2	4	-1	2
08/05/91	4000	48 hr	23.0	2	1	-1	0	1	0	12
08/05/91	4000	60 hr eve	16.0	2	3	1	2	0	1	13
08/08/91	2000	30 day	14.0	2	0	2	2	-1	-6	1
11/02/91	3000	56 day	-10.0	1	-2	1	NT	NT	NT	-1
01/13/92	4000	71 d dusk	-4.0	2	0	2	4	-2	0	0
01/17/92	2000	72 hr	-5.0	1	-1	4	3	0	-2	2
01/24/92	1000	120 hr	5.0	2	5	0	5	0	-3	4

Constituent: Total Alkalinity as CaCO3 (mg/l)				Sample Location						
Date	Flow BPD	Duration	Amb T (C)	1 - 6	1T - 2T	2T - 3T	1P - 2P	2P - 3P	3T/P-4	4 - 5
08/05/91	4000	48 hr	23.0	-2	-8	-4	-5	-4	-2	1
08/05/91	4000	60 hr eve	16.0	2	2	4	-2	3	-1	-12
08/08/91	2000	30 day	14.0	-8	-7	-8	-5	-8	-5	-1
11/02/91	3000	56 day	-10.0	NT	NT	NT	NT	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	-10	-8	-5	-8	-4	1	-10
01/17/92	2000	72 hr	-5.0	NT	NT	NT	NT	NT	NT	NT
01/24/92	1000	120 hr	5.0	-8	-12	-5	-8	-5	-1	1

NT = no test

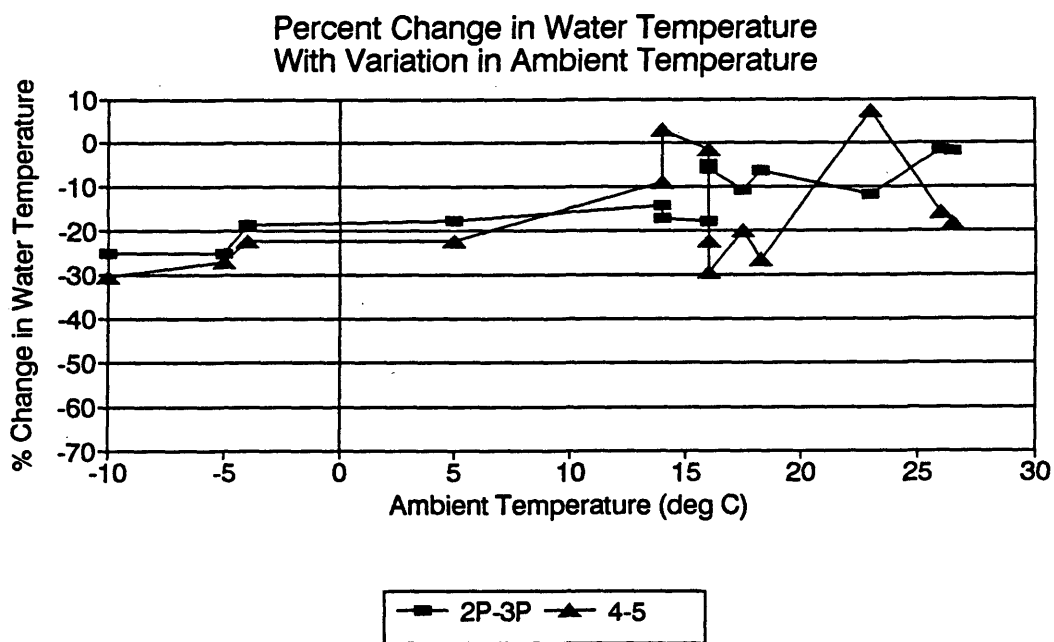
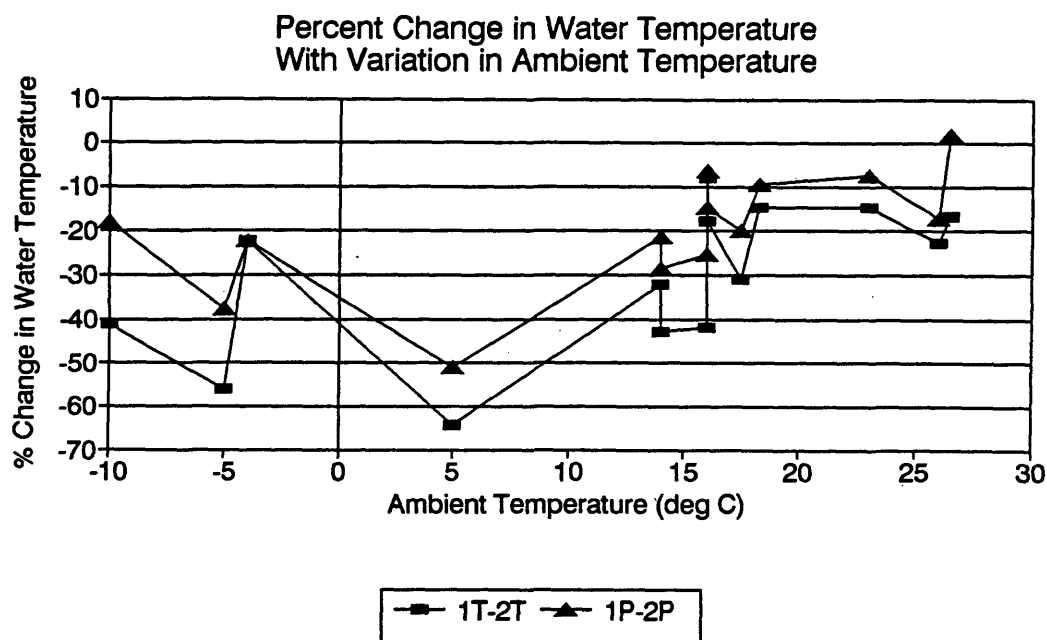


Figure B22 - % Change in Water Temperature vs Ambient Temperature

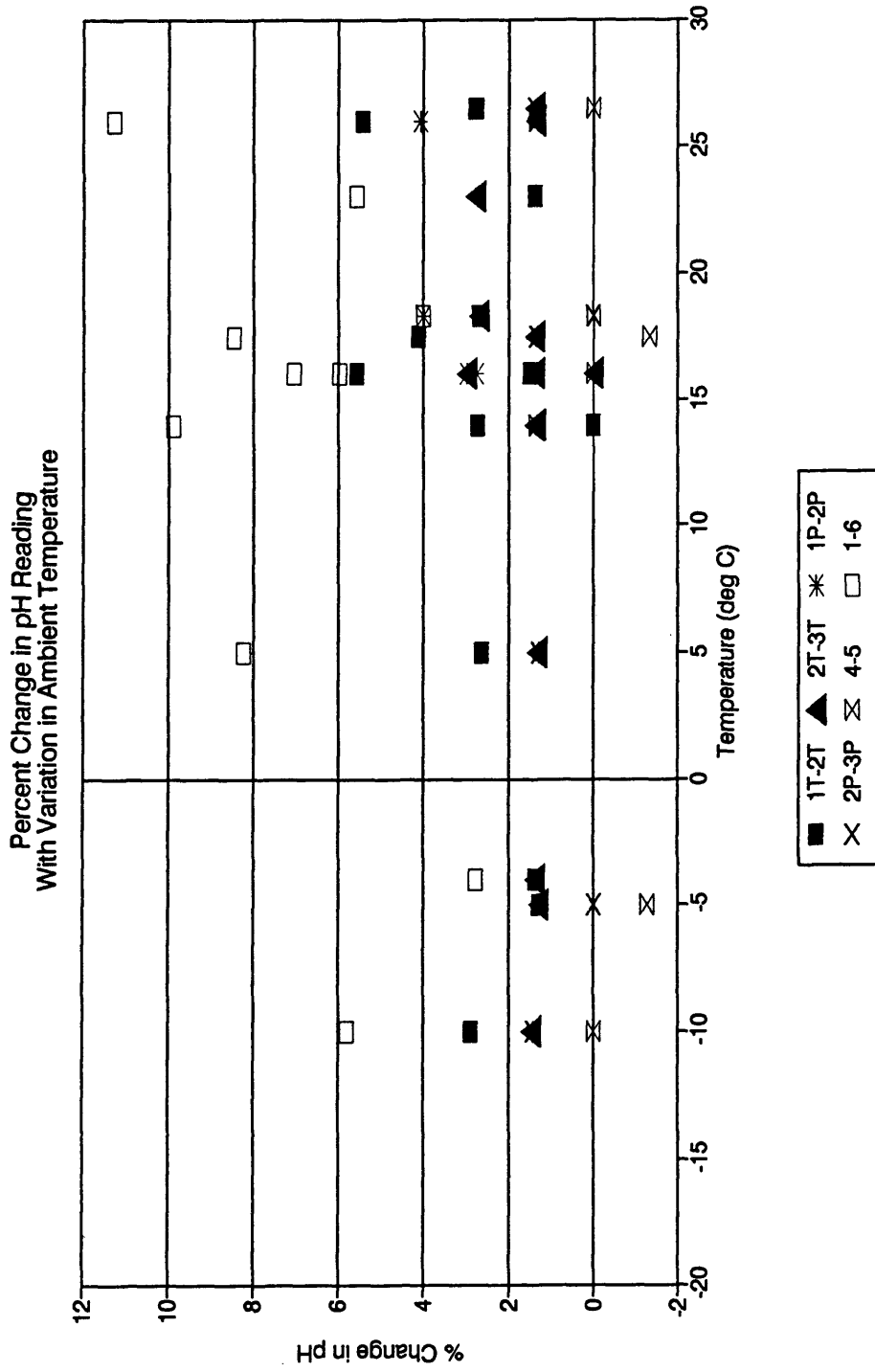


Figure B23 - % Change in pH vs Ambient Temperature

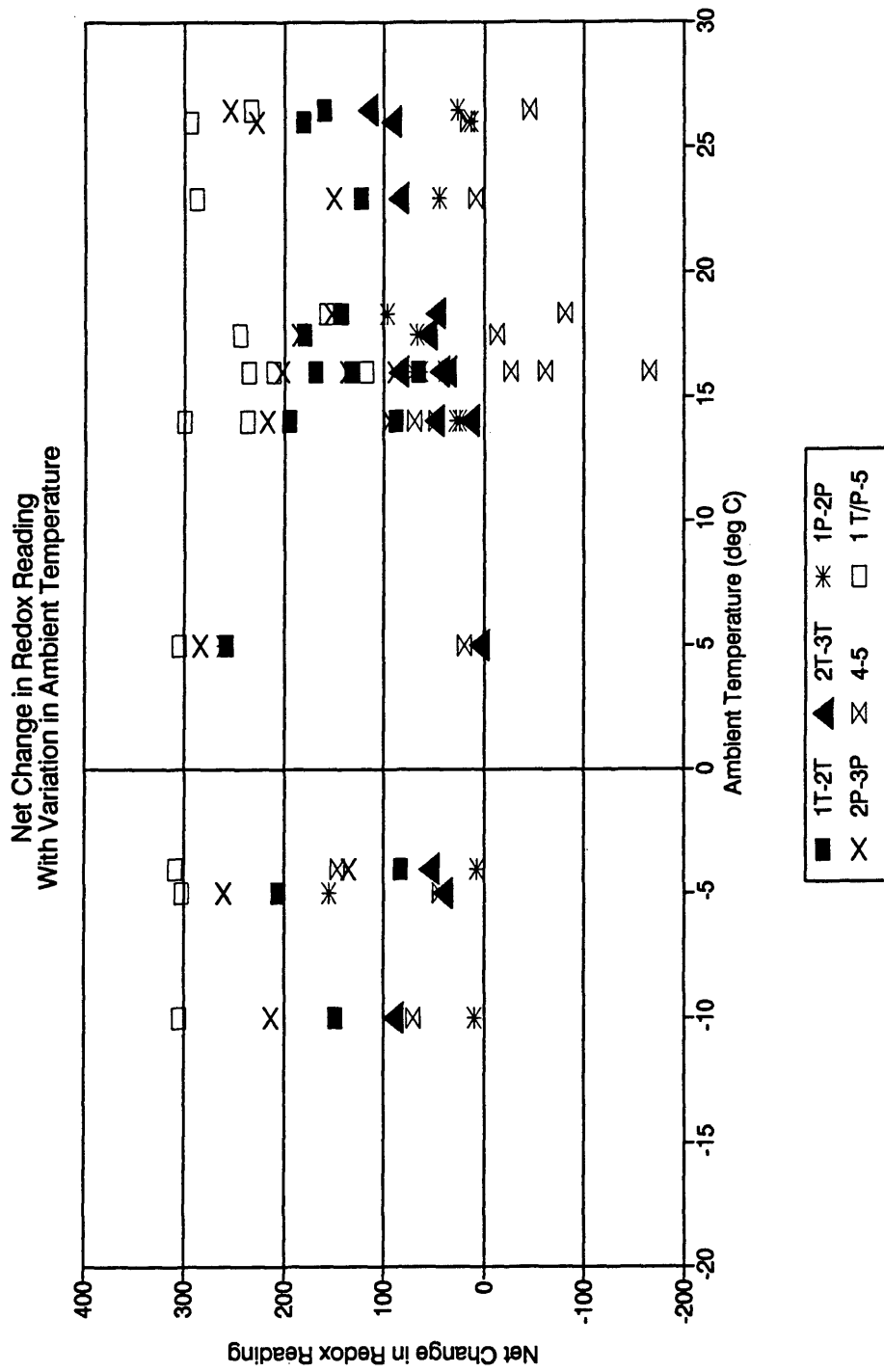


Figure B24 - Net Change in Redox vs Ambient Temperature

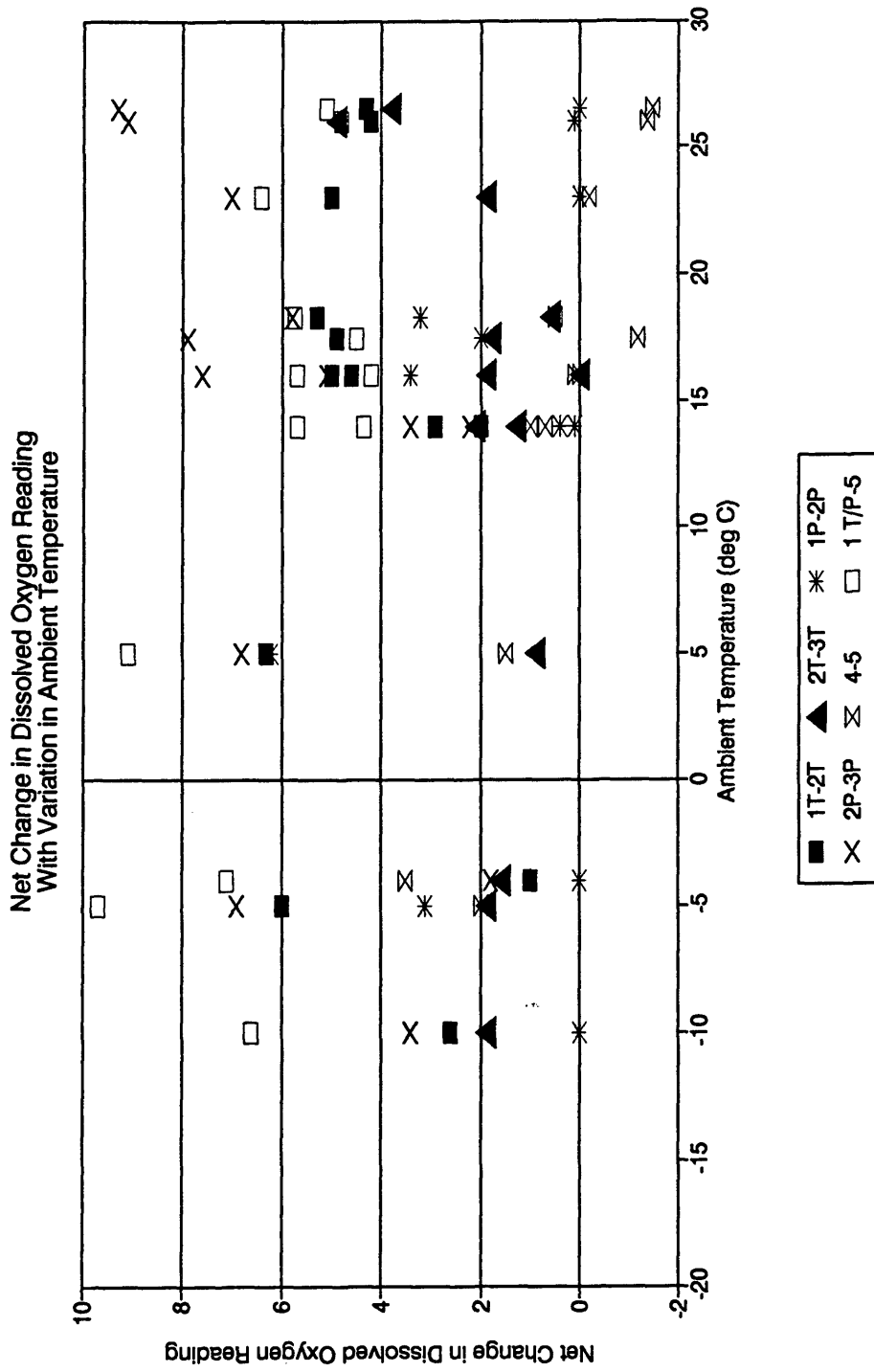


Figure B25 - Net Change in Dissolved Oxygen vs Ambient Temperature

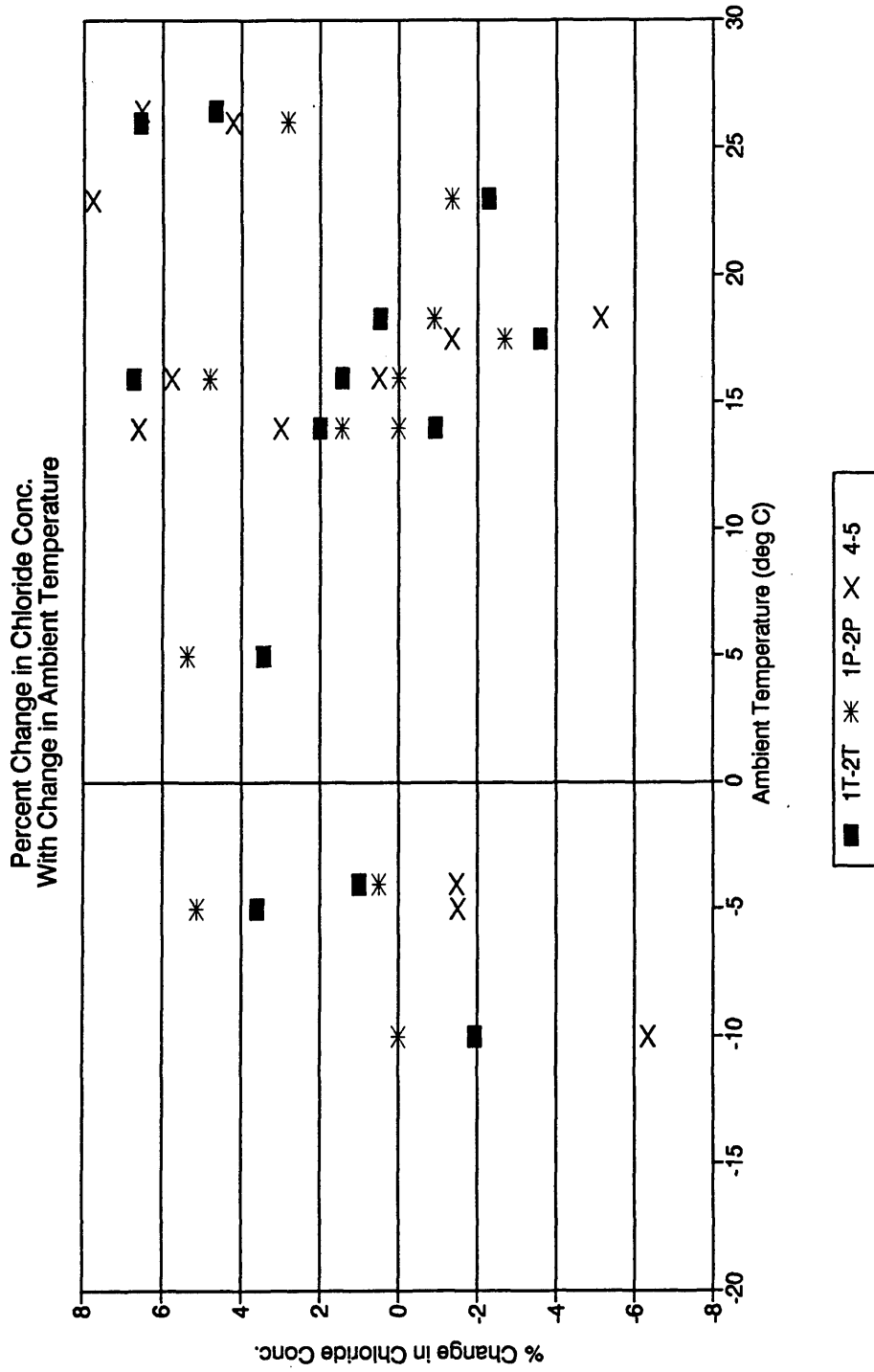


Figure B26 - % Change in Chloride Conc. vs Ambient Temperature

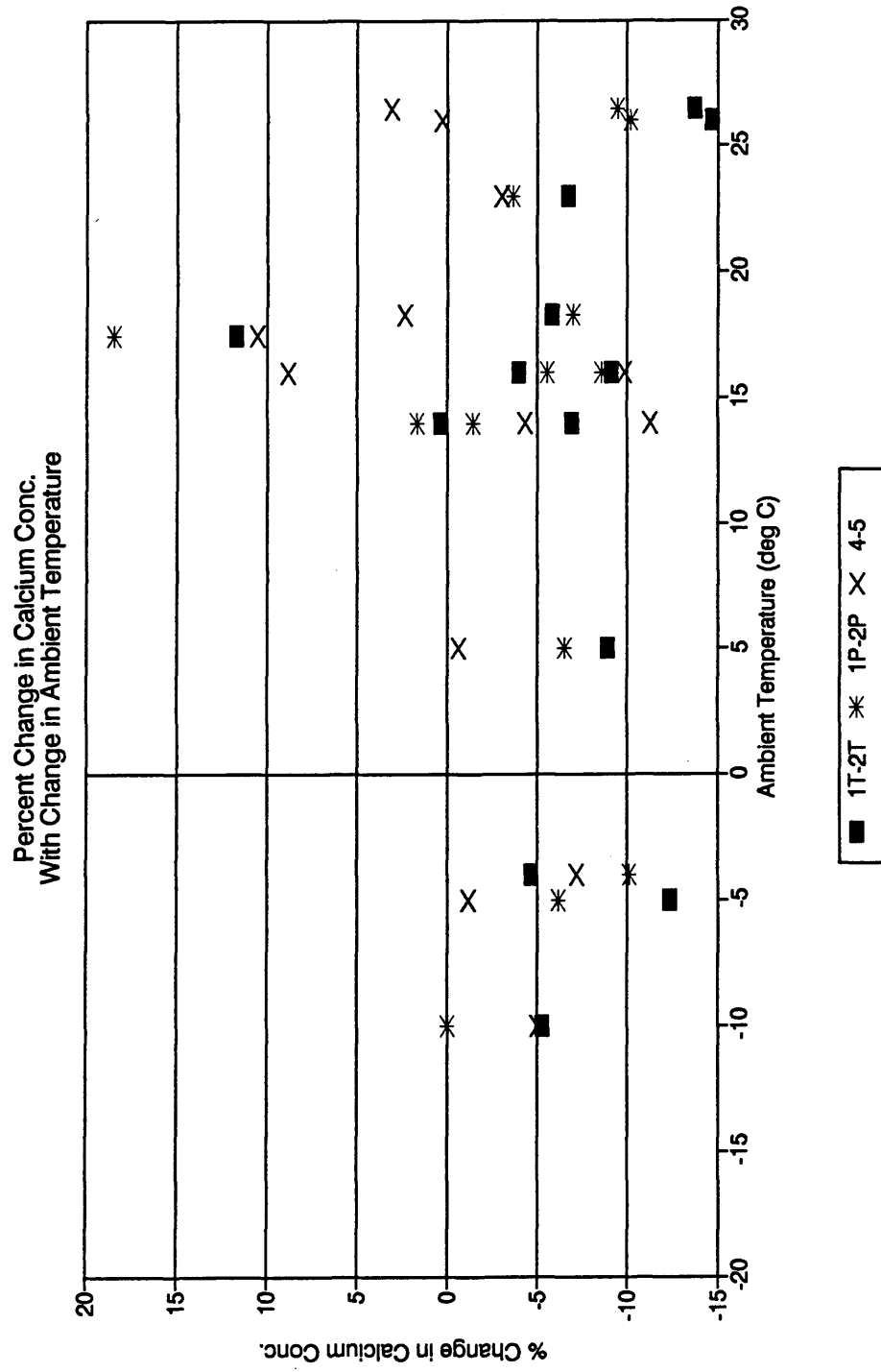


Figure B27 - % Change in Calcium Conc. vs Ambient Temperature

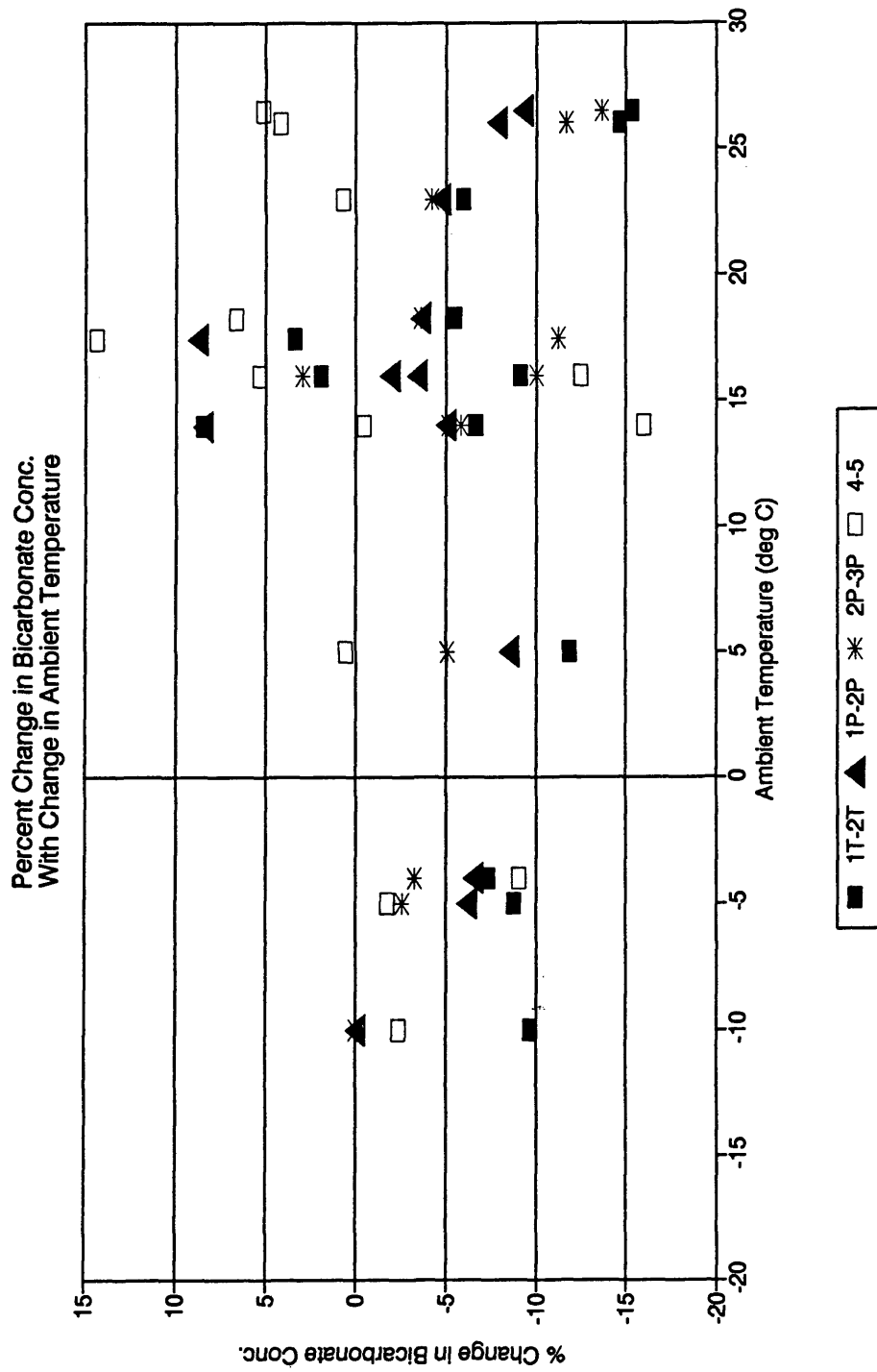


Figure B28 - % Change in Bicarbonate Conc. vs Ambient Temperature

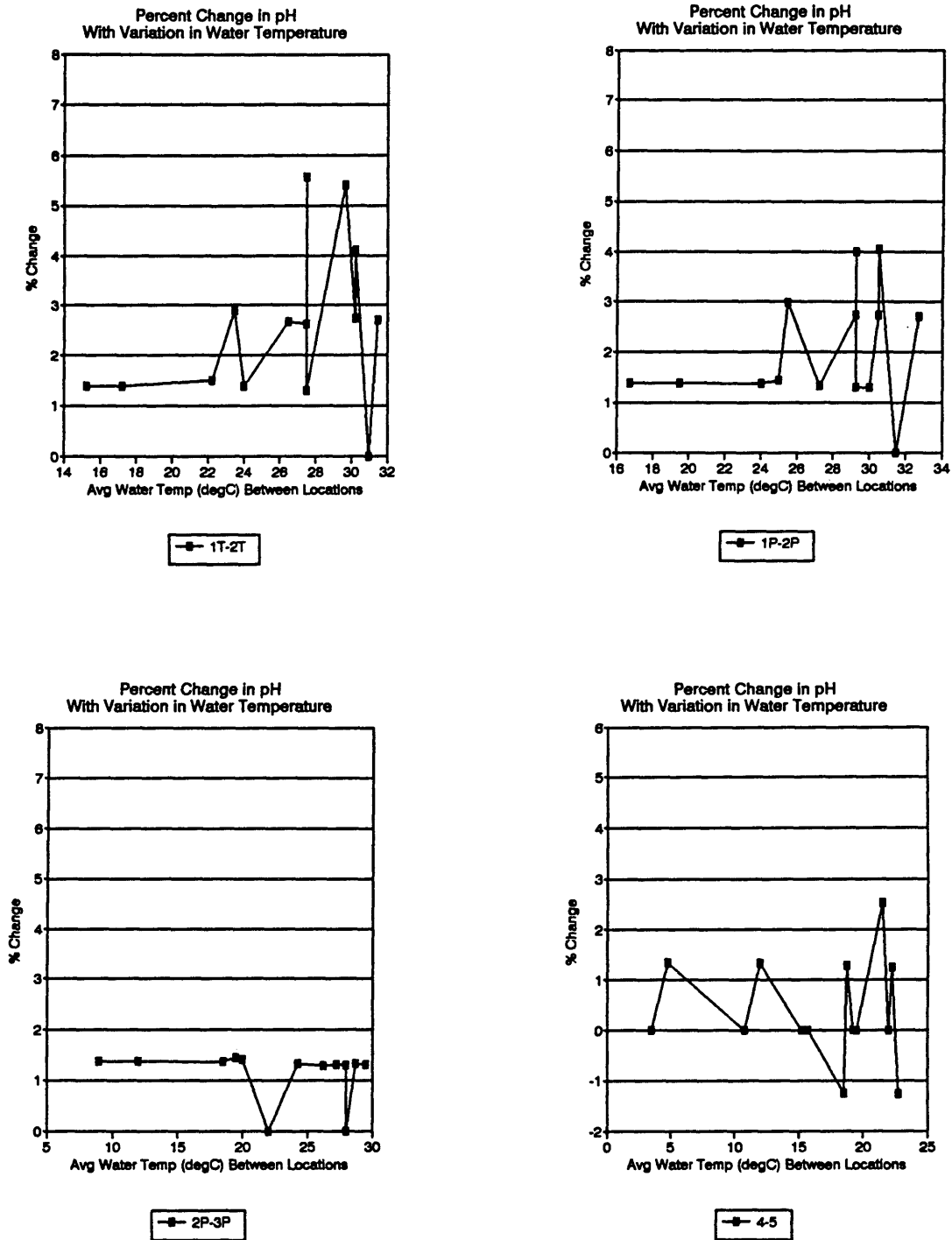


Figure B29 - % Change in pH vs Water Temperature

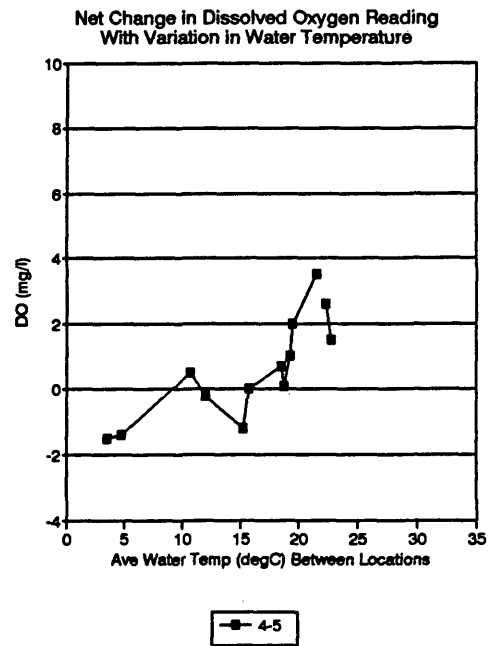
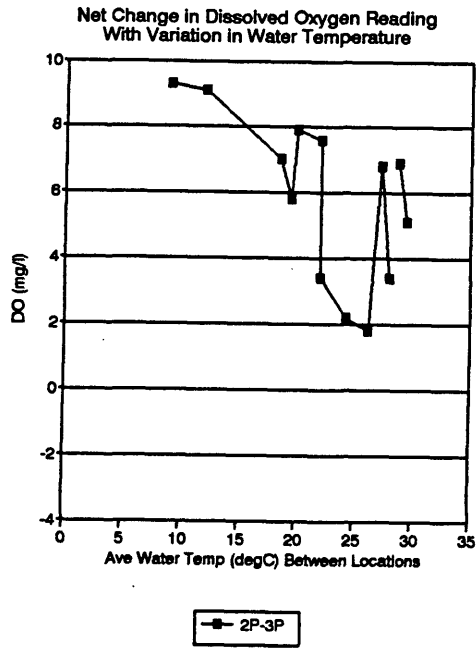
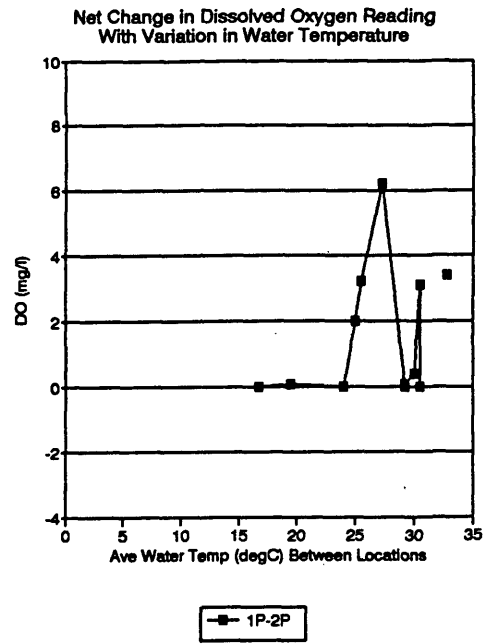
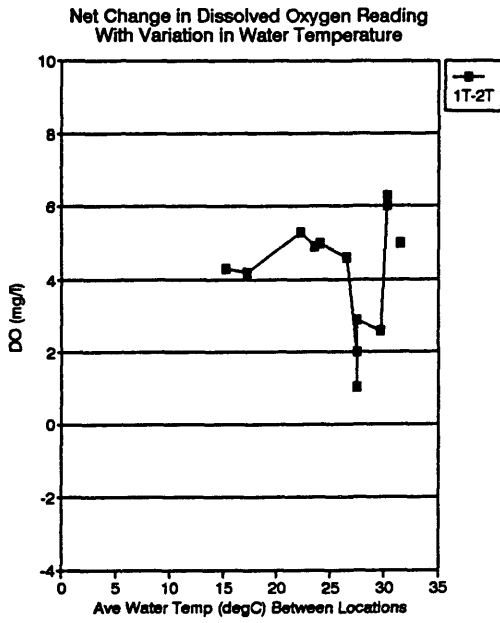


Figure B30 - Net Change in Dissolved Oxygen vs Water Temperature

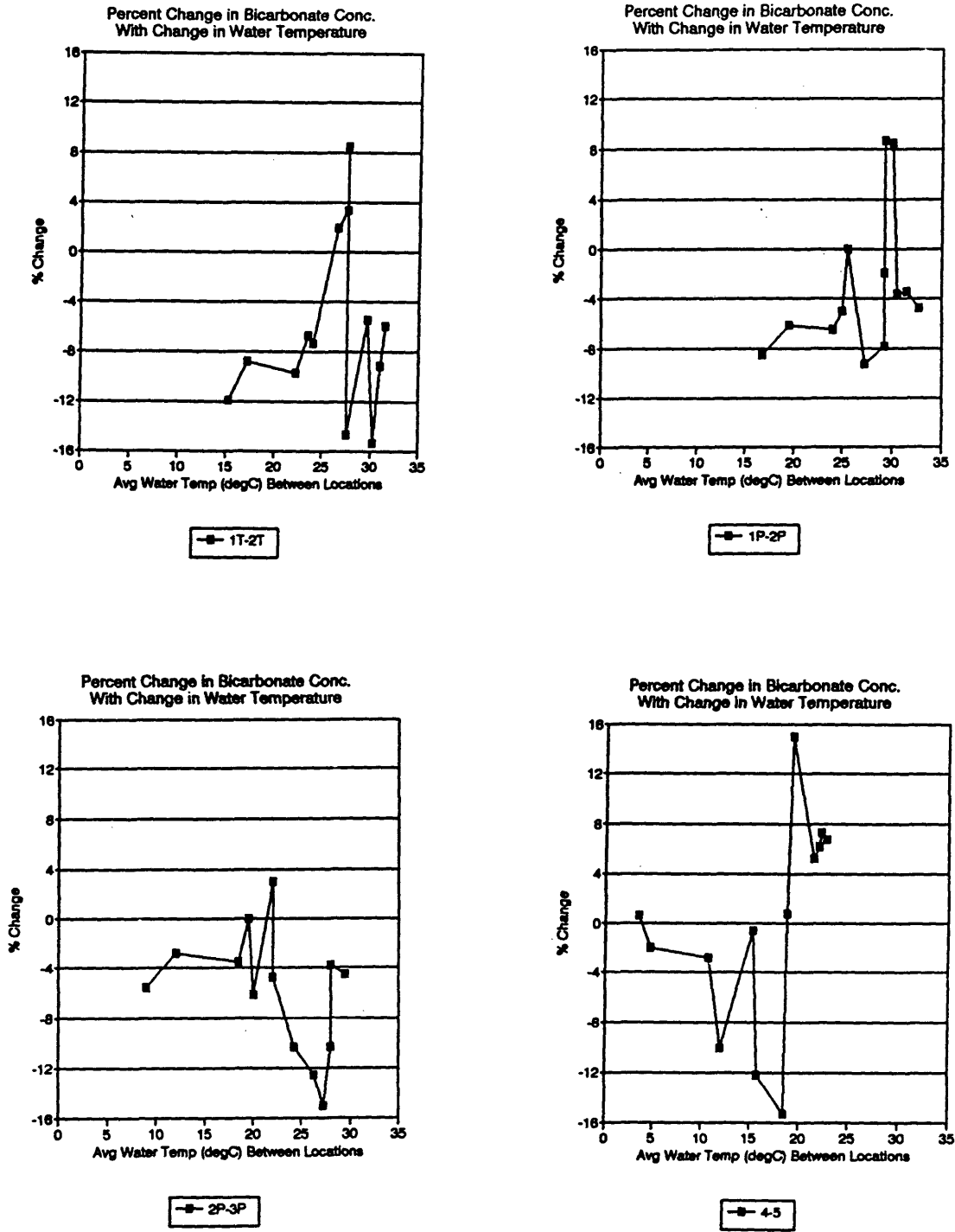


Figure B31 - % Change in Bicarbonate Conc. vs Water Temperature

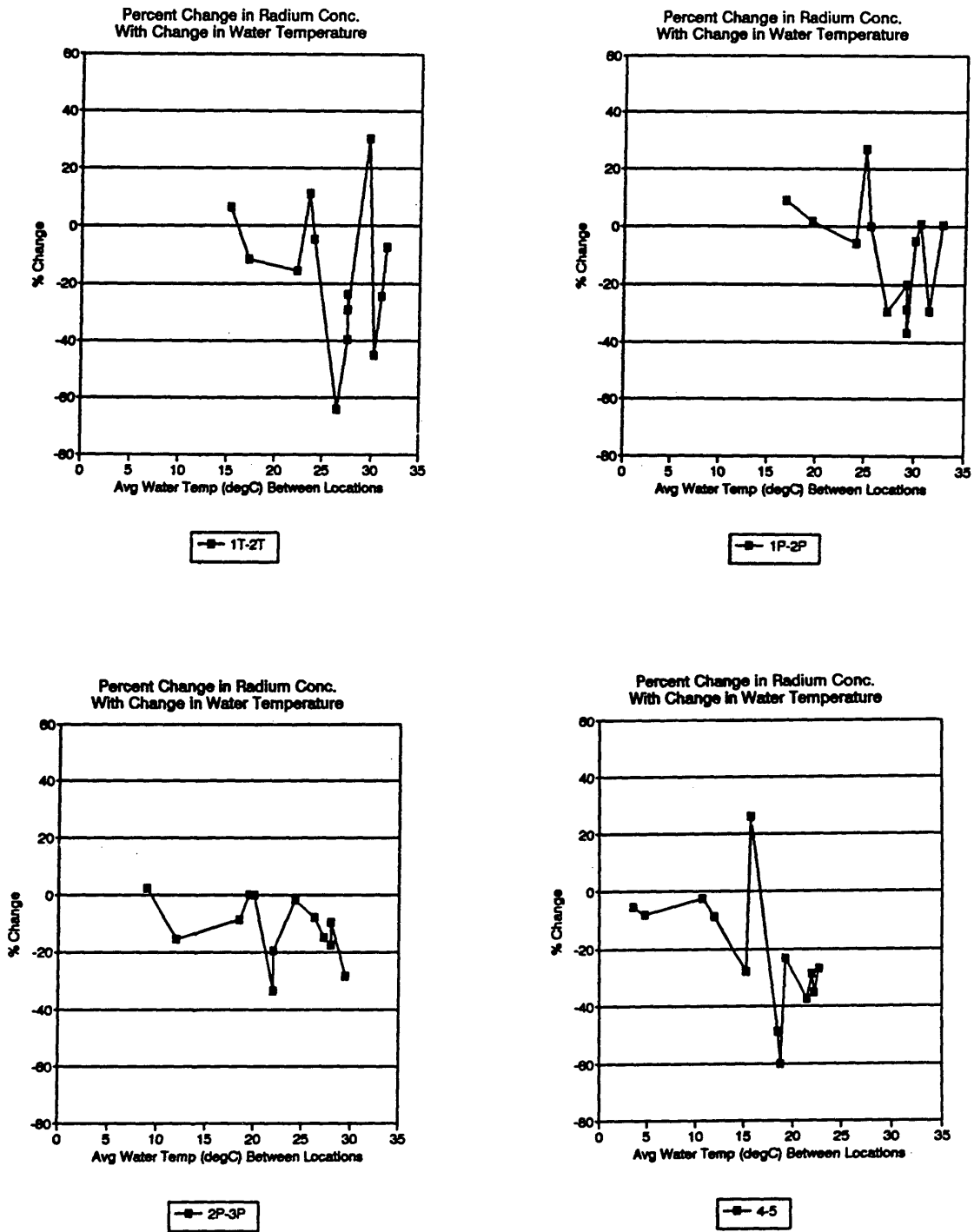


Figure B32 - % Change in Radium 226 Conc. vs Water Temperature

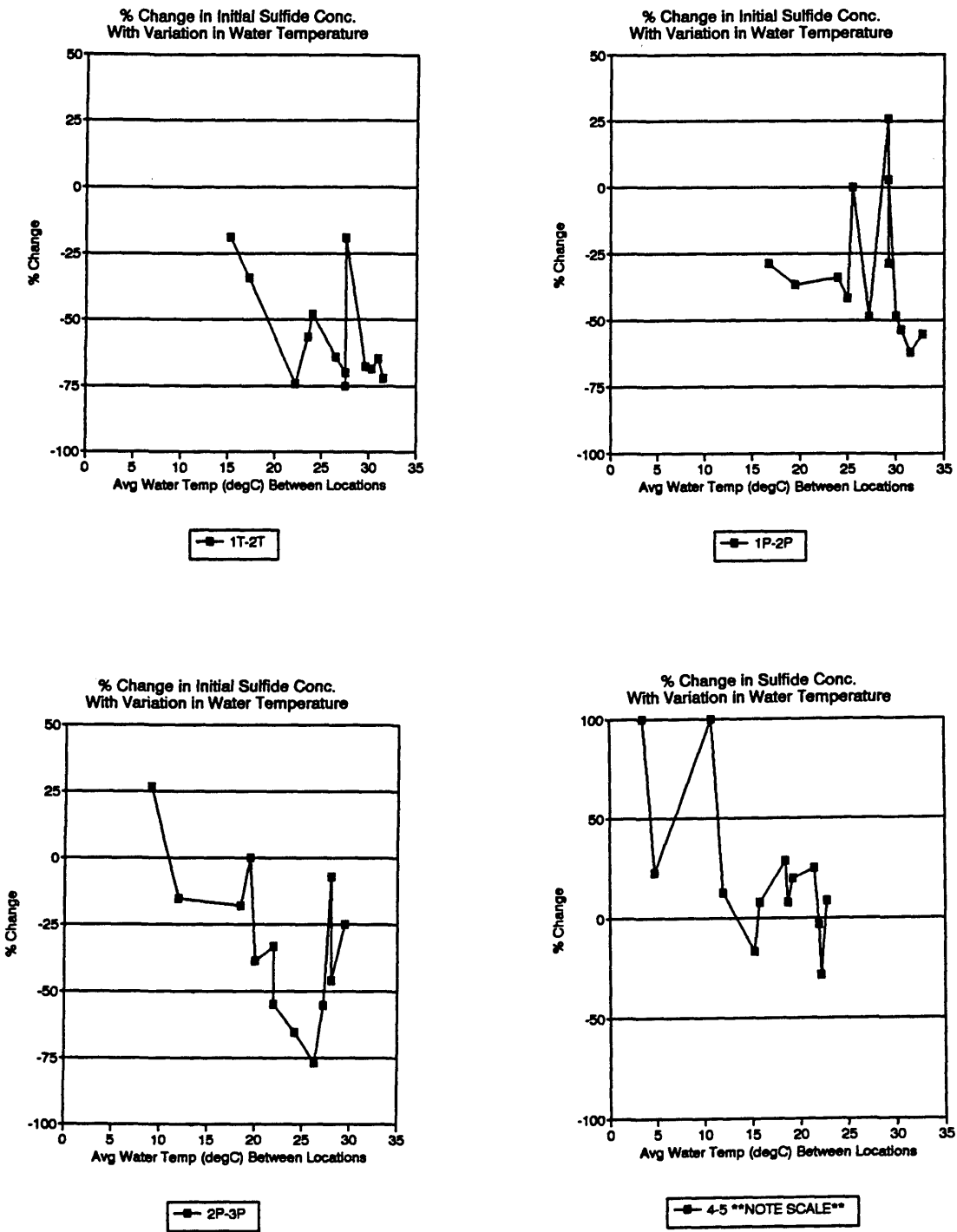


Figure B33 - % Change in Sulfide Conc. vs Water Temperature

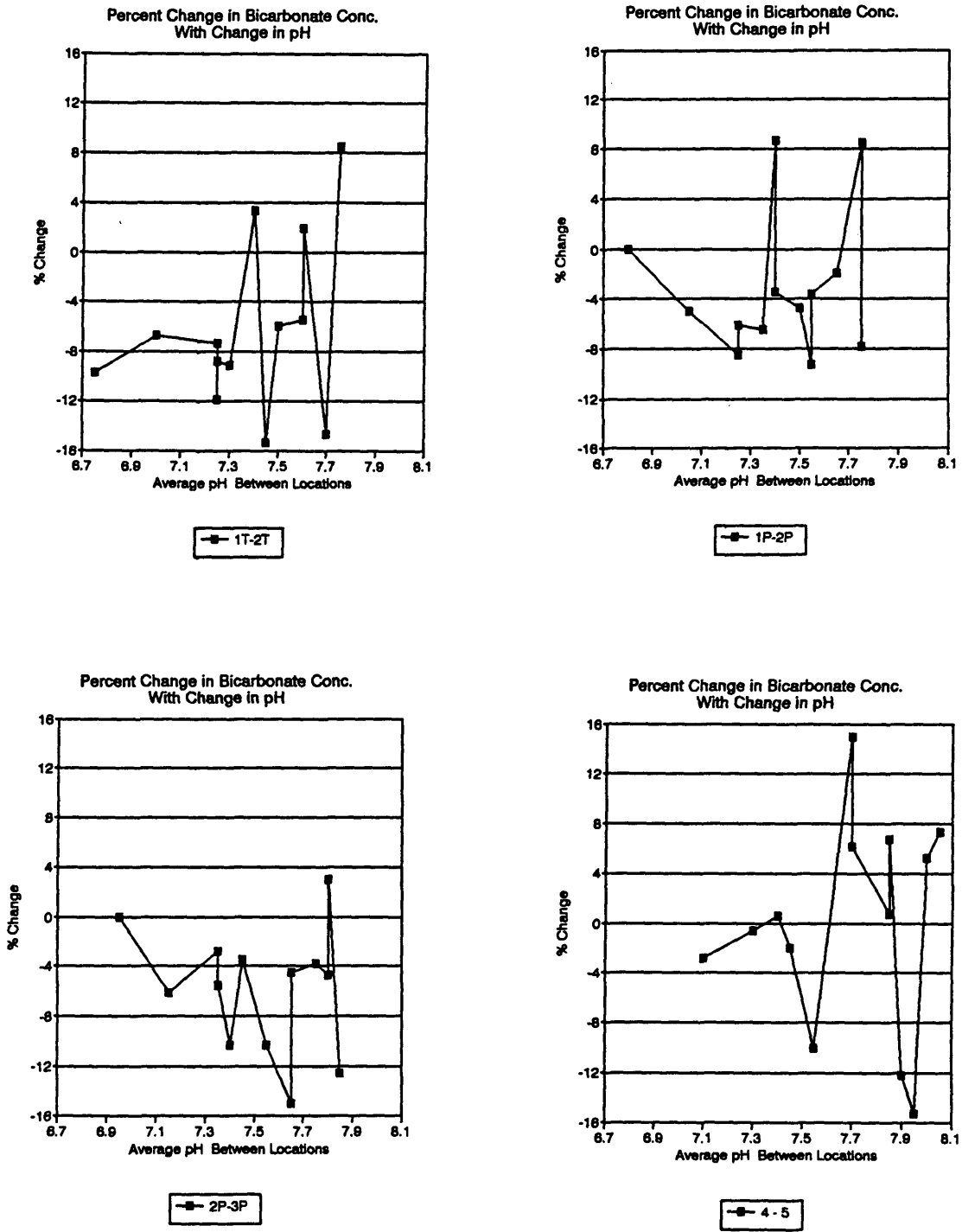


Figure B34 - % Change in Bicarbonate Conc. vs pH

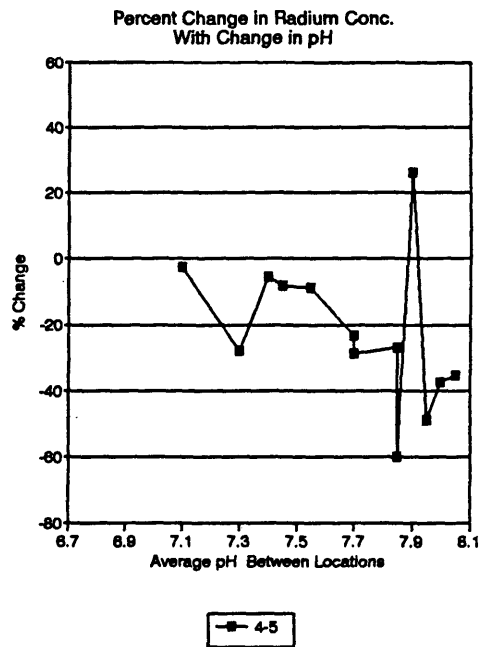
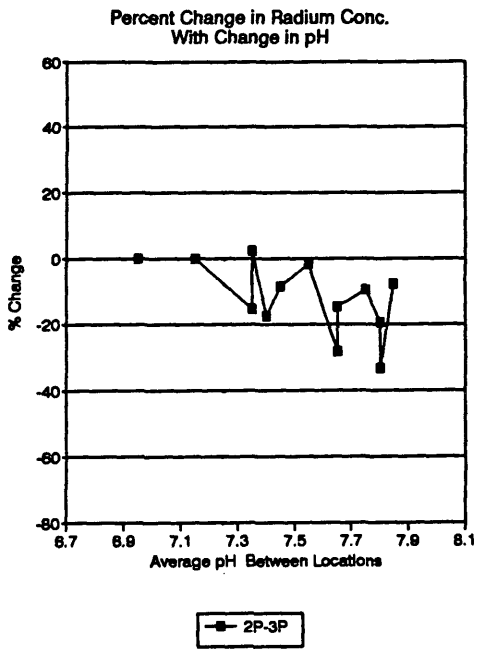
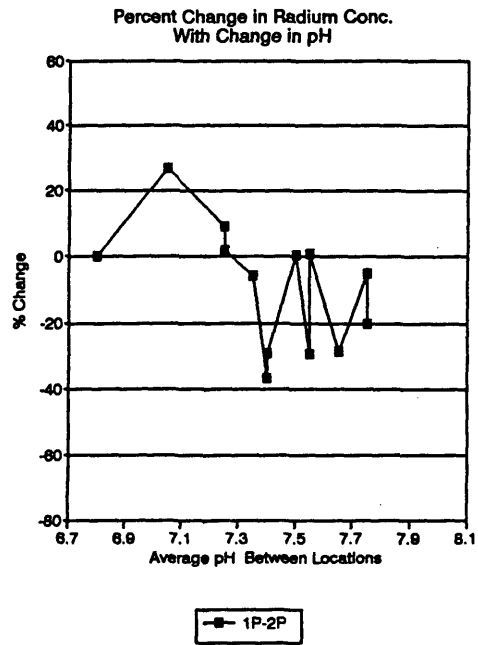
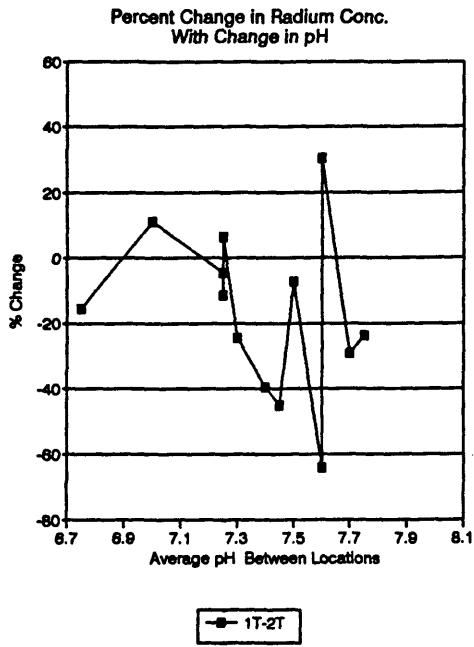


Figure B35 - % Change in Radium 226 Conc. vs pH

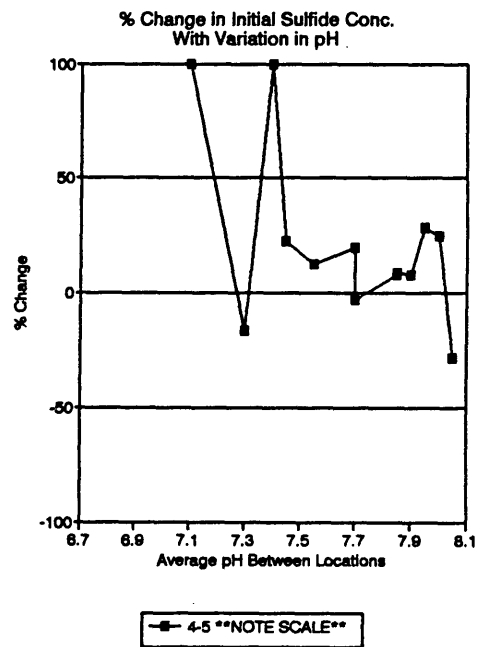
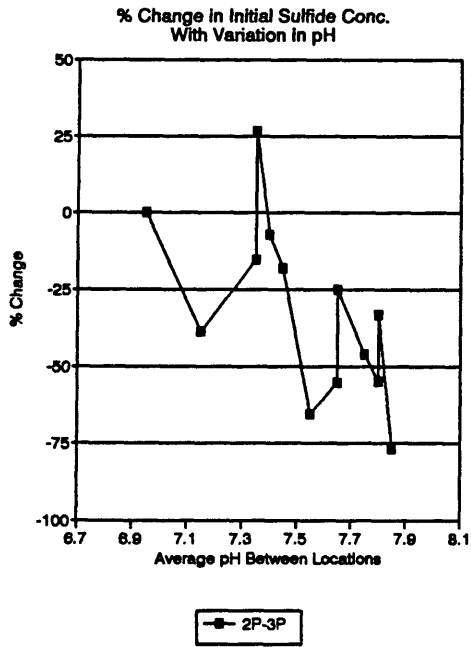
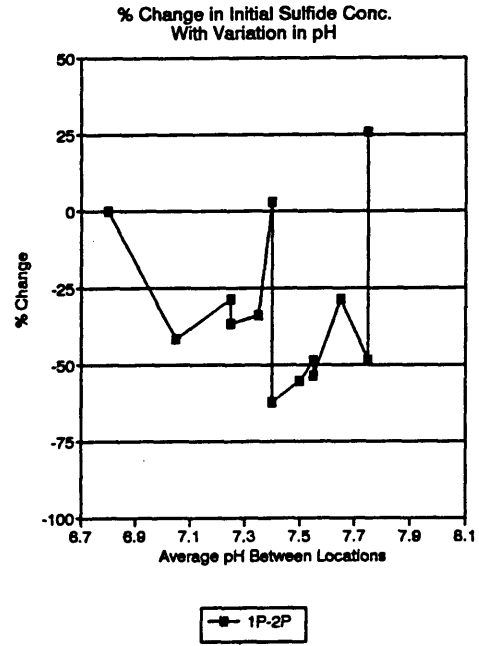
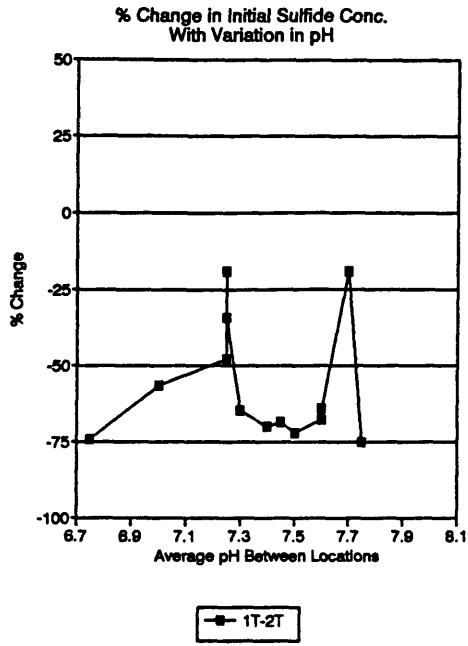


Figure B36 - % Change in Sulfide Conc. vs pH

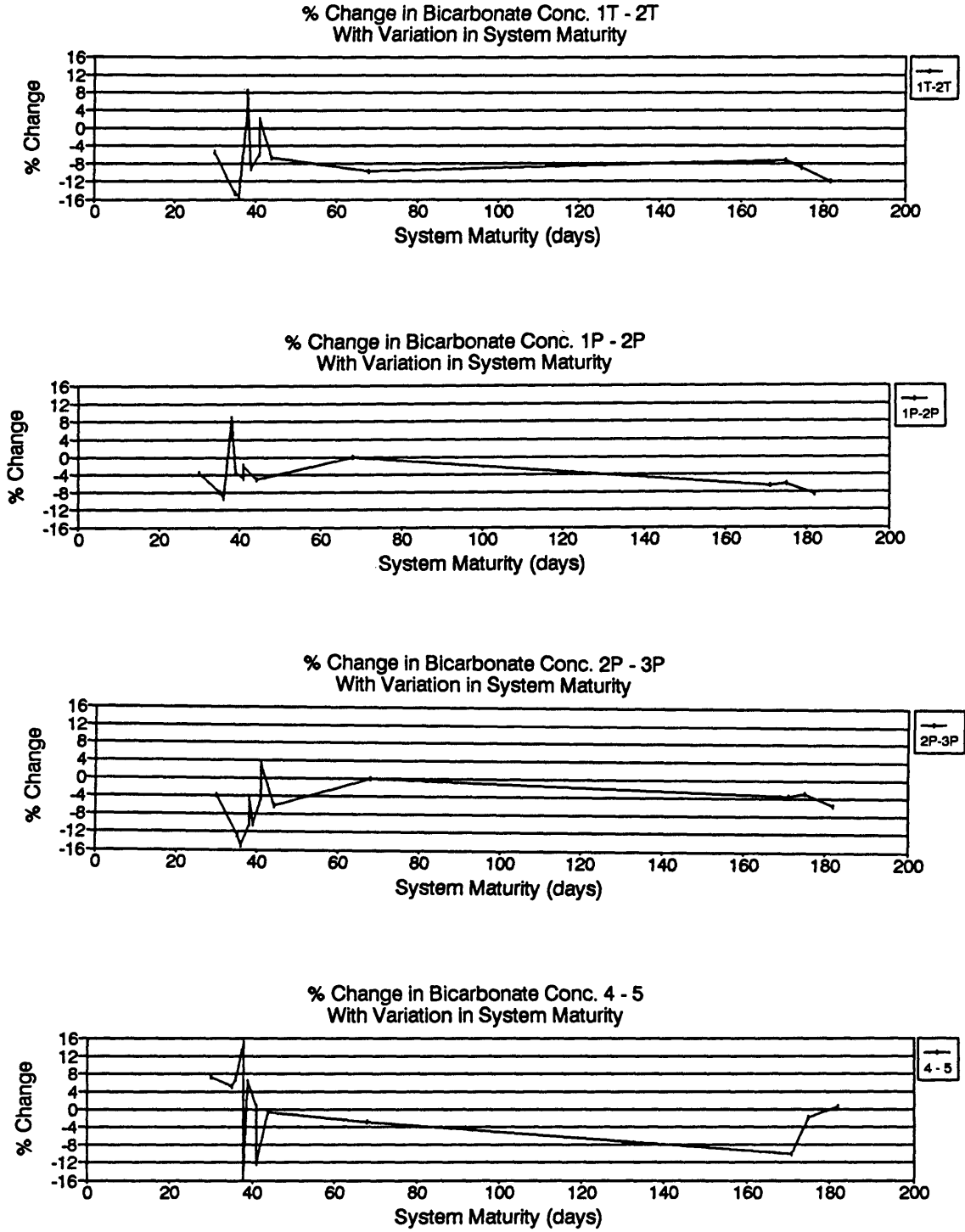


Figure B37 - % Change in Bicarbonate Conc. vs System Maturity

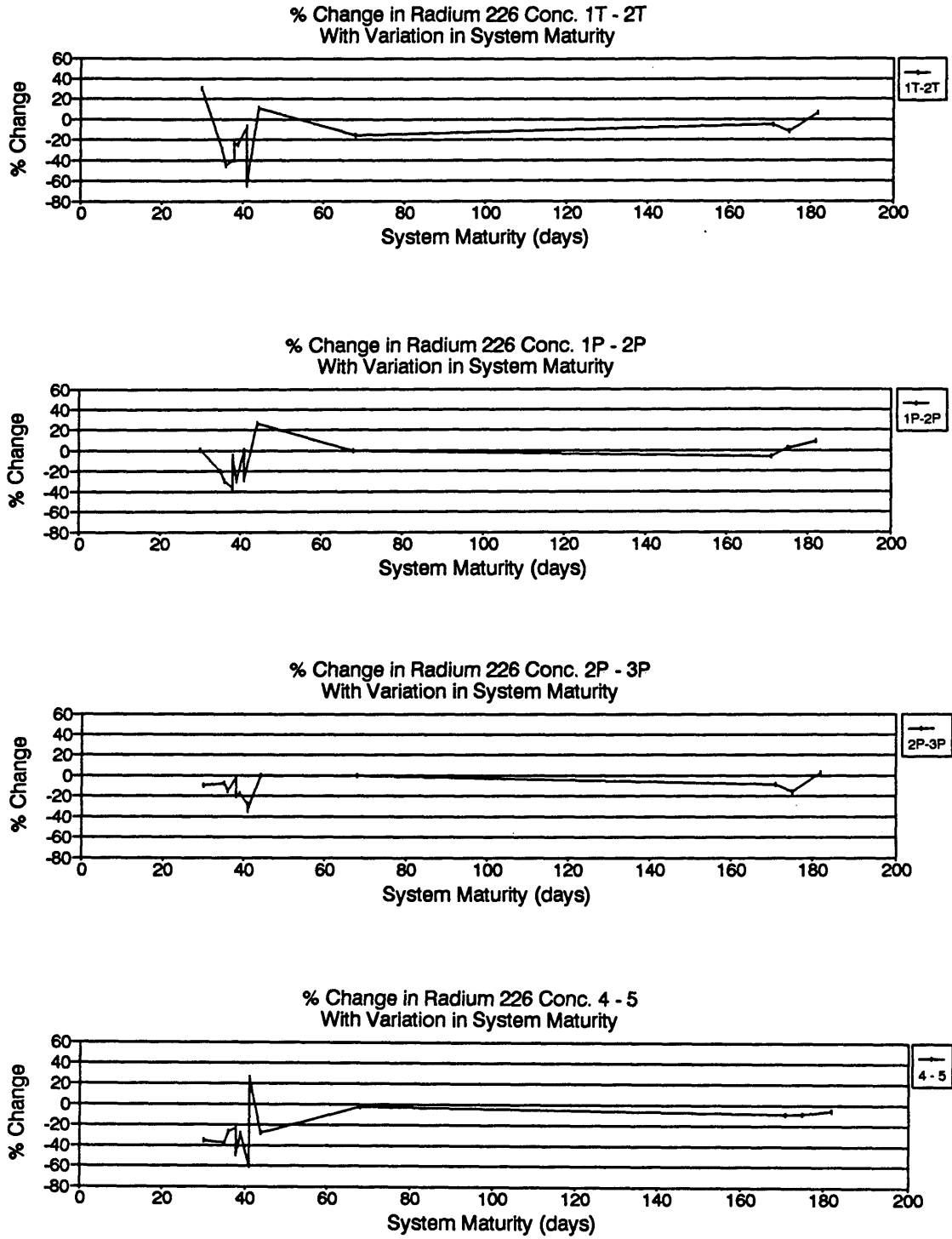


Figure B38 - % Change in Radium 226 Conc. vs System Maturity

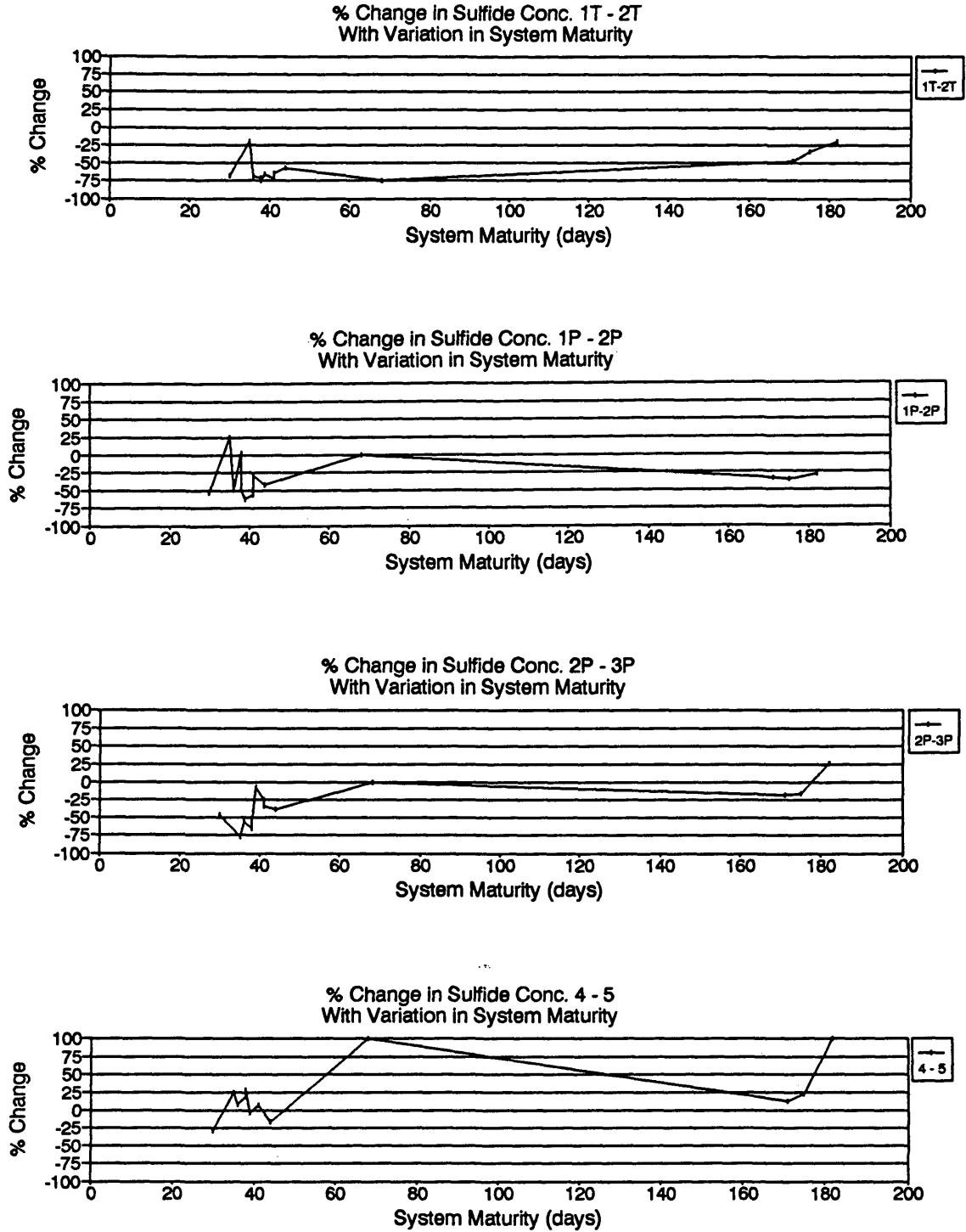


Figure B39 - % Change in Sulfide Conc. vs System Maturity

Table B18 - Legend for Wind and Solar Intensity Graphs

Date	Wind Intensity Estimation		Solar Intensity Estimation	
	Field Notes	Est. Wind Speed (MPH)	Relative Wind Speed	Field Notes
07/25/91	calm	1	2.5	clear
07/30/91	light wind	8	20	clear/sunny
07/31/91	5-8 MPH	8	20	clear/sunny
08/02/91	3-5 MPH	5	12.5	mostly cloudy
08/02/91	slight	2	5	dark (night)
08/03/91	2-3 MPH	3	7.5	clear
08/05/91	calm/occasional	2	5	partly cloudy
08/05/91	strong /storm	40	100	dark (night)
09/08/91	calm	1	2.5	overcast
11/02/91	mild breeze	3	7.5	clear/sunny
01/13/92	calm	1	2.5	dusk/clear
01/17/92	light wind	8	20	overcast
01/24/92	strong wind	30	75	partly cloudy
				Relative Solar Intensity
				90
				95
				100
				80
				0
				90
				85
				0
				75
				100
				70
				75
				85

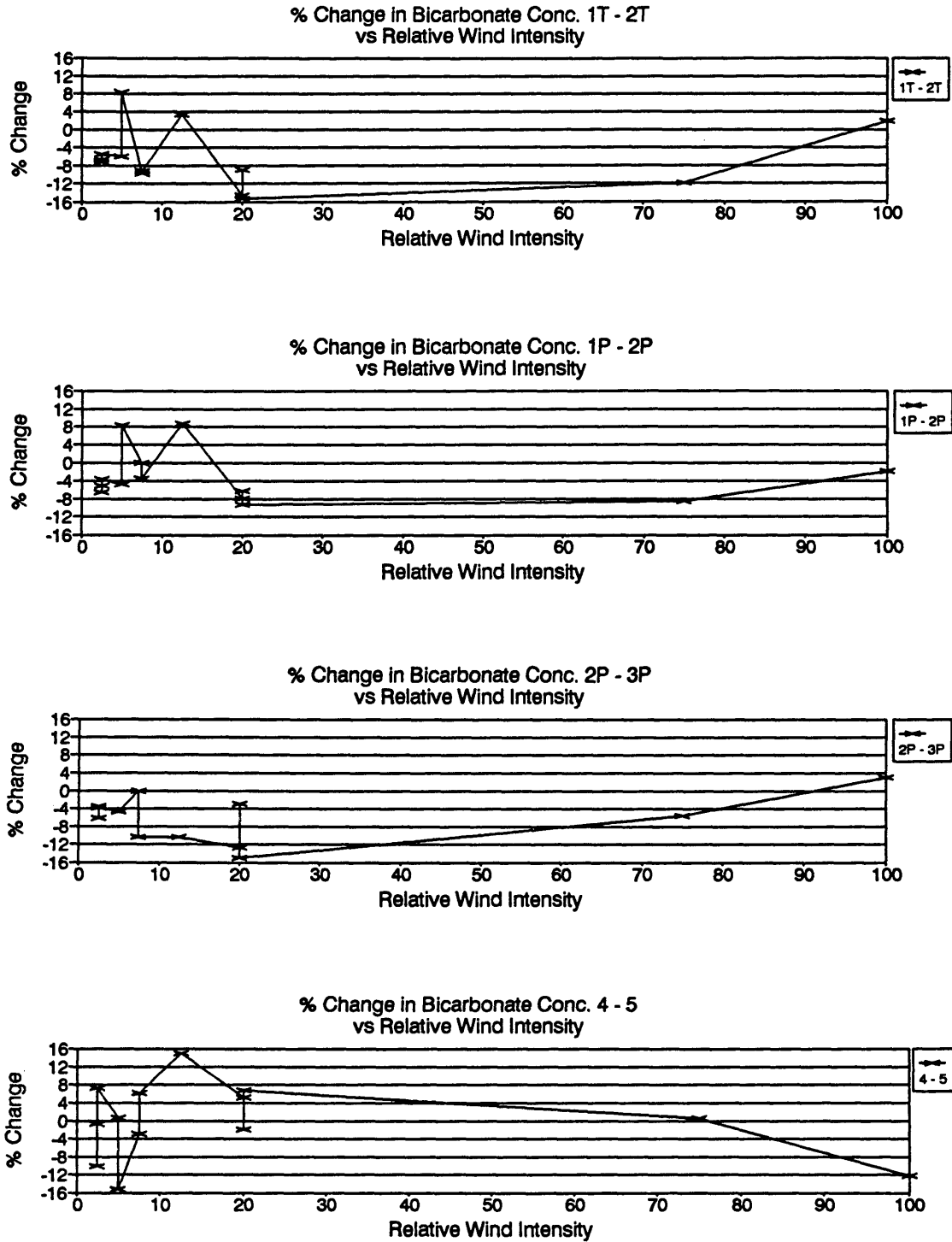


Figure B40 - % Change in Bicarbonate Conc. vs Relative Wind Intensity

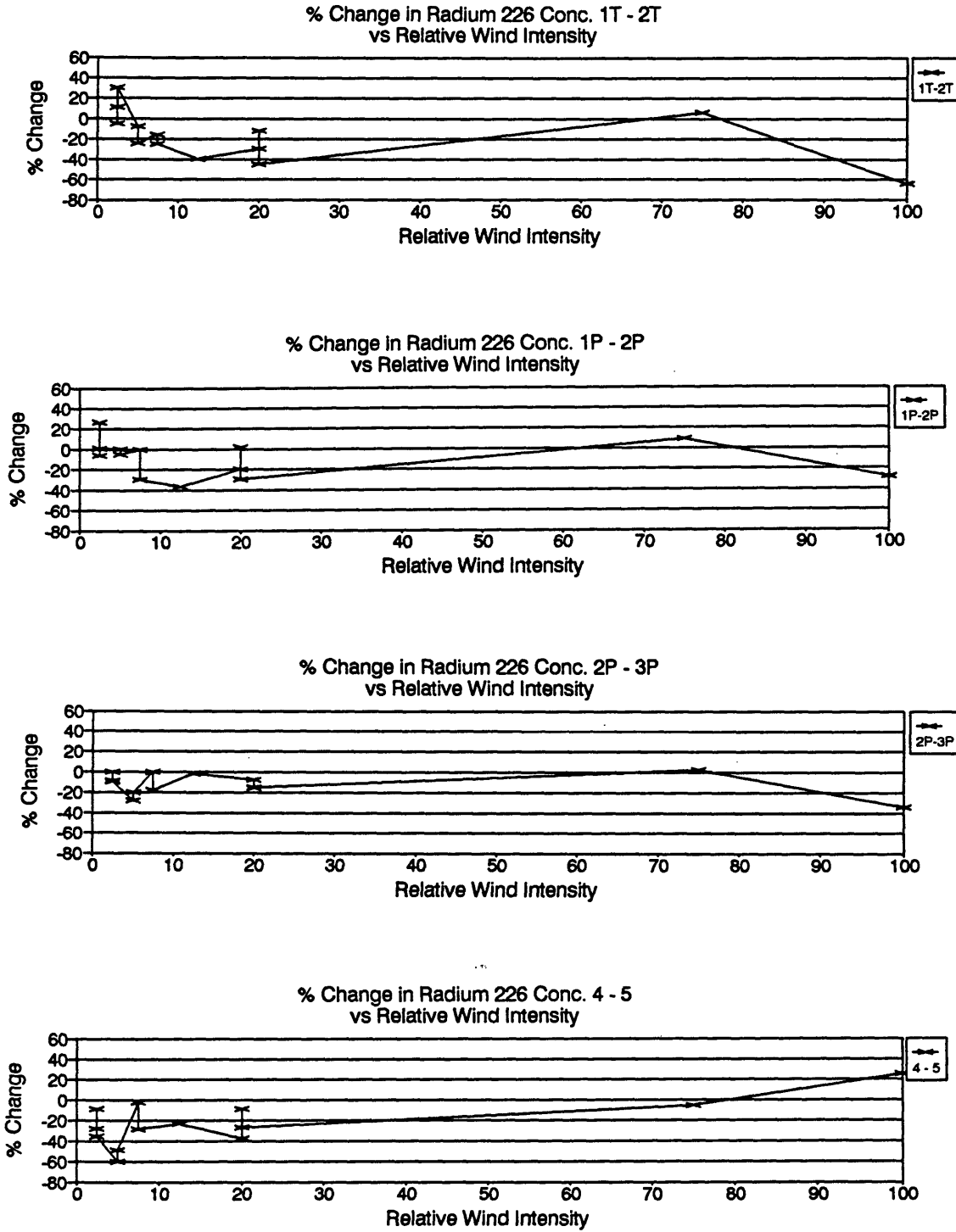


Figure B41 - % Change in Radium 226 Conc. vs Relative Wind Intensity

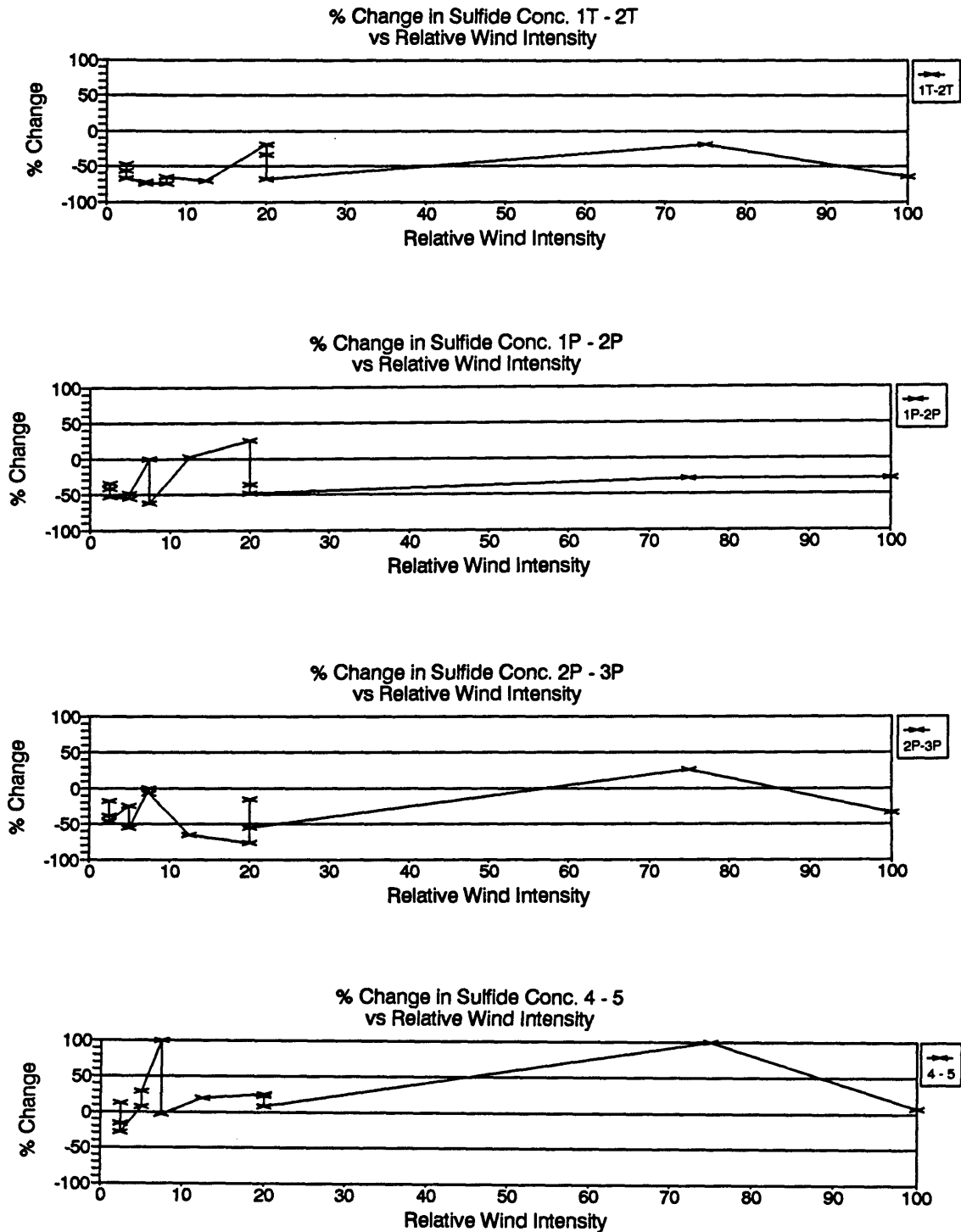


Figure B42 - % Change in Sulfide Conc. vs Relative Wind Intensity

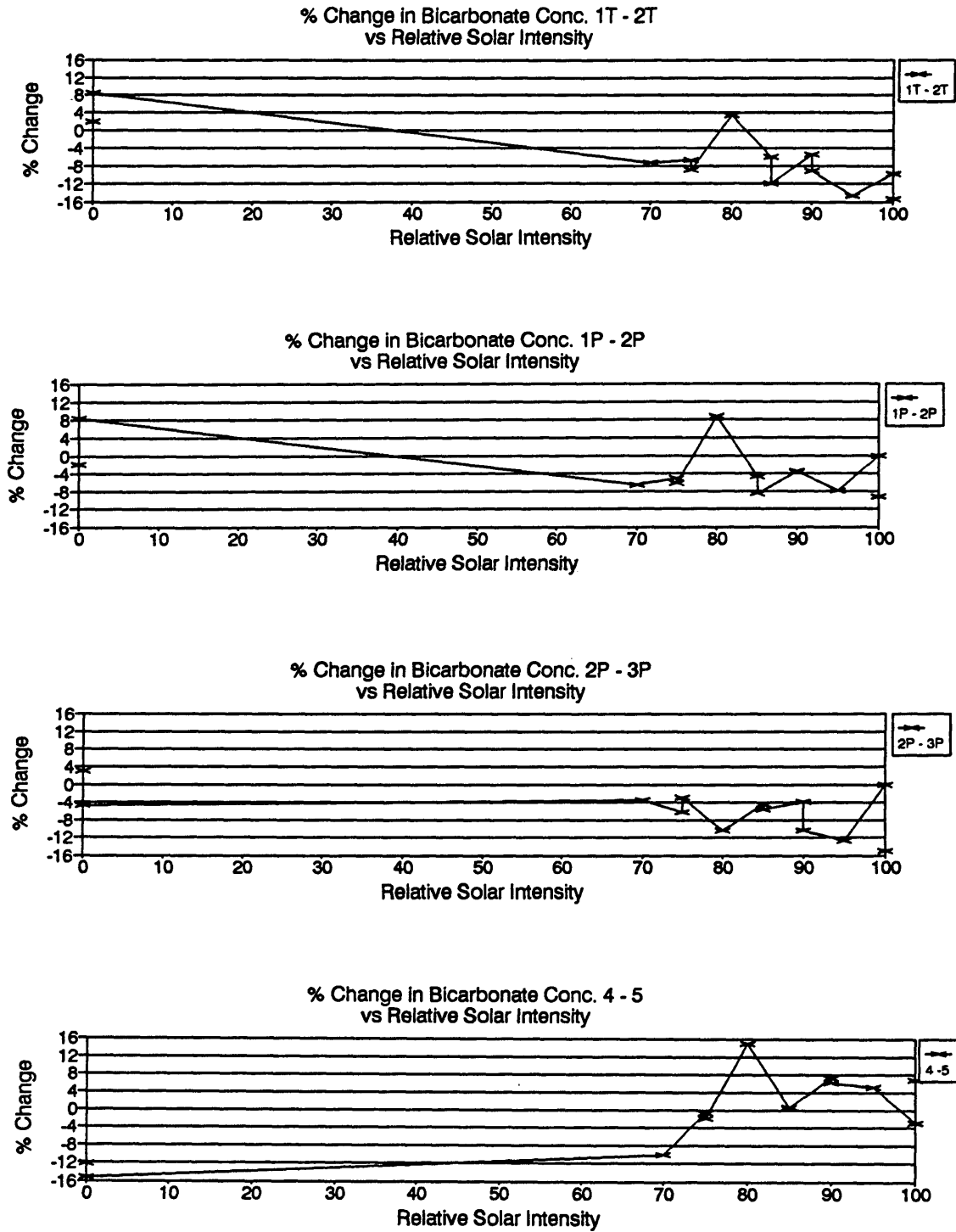


Figure B43 - % Change in Bicarbonate Conc. vs Relative Solar Intensity

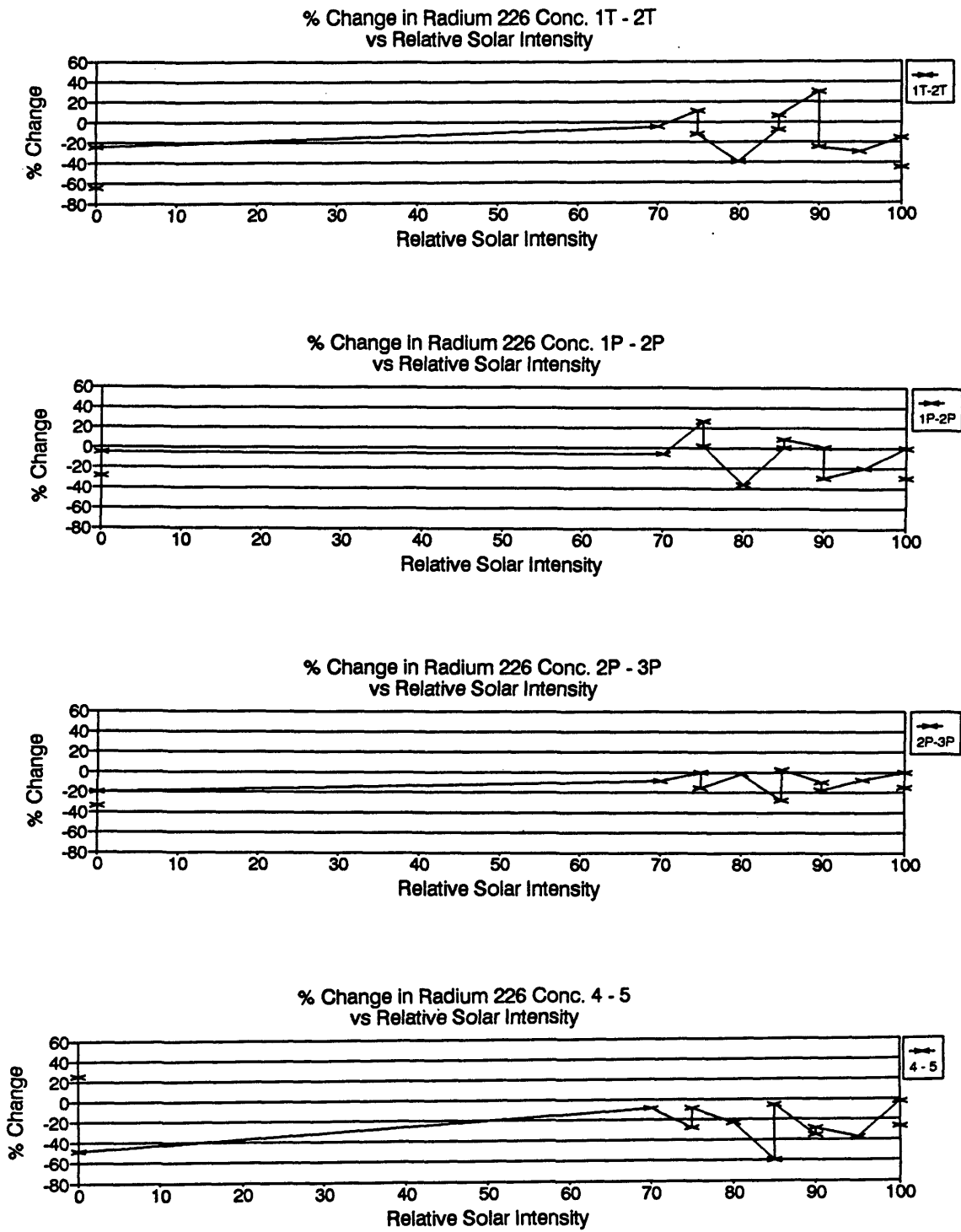


Figure B44 - % Change in Radium 226 Conc. vs Relative Solar Intensity

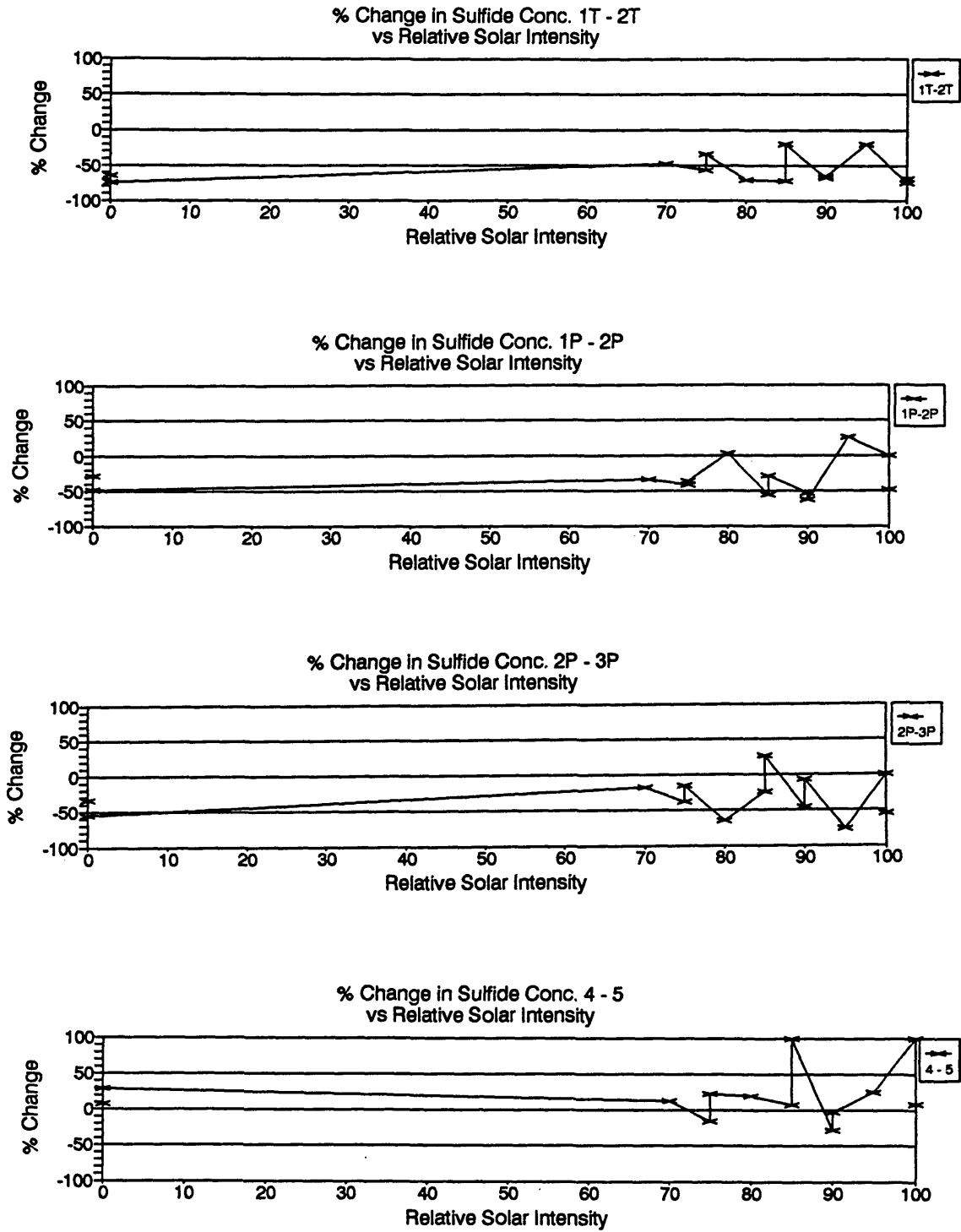


Figure B45 - % Change in Sulfide Conc. vs Relative Solar Intensity

Table B19 - Mass Removal of Potassium, Sodium and Chloride

Constituent: Potassium (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	-1.9	-2.4	-6.2	-1.4	0.0
07/30/91	1000	48 hr	26.0	-1.7	1.9	-0.6	1.4	-3.8
07/31/91	1000	72 hr	26.5	-1.0	-1.0	-0.2	-1.0	-2.9
08/02/91	2000	48 hr	17.5	7.9	2.2	11.8	3.2	0.0
08/02/91	2000	60 hr eve	14.0	1.3	-0.3	-2.2	10.2	15.3
08/03/91	2000	72 hr	16.0	-1.9	3.2	3.2	-6.3	22.9
08/05/91	4000	48 hr	23.0	9.5	-6.5	21.0	-22.3	-59.8
08/05/91	4000	60 hr eve	16.0	5.1	-3.2	10.8	-12.1	-53.4
09/08/91	2000	30 day	14.0	-2.2	-2.5	0.6	-3.8	2.5
11/02/91	3000	56 day	-10.0	1.9	0.0	NT	NT	-1.0
01/13/92	4000	71 d dusk	-4.0	1.9	-3.2	-10.8	5.7	19.1
01/17/92	2000	72 hr	-5.0	-5.1	2.5	1.0	-7.3	5.1
01/24/92	1000	120 hr	5.0	0.0	-0.6	-2.4	3.7	-6.7

Constituent: Sodium (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	-3.8	-0.5	-4.8	0.0	1.0
07/30/91	1000	48 hr	26.0	-3.3	0.5	-1.3	0.2	-5.7
07/31/91	1000	72 hr	26.5	-1.6	-1.1	-0.3	-1.9	-3.5
08/02/91	2000	48 hr	17.5	9.5	1.6	6.4	5.7	0.0
08/02/91	2000	60 hr eve	14.0	1.9	-4.1	-0.3	2.5	7.0
08/03/91	2000	72 hr	16.0	-2.9	0.3	3.8	-7.8	14.0
08/05/91	4000	48 hr	23.0	3.2	-5.7	10.2	-14.6	-61.1
08/05/91	4000	60 hr eve	16.0	-2.5	-1.3	2.5	-6.4	-61.1
09/08/91	2000	30 day	14.0	-1.9	-2.5	-1.6	-1.3	0.0
11/02/91	3000	56 day	-10.0	2.4	-0.5	NT	NT	8.6
01/13/92	4000	71 d dusk	-4.0	0.6	-5.1	-11.4	3.8	20.4
01/17/92	2000	72 hr	-5.0	-6.0	1.9	-2.9	-0.3	3.2
01/24/92	1000	120 hr	5.0	-1.1	-0.3	-2.1	1.4	-4.5

Constituent: Chloride (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	-0.5	0.0	1.0	-3.8	10.5
07/30/91	1000	48 hr	26.0	-2.2	0.5	-1.0	-0.8	-2.9
07/31/91	1000	72 hr	26.5	-1.6	1.1	-1.6	-0.5	-4.5
08/02/91	2000	48 hr	17.5	2.5	-0.6	1.9	4.5	1.9
08/02/91	2000	60 hr eve	14.0	0.6	1.3	-1.0	1.6	-6.9
08/03/91	2000	72 hr	16.0	-1.0	0.3	0.0	-7.6	-0.6
08/05/91	4000	48 hr	23.0	3.2	-8.9	1.9	-4.5	-21.6
08/05/91	4000	60 hr eve	16.0	-6.9	0.0	-6.4	0.6	-15.3
09/08/91	2000	30 day	14.0	-1.3	-5.1	0.0	-7.0	-3.8
11/02/91	3000	56 day	-10.0	1.9	-1.9	NT	NT	12.4
01/13/92	4000	71 d dusk	-4.0	-1.3	3.8	-0.6	-1.9	3.8
01/17/92	2000	72 hr	-5.0	-2.2	-1.0	-3.2	1.3	1.9
01/24/92	1000	120 hr	5.0	-1.1	0.3	-1.7	1.3	-2.2

NT = no test, kg/day = 2.2 lb/day,

Table B20 - Mass Removal of Calcium, Bicarbonate and Radium 226

Constituent: Calcium (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	9.5	6.2	11.4	6.7	-7.6
07/30/91	1000	48 hr	26.0	7.8	1.4	5.4	4.6	-0.3
07/31/91	1000	72 hr	26.5	7.2	2.7	4.9	6.4	-3.2
08/02/91	2000	48 hr	17.5	-9.9	1.8	-15.6	11.1	-17.6
08/02/91	2000	60 hr eve	14.0	-0.3	-3.5	-1.6	4.1	22.3
08/03/91	2000	72 hr	16.0	9.5	1.9	6.9	6.7	-18.4
08/05/91	4000	48 hr	23.0	14.0	4.5	7.8	12.7	12.7
08/05/91	4000	60 hr eve	16.0	8.3	-7.0	11.4	1.3	40.7
09/08/91	2000	30 day	14.0	7.6	1.6	1.6	6.7	9.5
11/02/91	3000	56 day	-10.0	9.1	-1.0	NT	NT	17.2
01/13/92	4000	71 d dusk	-4.0	10.2	13.4	22.3	-1.9	31.8
01/17/92	2000	72 hr	-5.0	13.4	-1.9	6.7	2.9	2.5
01/24/92	1000	120 hr	5.0	4.8	2.1	3.5	1.9	0.6

Constituent: Bicarbonate (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	26.8	9.5	19.1	19.1	-89.6
07/30/91	1000	48 hr	26.0	24.5	6.7	13.0	19.4	-14.0
07/31/91	1000	72 hr	26.5	25.6	10.3	15.4	22.7	-17.2
08/02/91	2000	48 hr	17.5	-9.9	12.7	-25.8	33.1	-84.6
08/02/91	2000	60 hr eve	14.0	-26.4	3.2	-26.4	15.9	99.2
08/03/91	2000	72 hr	16.0	29.9	3.5	11.1	32.8	-35.0
08/05/91	4000	48 hr	23.0	40.1	24.2	31.8	28.6	-8.9
08/05/91	4000	60 hr eve	16.0	-12.7	-25.4	12.7	-19.1	162.8
09/08/91	2000	30 day	14.0	25.4	25.4	19.1	22.3	3.8
11/02/91	3000	56 day	-10.0	57.2	23.8	NT	NT	28.6
01/13/92	4000	71 d dusk	-4.0	57.2	36.2	50.9	25.4	141.2
01/17/92	2000	72 hr	-5.0	31.8	6.4	22.3	9.5	12.7
01/24/92	1000	120 hr	5.0	22.3	9.1	15.9	9.5	-1.9

Constituent: Radium 226 (uCi/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	-4.1	5.5	-0.1	1.3	9.8
07/30/91	1000	48 hr	26.0	1.3	-0.2	0.9	0.3	1.8
07/31/91	1000	72 hr	26.5	2.4	-0.3	1.6	0.6	1.4
08/02/91	2000	48 hr	17.5	5.3	0.0	4.9	0.1	3.1
08/02/91	2000	60 hr eve	14.0	2.3	-0.0	0.5	1.8	8.5
08/03/91	2000	72 hr	16.0	2.8	0.3	3.3	1.4	3.9
08/05/91	4000	48 hr	23.0	1.8	2.2	-0.1	6.1	23.7
08/05/91	4000	60 hr eve	16.0	13.7	-6.1	6.1	5.1	-3.4
09/08/91	2000	30 day	14.0	-0.7	0.0	-1.7	0.0	4.6
11/02/91	3000	56 day	-10.0	1.9	-2.9	NT	NT	0.7
01/13/92	4000	71 d dusk	-4.0	1.2	1.1	1.5	2.0	4.1
01/17/92	2000	72 hr	-5.0	0.9	-2.1	-0.2	1.3	1.3
01/24/92	1000	120 hr	5.0	-0.3	0.4	-0.4	-0.1	0.4

*NT = no test, kg/day = 2.2 lb/day, uCi/day = 1,000,000 pCi/day

Table B21 - Mass Removal of Sulfide and Sulfate

Constituent: Sulfide (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	7.3	0.0	5.7	4.9	6.1
07/30/91	1000	48 hr	26.0	0.8	1.4	-1.0	3.0	-2.0
07/31/91	1000	72 hr	26.5	3.1	-0.8	2.2	2.5	-0.7
08/02/91	2000	48 hr	17.5	6.6	0.0	-0.3	6.2	-3.8
08/02/91	2000	60 hr eve	14.0	11.4	-5.1	7.4	8.4	-8.7
08/03/91	2000	72 hr	16.0	6.1	-3.6	5.9	0.7	0.6
08/05/91	4000	48 hr	23.0	19.8	3.7	15.3	6.9	-4.2
08/05/91	4000	60 hr eve	16.0	13.7	-17.1	6.1	7.1	-3.3
09/08/91	2000	30 day	14.0	7.6	2.3	5.6	5.2	4.5
11/02/91	3000	56 day	-10.0	9.9	1.5	NT	NT	-26.7
01/13/92	4000	71 d dusk	-4.0	12.2	0.0	6.6	4.6	-6.4
01/17/92	2000	72 hr	-5.0	3.6	1.9	3.8	1.6	-4.7
01/24/92	1000	120 hr	5.0	0.5	0.5	0.8	-0.7	-5.3

Constituent: Sulfate (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T-2T	2T-3T	1P-2P	2P-3P	4 - 5
07/25/91	3000	30 day	18.3	-1.4	1.4	8.1	-18.9	74.2
07/30/91	1000	48 hr	26.0	-7.5	-0.6	-2.5	-4.1	-11.8
07/31/91	1000	72 hr	26.5	-14.0	8.1	-11.4	-1.5	-23.1
08/02/91	2000	48 hr	17.5	-7.9	-2.5	-14.9	22.7	17.4
08/02/91	2000	60 hr eve	14.0	2.9	6.7	-5.4	10.9	-76.5
08/03/91	2000	72 hr	16.0	-2.5	-4.4	2.9	-30.8	18.5
08/05/91	4000	48 hr	23.0	25.4	-49.1	26.7	-31.9	-136.9
08/05/91	4000	60 hr eve	16.0	-14.0	3.1	-13.4	14.3	-252.4
09/08/91	2000	30 day	14.0	-17.2	-14.1	0.6	-31.6	-6.2
11/02/91	3000	56 day	-10.0	-26.7	-8.9	NT	NT	61.0
01/13/92	4000	71 d dusk	-4.0	-15.3	6.7	-22.3	-7.9	-8.5
01/17/92	2000	72 hr	-5.0	-7.8	-5.3	-10.5	1.2	8.0
01/24/92	1000	120 hr	5.0	-16.1	0.6	-13.2	-1.3	7.2

NT* = no test, kg/day = 2.2 lb/day

Table B22 - Mass Removal of Benzene, Toluene and Ethylbenzene

Constituent: Benzene (g/day)				Sample Location		
Date	Flow BPD	Duration	Amb T (C)	1T-2T	1P-2P	4 - 5
07/25/91	3000	30 day	18.3	8.6	NT	0.9
07/30/91	1000	48 hr	26.0	2.7	1.9	NT
07/31/91	1000	72 hr	26.5	2.7	1.9	NT
08/02/91	2000	48 hr	17.5	7.4	5.4	NT
08/02/91	2000	60 hr eve	14.0	8.1	6.3	NT
08/03/91	2000	72 hr	16.0	8.6	6.6	NT
08/05/91	4000	48 hr	23.0	16.3	9.5	NT
08/05/91	4000	60 hr eve	16.0	14.8	7.6	NT
08/08/91	2000	30 day	14.0	17.7	11.4	NT
11/02/91	3000	56 day	-10.0	18.6	NT	NT
01/13/92	4000	71 d dusk	-4.0	11.3	7.6	NT
01/17/92	2000	72 hr	-5.0	5.8	4.3	NT
01/24/92	1000	120 hr	5.0	3.9	2.5	NT

Constituent: Toluene (g/day)				Sample Location		
Date	Flow BPD	Duration	Amb T (C)	1T-2T	1P-2P	4 - 5
07/25/91	3000	30 day	18.3	15.4	NT	1.1
07/30/91	1000	48 hr	26.0	4.3	3.3	NT
07/31/91	1000	72 hr	26.5	4.3	3.4	NT
08/02/91	2000	48 hr	17.5	13.6	11.0	NT
08/02/91	2000	60 hr eve	14.0	13.4	10.5	NT
08/03/91	2000	72 hr	16.0	15.0	12.1	NT
08/05/91	4000	48 hr	23.0	29.3	19.1	NT
08/05/91	4000	60 hr eve	16.0	26.1	15.9	NT
08/08/91	2000	30 day	14.0	30.9	21.0	NT
11/02/91	3000	56 day	-10.0	31.5	NT	NT
01/13/92	4000	71 d dusk	-4.0	18.1	12.1	NT
01/17/92	2000	72 hr	-5.0	10.7	9.1	NT
01/24/92	1000	120 hr	5.0	5.4	4.5	NT

Constituent: Ethylbenzene (g/day)				Sample Location		
Date	Flow BPD	Duration	Amb T (C)	1T-2T	1P-2P	4 - 5
07/25/91	3000	30 day	18.3	5.2	NT	0.6
07/30/91	1000	48 hr	26.0	1.8	1.0	NT
07/31/91	1000	72 hr	26.5	1.8	1.1	NT
08/02/91	2000	48 hr	17.5	4.8	3.6	NT
08/02/91	2000	60 hr eve	14.0	5.3	3.9	NT
08/03/91	2000	72 hr	16.0	5.1	3.7	NT
08/05/91	4000	48 hr	23.0	9.0	5.3	NT
08/05/91	4000	60 hr eve	16.0	8.1	4.5	NT
08/08/91	2000	30 day	14.0	12.0	8.6	NT
11/02/91	3000	56 day	-10.0	10.7	NT	NT
01/13/92	4000	71 d dusk	-4.0	7.3	5.2	NT
01/17/92	2000	72 hr	-5.0	3.2	2.6	NT
01/17/92	2000	72 hr	5.0	4.1	3.1	NT

NT^a = no test

Table B23 - Mass Removal of Xylenes and Total Phenolics

Constituent: Xylenes (g/day)				Sample Location		
Date	Flow BPD	Duration	Amb T (C)	1T - 2T	1P - 2P	4 - 5
07/25/91	3000	30 day	18.3	11.1	NT	1.0
07/30/91	1000	48 hr	26.0	3.3	2.1	NT
07/31/91	1000	72 hr	26.5	3.3	2.3	NT
08/02/91	2000	48 hr	17.5	9.7	7.3	NT
08/02/91	2000	60 hr eve	14.0	10.8	8.0	NT
08/03/91	2000	72 hr	16.0	8.9	5.7	NT
08/05/91	4000	48 hr	23.0	21.0	12.1	NT
08/05/91	4000	60 hr eve	16.0	19.0	10.2	NT
08/08/91	2000	30 day	14.0	21.7	14.0	NT
11/02/91	3000	56 day	-10.0	21.5	NT	NT
01/13/92	4000	71 d dusk	-4.0	15.0	9.5	NT
01/17/92	2000	72 hr	-5.0	7.3	5.9	NT
01/24/92	1000	120 hr	5.0	3.7	3.1	NT

Constituent: Total Phenolics (g/day)				Sample Location		
Date	Flow BPD	Duration	Amb T (C)	1T - 2T	1P - 2P	4 - 5
07/25/91	3000	30 day	18.3	9.5	NT	0.0
07/30/91	1000	48 hr	26.0	NT	NT	6.4 *
07/31/91	1000	72 hr	26.5	NT	NT	12.7 *
08/02/91	2000	48 hr	17.5	NT	NT	-18.1 *
08/02/91	2000	60 hr eve	14.0	NT	NT	25.4 *
08/03/91	2000	72 hr	16.0	NT	NT	6.4 *
08/08/91	2000	30 day	14.0	0.0	-6.4	6.4
11/02/91	3000	56 day	-10.0	4.8	NT	47.7
01/13/92	4000	71 d dusk	-4.0	NT	NT	12.7 *
01/17/92	2000	72 hr	-5.0	NT	NT	0.0
01/24/92	1000	120 hr	5.0	NT	NT	0.0

NT* = no test, *** data in this row is based on estimated inflow concentration

Table B24 - Mass Removal of TDS, Magnesium and Alkalinity

Constituent: Total Dissolved Solids @ 180 deg C (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T - 2T	2T - 3T	1P - 2P	2P - 3P	4 - 5
07/25/91	3000	30 day	18.3	0.0	0.0	-4.8	14.3	-38.2
07/30/91	1000	48 hr	26.0	NT	4.8	8.0	8.0	-44.5
07/31/91	1000	72 hr	26.5	NT	1.8	6.4	9.5	-117.7
08/02/91	2000	48 hr	17.5	-31.8	3.2	-35.0	-70.0	-50.9
08/02/91	2000	60 hr eve	14.0	-12.7	-6.4	-12.7	12.7	-12.7
08/03/91	2000	72 hr	16.0	15.9	-3.2	12.7	6.4	-31.8
08/05/91	4000	48 hr	23.0	19.1	6.4	25.4	50.9	-216.2
08/05/91	4000	60 hr eve	16.0	-6.4	-25.4	6.4	0.0	-229.0
08/08/91	2000	30 day	14.0	9.5	12.7	-6.4	28.6	82.7
11/02/91	3000	56 day	-10.0	19.1	-9.5	NT	NT	57.2
01/13/92	4000	71 d dusk	-4.0	25.4	19.1	19.1	12.7	50.9
01/17/92	2000	72 hr	-5.0	19.1	0.0	19.1	-6.4	31.8
01/24/92	1000	120 hr	5.0	4.8	6.4	1.8	3.2	6.4

Constituent: Magnesium (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T - 2T	2T - 3T	1P - 2P	2P - 3P	4 - 5
07/25/91	3000	30 day	18.3	-1.0	0.0	-1.0	0.0	-1.9
07/30/91	1000	48 hr	26.0	NT	0.2	-0.3	0.2	-2.5
07/31/91	1000	72 hr	26.5	NT	-0.3	0.0	-0.2	-1.9
08/02/91	2000	48 hr	17.5	1.3	-0.3	0.3	0.6	-0.6
08/02/91	2000	60 hr eve	14.0	0.0	-1.3	0.0	-0.6	-1.9
08/03/91	2000	72 hr	16.0	-0.3	-0.6	0.6	-1.3	-1.3
08/05/91	4000	48 hr	23.0	-0.6	0.6	0.0	-0.6	-16.5
08/05/91	4000	60 hr eve	16.0	-1.9	-0.6	-1.3	0.0	-19.1
08/08/91	2000	30 day	14.0	0.0	-0.6	-0.6	0.3	-0.6
11/02/91	3000	56 day	-10.0	1.0	-0.5	NT	NT	1.0
01/13/92	4000	71 d dusk	-4.0	0.0	-1.3	-2.5	1.3	0.0
01/17/92	2000	72 hr	-5.0	0.3	-1.3	-1.0	0.0	-1.3
01/24/92	1000	120 hr	5.0	-0.8	0.0	-0.8	0.0	-1.3

Constituent: Total Alkalinity as CaCO3 (kg/day)				Sample Location				
Date	Flow BPD	Duration	Amb T (C)	1T - 2T	2T - 3T	1P - 2P	2P - 3P	4 - 5
08/05/91	4000	48 hr	23.0	33.7	19.7	26.7	23.5	-7.6
08/05/91	4000	60 hr eve	16.0	-8.9	-20.4	12.1	-14.0	132.3
08/08/91	2000	30 day	14.0	21.0	21.9	16.2	17.8	3.2
11/02/91	3000	56 day	-10.0	NT	NT	NT	NT	0.0
01/13/92	4000	71 d dusk	-4.0	50.2	29.3	41.3	22.9	115.7
01/17/92	2000	72 hr	-5.0	NT	NT	NT	NT	0.0
01/24/92	1000	120 hr	5.0	18.3	6.8	13.2	7.5	-2.5

NT = no test

APPENDIX C
DESIGN CRITERIA

Table C1 - Design Criteria for Bicarbonate and Radium 226

Constituent: Bicarbonate (kg/day) and (mg/l)								
Date	Flow BPD	Duration	Amb T (C)	Load 1T/P	Cred 1T	Cred 1P	Load 2P	Cred 2P
07/25/91	3000	30 day	18.3	525	60	40	508	40
07/30/91	1000	48 hr	26.0	167	154	82	154	122
07/31/91	1000	72 hr	26.5	167	181	97	152	143
08/02/91	2000	48 hr	17.5	295	-31	-81	321	104
08/02/91	2000	60 hr eve	14.0	311	-83	-83	337	50
08/03/91	2000	72 hr	16.0	328	94	35	316	103
08/05/91	4000	48 hr	23.0	674	63	50	642	45
08/05/91	4000	60 hr eve	16.0	655	-20	20	642	-30
09/08/91	2000	30 day	14.0	382	80	60	363	70
11/02/91	3000	56 day	-10.0	591	120	NT	NT	0
01/13/92	4000	71 d dusk	-4.0	782	90	80	731	40
01/17/92	2000	72 hr	-5.0	363	100	70	340	30
01/24/92	1000	120 hr	5.0	188	140	100	172	60

Constituent: Radium 226 (uCi/day) and (pCi/l)								
Date	Flow BPD	Duration	Amb T (C)	Load 1T/P	Cred 1T	Cred 1P	Load 4	Cred 4
01/24/92	1000	120 hr	5.0	4.0	-1.7	-2.3	8.0	1.4
07/30/91	1000	48 hr	26.0	4.4	8.1	5.5	4.9	5.8
07/31/91	1000	72 hr	26.5	5.4	15.4	10.0	5.3	4.5
09/08/91	2000	30 day	14.0	6.3	-2.2	-5.3	16.3	7.2
01/17/92	2000	72 hr	-5.0	8.1	2.9	-0.5	15.4	2.0
08/02/91	2000	60 hr eve	14.0	9.8	7.3	1.5	17.4	13.3
08/03/91	2000	72 hr	16.0	11.3	8.7	10.3	13.7	6.2
11/02/91	3000	56 day	-10.0	12.3	4.0	NT	26.8	0.7
08/02/91	2000	48 hr	17.5	13.4	16.8	15.5	13.1	4.8
07/25/91	3000	30 day	18.3	13.5	-8.6	-0.2	27.7	10.3
08/05/91	4000	60 hr eve	16.0	21.4	21.6	9.6	13.2	-2.7
08/05/91	4000	48 hr	23.0	21.5	2.5	-0.2	39.3	18.6
01/13/92	4000	71 d dusk	-4.0	25.4	1.9	2.3	46.9	3.2

NT = no test, kg/day = 2.2 lb/day, uCi = 1,000,000 pCi

LOAD X = mass loading of constituent into cell "X" (kg/day) or (uCi/day)

Cred X = Concentration Reduction Through Cell "X" (mg/l) or (pCi/l)

Table C2 - Design Criteria for Sulfide and Total Phenolics

Constituent: Sulfide (kg/day) and (mg/l)

Date	Flow BPD	Duration	Amb T (C)	Load 1T/P	Cred 1T	Cred 1P	Load 2P	Cred 2P
07/25/91	3000	30 day	18.3	10.7	15.2	12.0	5.0	4.8
07/30/91	1000	48 hr	28.0	3.9	4.8	-8.4	5.0	24.0
07/31/91	1000	72 hr	28.5	4.5	19.2	13.6	2.3	8.0
08/02/91	2000	48 hr	17.5	9.4	20.8	-0.8	9.7	20.0
08/02/91	2000	60 hr eve	14.0	15.3	36.0	23.2	7.9	13.6
08/03/91	2000	72 hr	18.0	9.4	19.2	18.4	3.6	0.6
08/05/91	4000	48 hr	23.0	27.5	31.2	24.0	12.2	4.8
08/05/91	4000	60 hr eve	18.0	21.4	21.6	9.6	15.3	8.0
09/08/91	2000	30 day	14.0	13.5	24.0	17.6	7.9	9.6
11/02/91	3000	56 day	-10.0	13.4	20.8	NT	NT	NT
01/13/92	4000	71 d dusk	-4.0	25.4	19.2	13.6	16.8	4.8
01/17/92	2000	72 hr	-5.0	10.4	11.2	12.0	6.6	3.2
01/24/92	1000	120 hr	5.0	2.7	3.2	4.8	1.9	-3.2

Constituent: Total Phenolics (g/day) and (mg/l)

Date	Flow BPD	Duration	Amb T (C)	Load 4	Cred 4
07/30/91	1000	48 hr	26.0	9.5	0.02 *
07/31/91	1000	72 hr	26.5	12.7	0.04 *
01/24/92	1000	120 hr	5.0	28.6	0.00
08/02/91	2000	48 hr	17.5	31.8	-0.03 *
07/25/91	3000	30 day	18.3	38.2	0.00
08/03/91	2000	72 hr	18.0	50.9	0.01 *
09/08/91	2000	30 day	14.0	57.2	0.01
08/02/91	2000	60 hr eve	14.0	63.6	0.04 *
01/17/92	2000	72 hr	-5.0	78.3	0.00
11/02/91	3000	56 day	-10.0	114.5	0.05
01/13/92	4000	71 d dusk	-4.0	139.9	0.01 *

NT = no test, kg/day = 2.2 lb/day, **, data in this row is based on estimated inflow concentration

LOAD X = mass loading of constituent into cell *X*, (kg/day) or (g/day)

Cred X = Concentration Reduction Through Cell *X*, (mg/l)

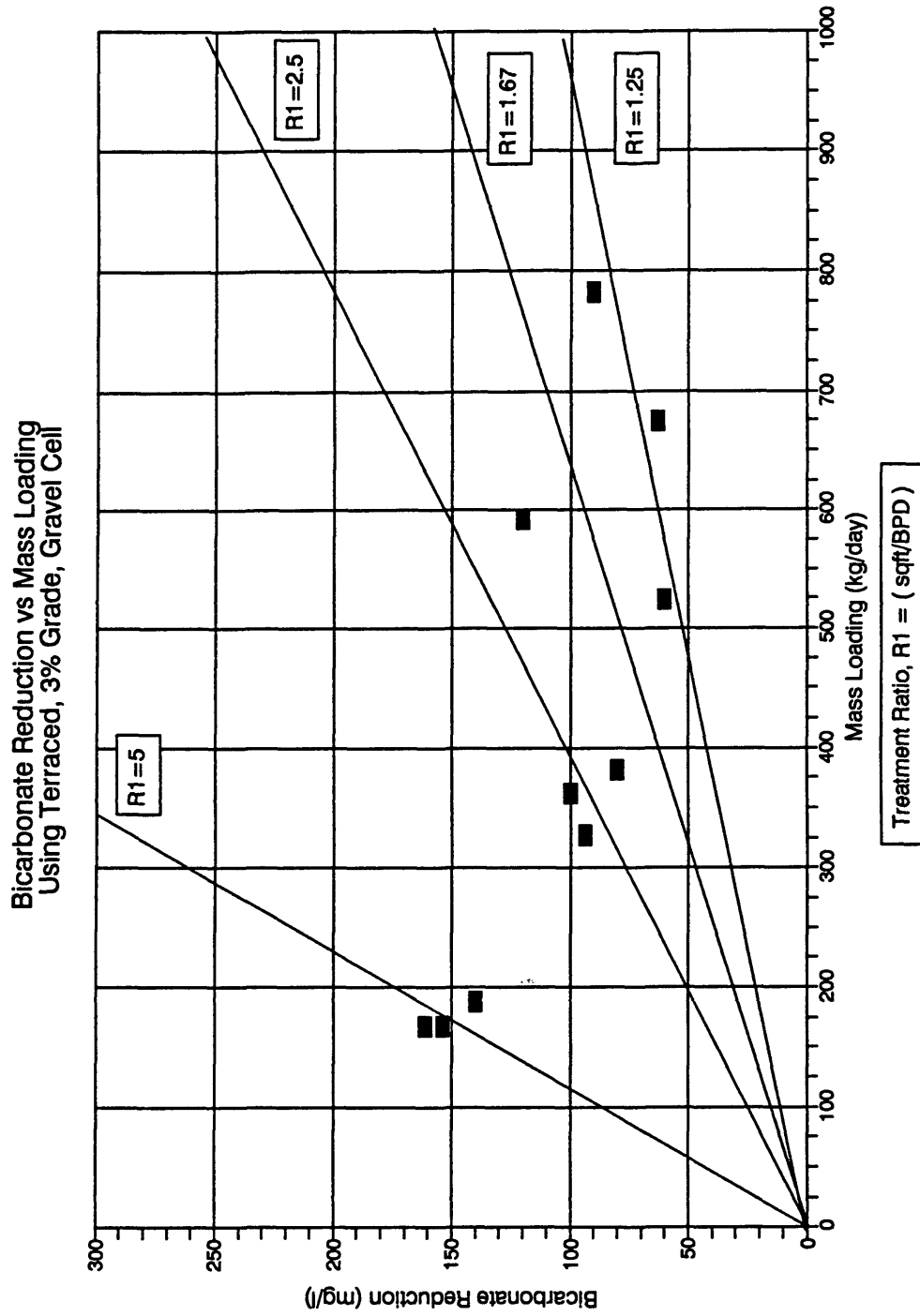


Figure C1 - Bicarbonate Reduction vs Mass Loading Using Terraced, 3% Grade, Gravel Cell

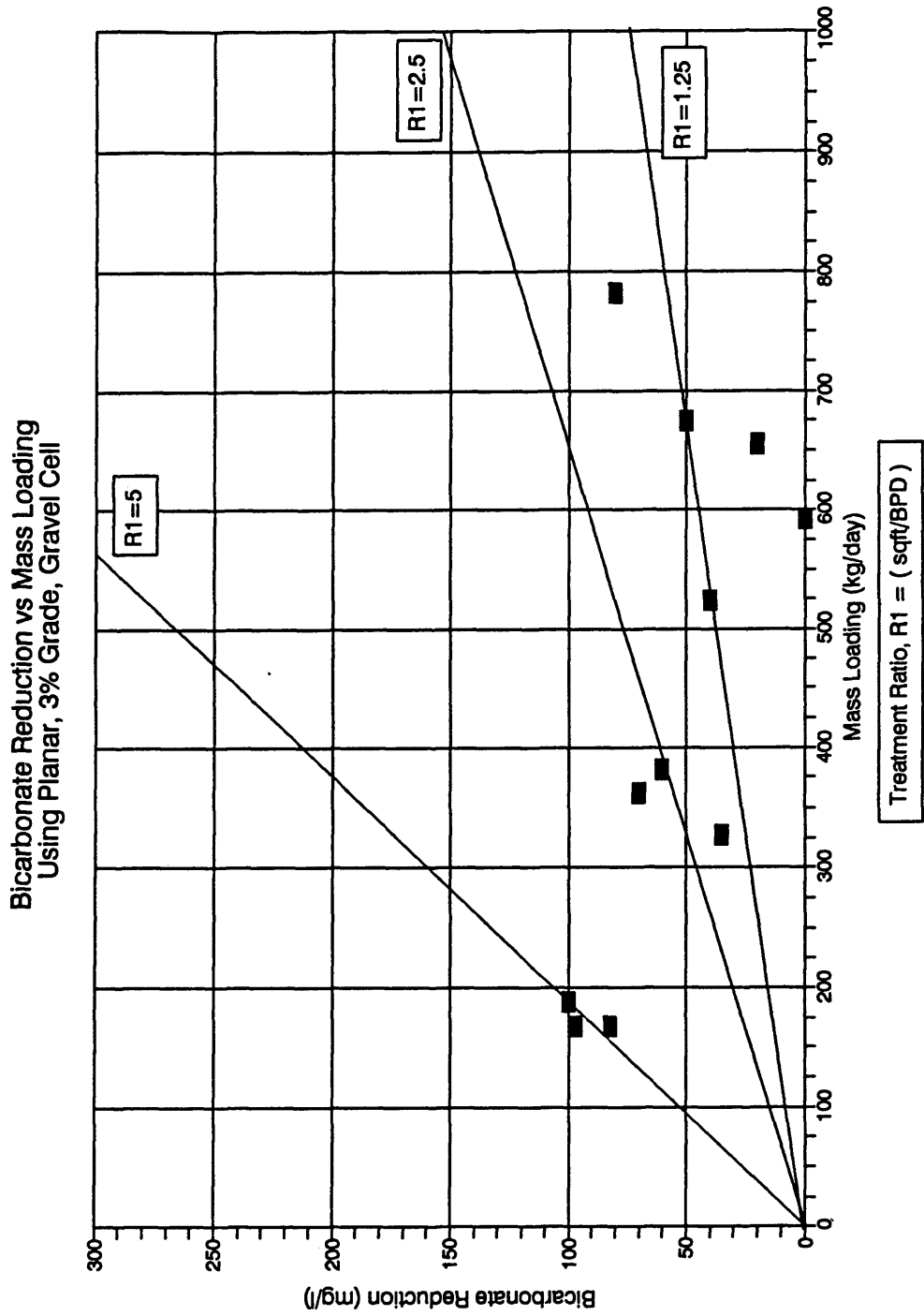


Figure C2 - Bicarbonate Reduction vs Mass Loading Using Planar, 3% Grade, Gravel Cell

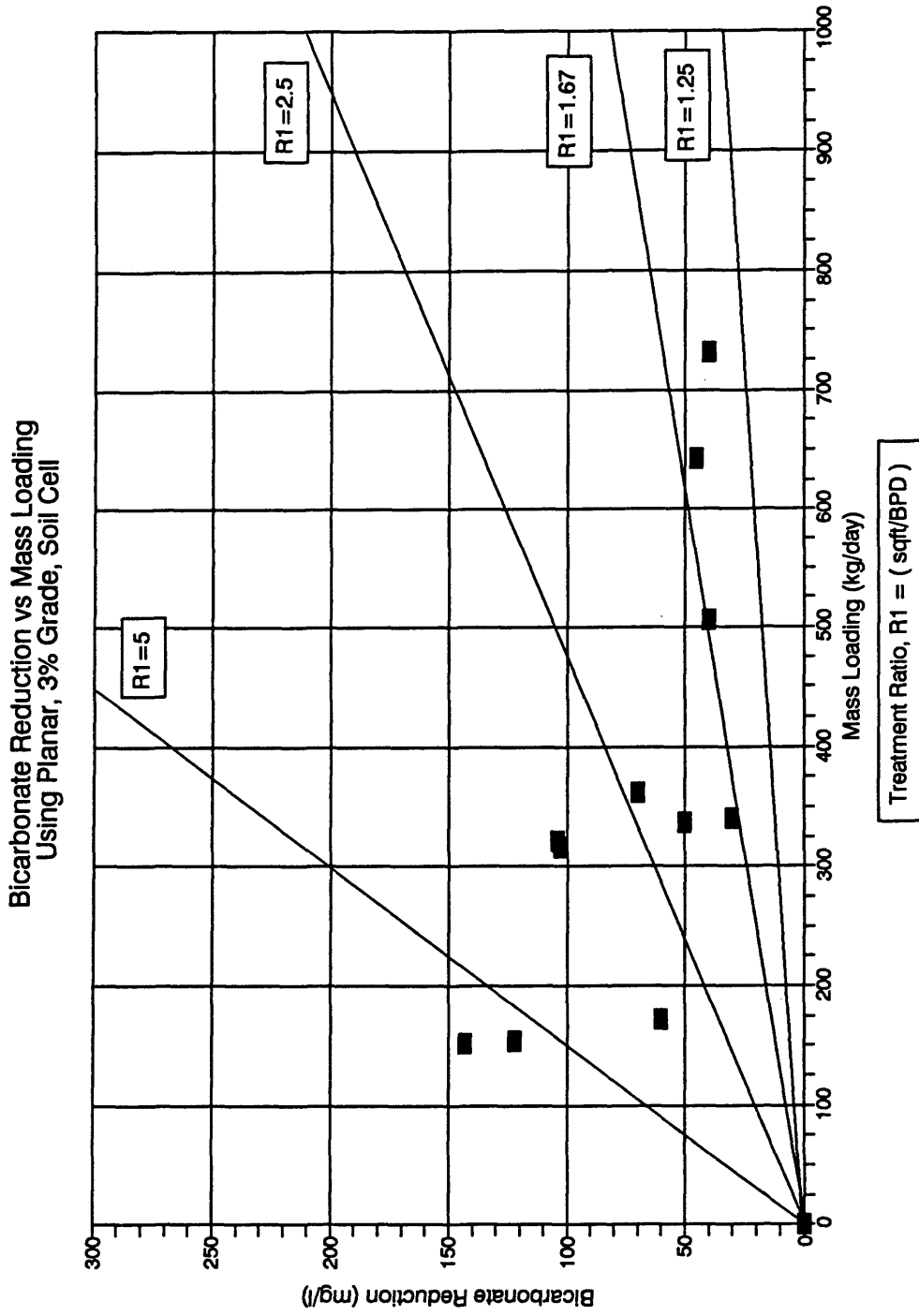


Figure C3 - Bicarbonate Reduction vs Mass Loading Using Planar, 3% Grade, Soil Cell

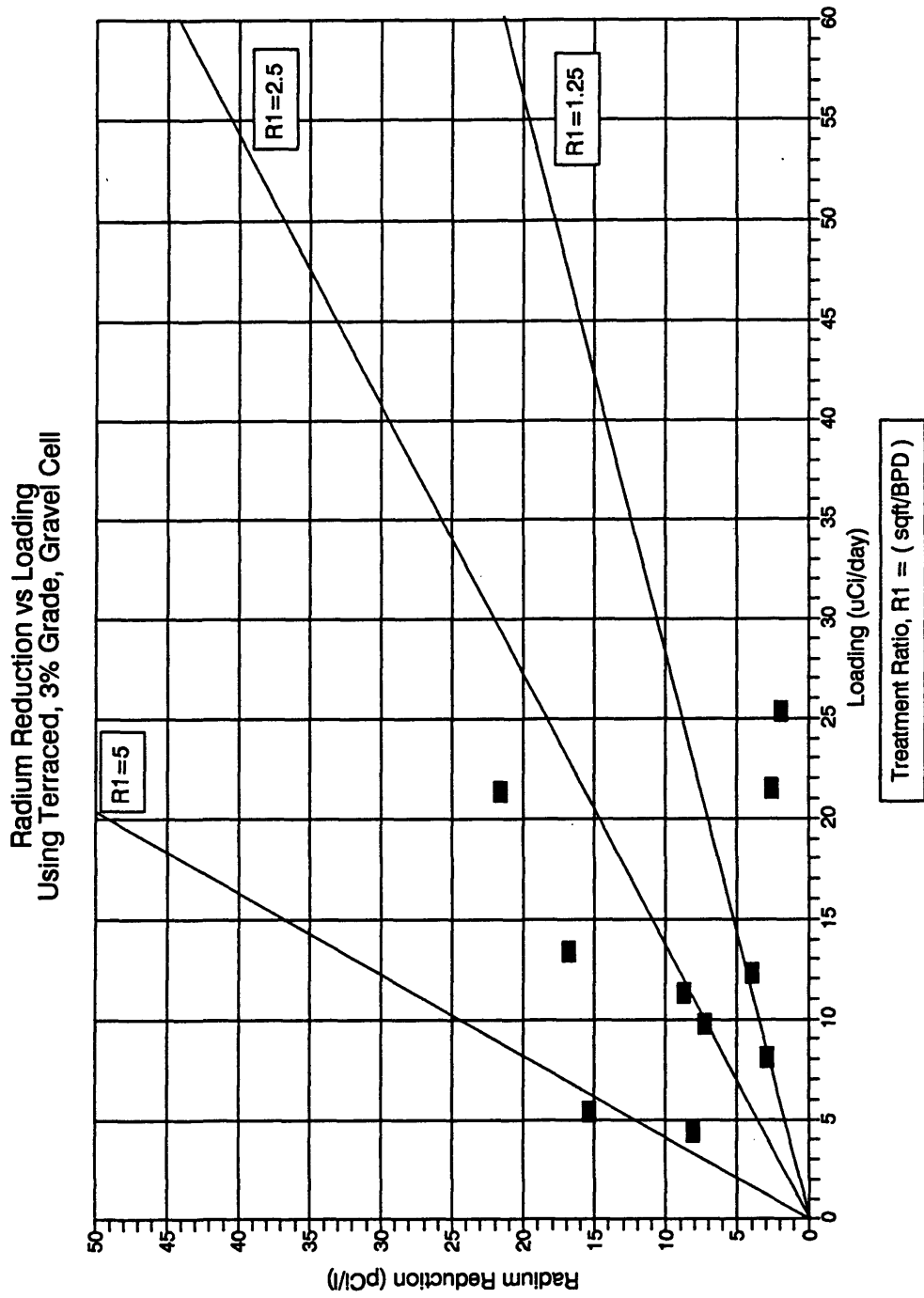


Figure C4 - Radium 226 Reduction vs Mass Loading Using Terraced, 3% Grade, Gravel Cell

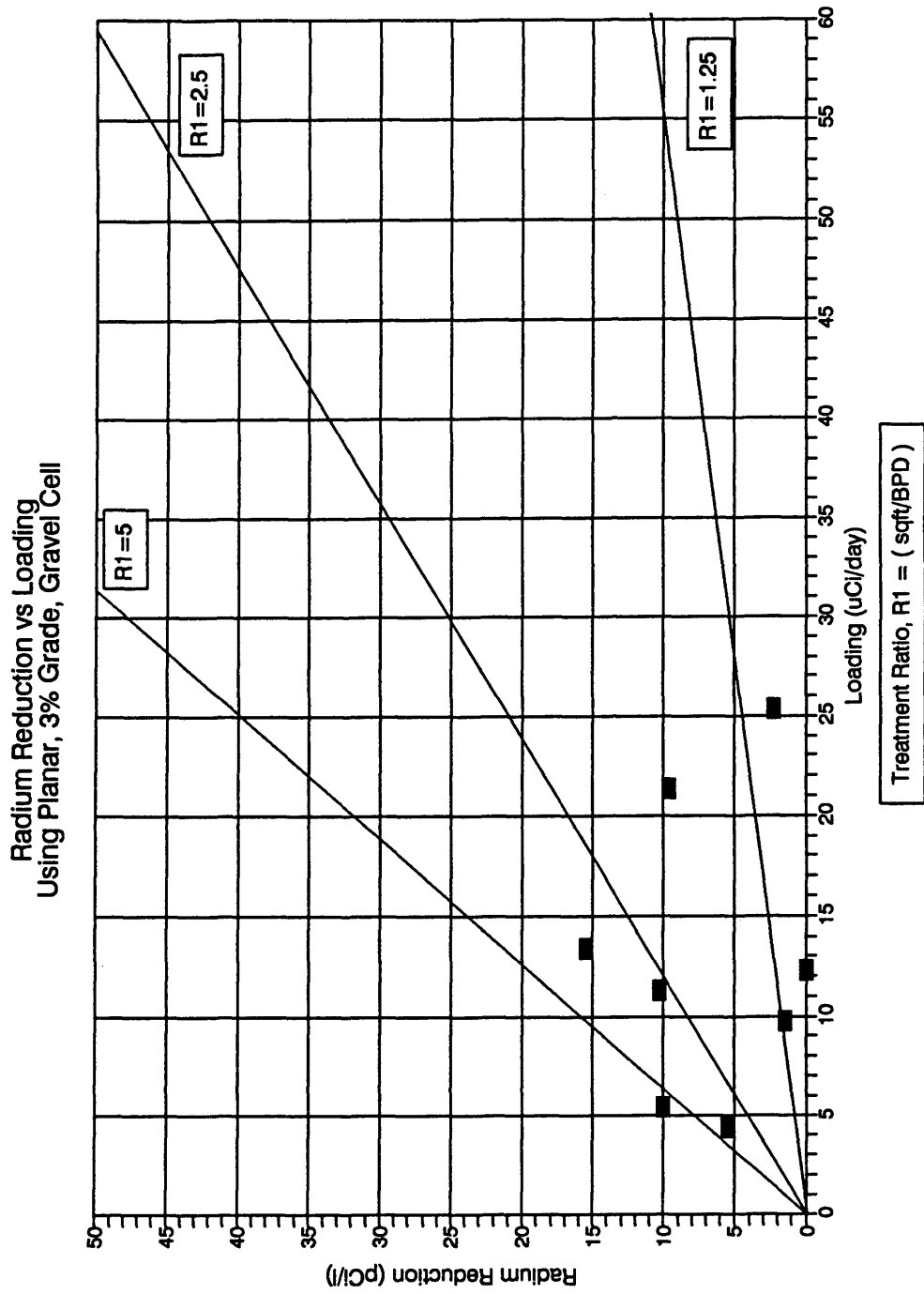


Figure C5 - Radium 226 Reduction vs Mass Loading Using Planar, 3% Grade, Gravel Cell

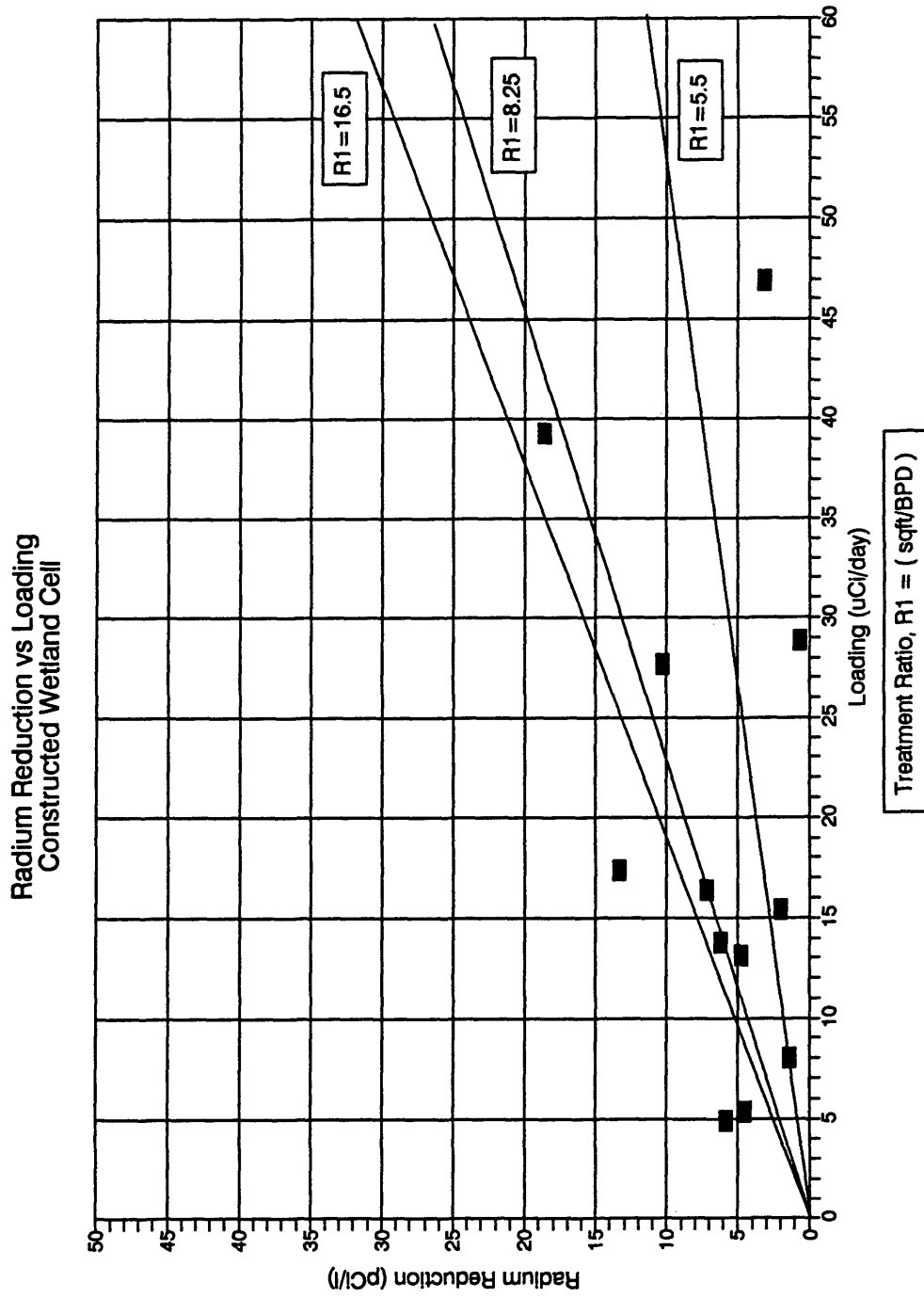


Figure C6 - Radium 226 Reduction vs Mass Loading Using Constructed Wetland Cell

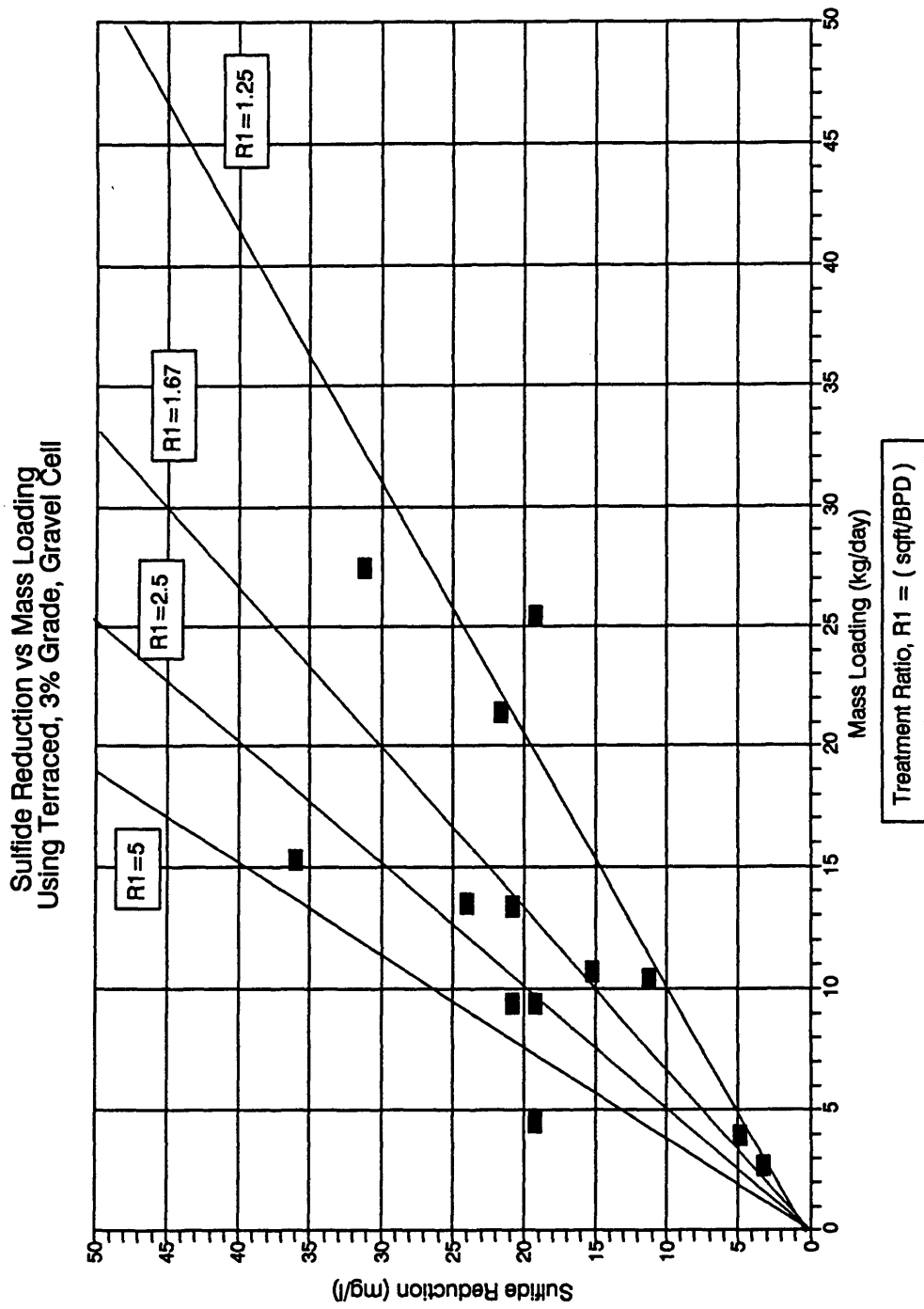


Figure C7 - Sulfide Reduction vs Mass Loading Using Terraced, 3% Grade, Gravel Cell

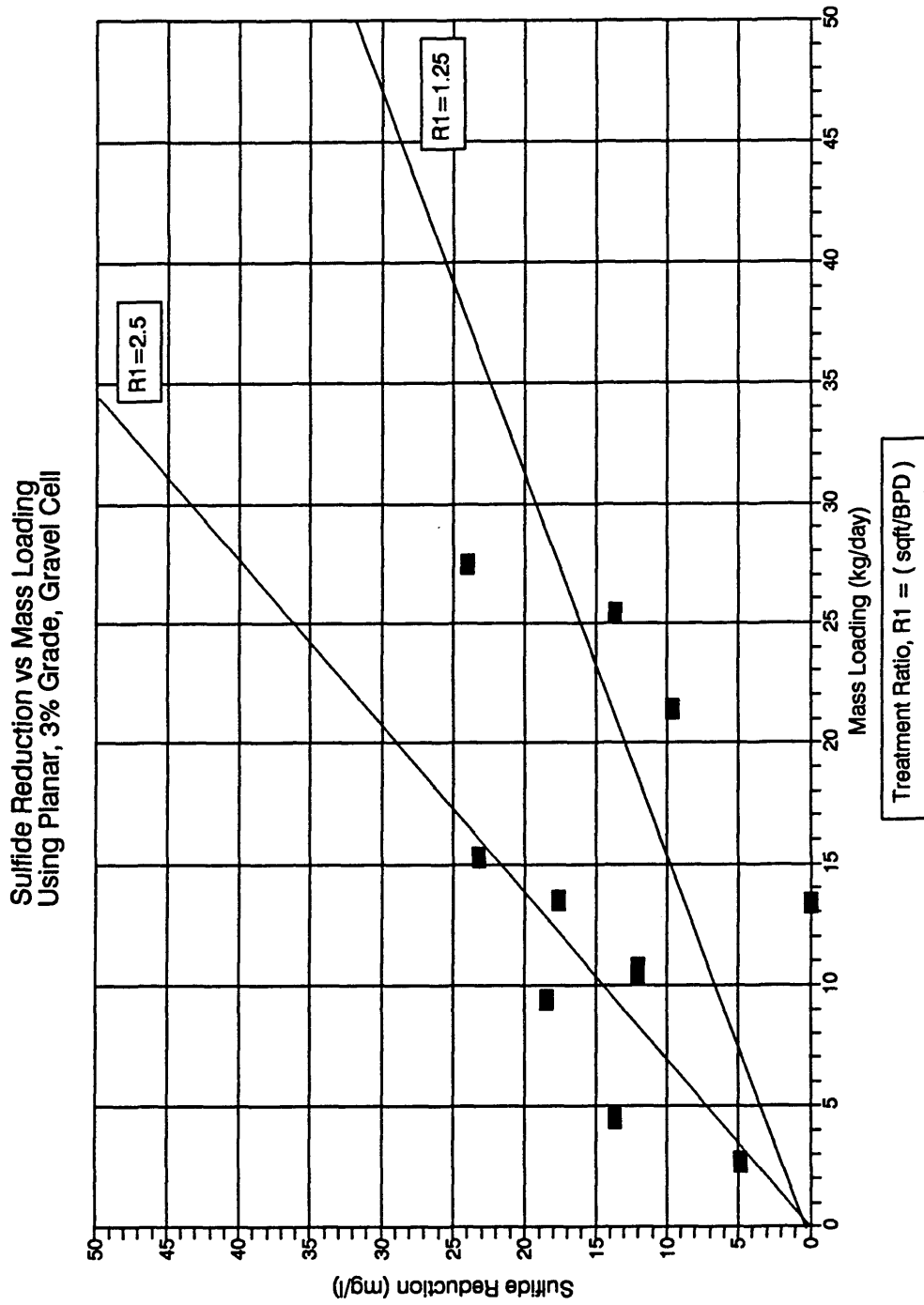


Figure C8 - Sulfide Reduction vs Mass Loading Using Planar, 3% Grade, Gravel Cell

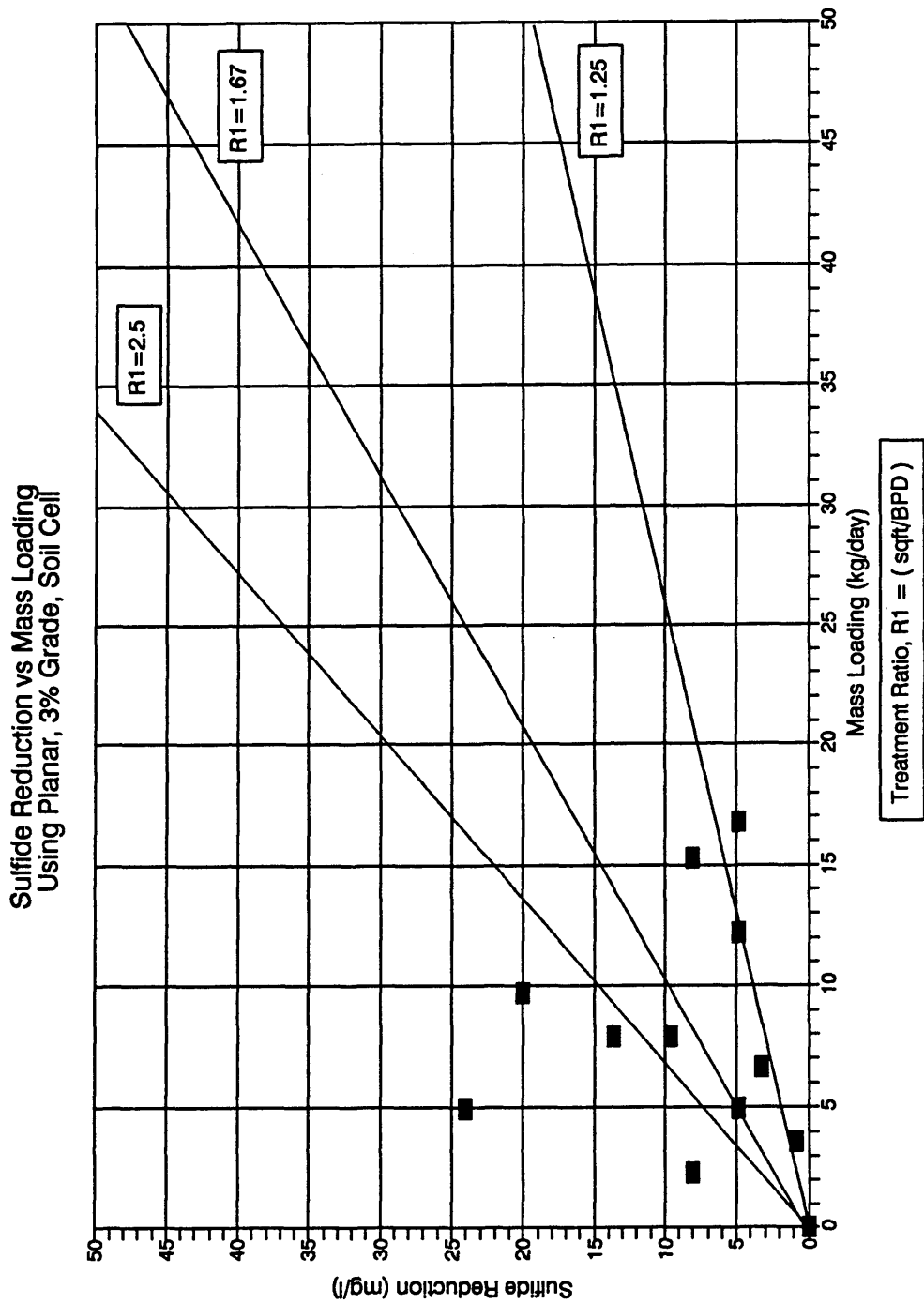


Figure C9 - Sulfide Reduction vs Mass Loading Using Planar, 3% Grade, Soil Cell

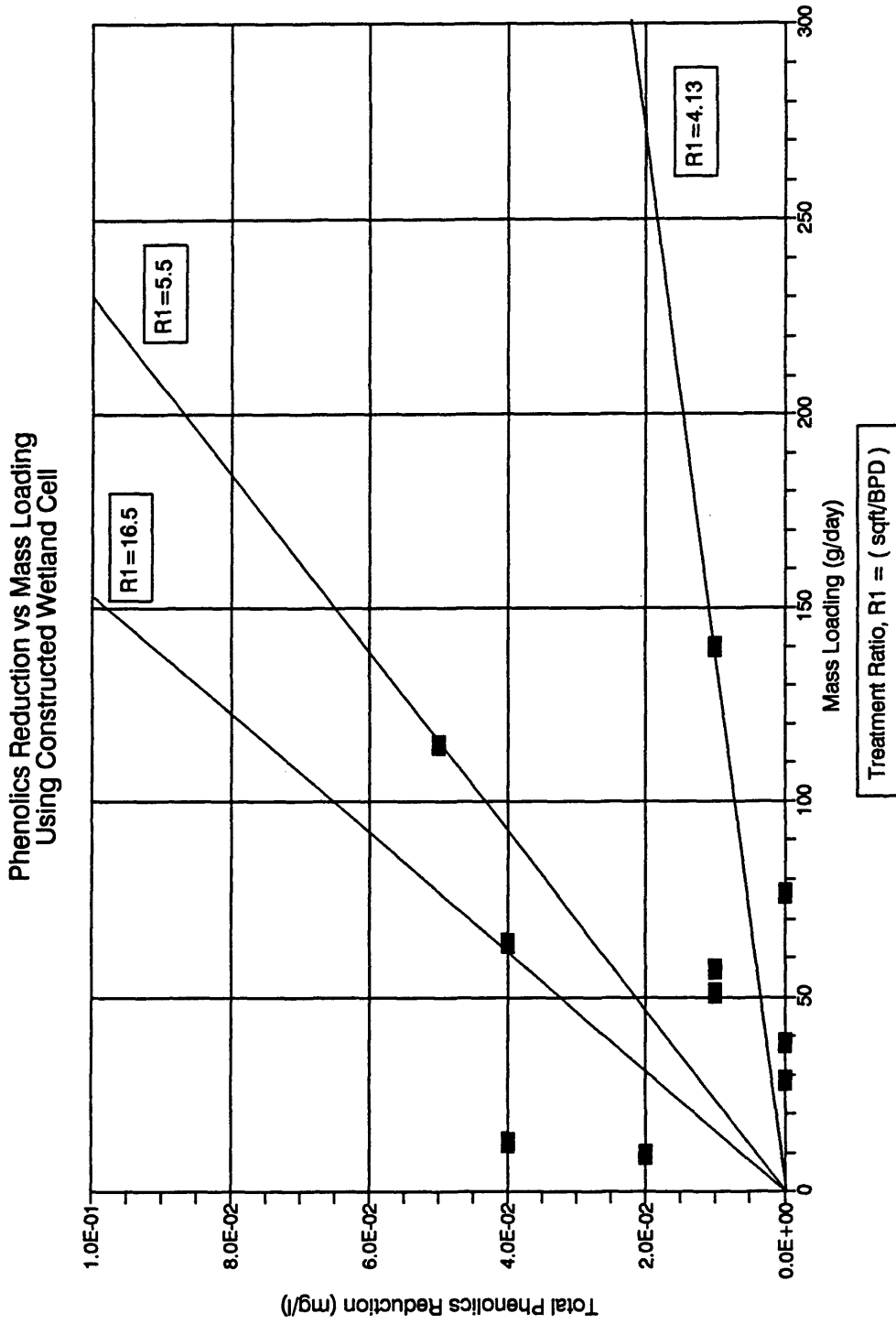


Figure C10 - Total Phenolics Reduction vs Mass Loading Using Constructed Wetland Cell

Table C3 - Linear Regressions for Bicarbonate Removal Factors (K2)

Bicarbonate Design Criteria			Bicarbonate Design Criteria			Bicarbonate Design Criteria		
Linear Regression for: 1000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 1000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 2000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	20.79212		Std Err of Y Est	7.502794		Std Err of Y Est	50.53836	
R Squared	-2.78118		R Squared	0.394711		R Squared	-0.37147	
No. of Observations	3		No. of Observations	3		No. of Observations	3	
Degrees of Freedom	2		Degrees of Freedom	2		Degrees of Freedom	2	
X Coefficient(s)	0.868942		X Coefficient(s)	0.534819		X Coefficient(s)	0.868439	
Std Err of Coef.	0.068936		Std Err of Coef.	0.024878		Std Err of Coef.	0.183132	
Linear Regression for: 2000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 2000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 4000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	15.28794		Std Err of Y Est	14.83105		Std Err of Y Est	34.86164	
R Squared	-1.21307		R Squared	0.3232		R Squared	-0.14784	
No. of Observations	3		No. of Observations	3		No. of Observations	5	
Degrees of Freedom	2		Degrees of Freedom	2		Degrees of Freedom	4	
X Coefficient(s)	0.25385		X Coefficient(s)	0.155421		X Coefficient(s)	0.209831	
Std Err of Coef.	0.024828		Std Err of Coef.	0.023922		Std Err of Coef.	0.048413	
Linear Regression for: 3000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 3000 BPD Planar, 3% Grade, Soil Cell			Linear Regression for: 6000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Not Enough Data for Regression		
Constant	0		Constant	0		Slope = 0.079		
Std Err of Y Est	34.74713		Std Err of Y Est	28.92342				
R Squared	0.329243		R Squared	-0.11926				
No. of Observations	2		No. of Observations	2				
Degrees of Freedom	1		Degrees of Freedom	1				
X Coefficient(s)	0.163898		X Coefficient(s)	0.033572				
Std Err of Coef.	0.043947		Std Err of Coef.	0.037848				
Linear Regression for: 4000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 4000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 8000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	11.02881		Std Err of Y Est	25.48304		Std Err of Y Est	23.38998	
R Squared	0.666298		R Squared	0.278461		R Squared	0.155723	
No. of Observations	2		No. of Observations	3		No. of Observations	2	
Degrees of Freedom	1		Degrees of Freedom	2		Degrees of Freedom	1	
X Coefficient(s)	0.105847		X Coefficient(s)	0.073145		X Coefficient(s)	0.033605	
Std Err of Coef.	0.01068		Std Err of Coef.	0.020638		Std Err of Coef.	0.024042	

Table C4 - Linear Regressions for Radium 226 Removal Factors (K2)

Radium Design Criteria			Radium Design Criteria			Radium Design Criteria		
Linear Regression for: 1000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 1000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 2000 BPD Wetland Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	3.391695		Std Err of Y Est	2.015639		Std Err of Y Est	3.258754	
R Squared	0.568264		R Squared	0.598736		R Squared	-1.07818	
No. of Observations	2		No. of Observations	2		No. of Observations	3	
Degrees of Freedom	1		Degrees of Freedom	1		Degrees of Freedom	2	
X Coefficient(s)	2.446487		X Coefficient(s)	1.810295		X Coefficient(s)	0.543221	
Std Err of Coef.	0.486199		Std Err of Coef.	0.288942		Std Err of Coef.	0.300899	
Linear Regression for: 2000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 2000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 4000 BPD Wetland Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	3.923609		Std Err of Y Est	5.658157		Std Err of Y Est	3.722752	
R Squared	0.542765		R Squared	0.38118		R Squared	0.205339	
No. of Observations	4		No. of Observations	3		No. of Observations	5	
Degrees of Freedom	3		Degrees of Freedom	2		Degrees of Freedom	4	
X Coefficient(s)	0.892429		X Coefficient(s)	0.840085		X Coefficient(s)	0.452739	
Std Err of Coef.	0.181195		Std Err of Coef.	0.281652		Std Err of Coef.	0.109073	
Linear Regression for: 3000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 3000 BPD Planar, 3% Grade, Soil Cell			Linear Regression for: 6000 BPD Wetland Cell		
Not Enough Data for Regression			Not Enough Data for Regression			Regression Output:		
						Constant	0	
						Std Err of Y Est	6.944591	
						R Squared	-0.0466	
						No. of Observations	2	
						Degrees of Freedom	1	
						X Coefficient(s)	0.191247	
						Std Err of Coef.	0.173865	
Linear Regression for: 4000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 4000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 8000 BPD Wetland Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	11.88745		Std Err of Y Est	5.841437		Std Err of Y Est	12.20607	
R Squared	-0.08804		R Squared	-0.28063		R Squared	-0.25844	
No. of Observations	3		No. of Observations	2		No. of Observations	2	
Degrees of Freedom	2		Degrees of Freedom	1		Degrees of Freedom	1	
X Coefficient(s)	0.360627		X Coefficient(s)	0.239135		X Coefficient(s)	0.235139	
Std Err of Coef.	0.295658		Std Err of Coef.	0.175536		Std Err of Coef.	0.189388	

Table C5 - Linear Regressions for Sulfide Removal Factors (K2)

Sulfide Design Criteria			Sulfide Design Criteria			Sulfide Design Criteria		
Linear Regression for: 1000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 1000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 2000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Not Enough Data for Regression		
Std Err of Y Est	7.132483		Std Err of Y Est	2.856366				
R Squared	0.344879		R Squared	0.788844				
No. of Observations	3		No. of Observations	2				
Degrees of Freedom	2		Degrees of Freedom	1				
X Coefficient(s)	2.657195		X Coefficient(s)	0.726072				
Std Err of Coef.	1.093898		Std Err of Coef.	0.147474				
Linear Regression for: 2000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 2000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 4000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	5.760144		Std Err of Y Est	3.519734		Std Err of Y Est	5.083463	
R Squared	0.592432		R Squared	0.411837		R Squared	0.573627	
No. of Observations	5		No. of Observations	4		No. of Observations	5	
Degrees of Freedom	4		Degrees of Freedom	3		Degrees of Freedom	4	
X Coefficient(s)	1.949859		X Coefficient(s)	1.45273		X Coefficient(s)	1.456922	
Std Err of Coef.	0.217524		Std Err of Coef.	0.142177		Std Err of Coef.	0.306305	
Linear Regression for: 3000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 3000 BPD Planar, 3% Grade, Soil Cell			Linear Regression for: 6000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Not Enough Data for Regression		
Std Err of Y Est	1.124033		Std Err of Y Est	9.370548				
R Squared	0.919423		R Squared	-0.21954				
No. of Observations	2		No. of Observations	2		Slope = 0.960		
Degrees of Freedom	1		Degrees of Freedom	1				
X Coefficient(s)	1.504788		X Coefficient(s)	0.438279				
Std Err of Coef.	0.065719		Std Err of Coef.	0.547866				
Linear Regression for: 4000 BPD Terraced, 3% Grade, Gravel Cell			Linear Regression for: 4000 BPD Planar, 3% Grade, Gravel Cell			Linear Regression for: 8000 BPD Planar, 3% Grade, Soil Cell		
Regression Output:			Regression Output:			Regression Output:		
Constant	0		Constant	0		Constant	0	
Std Err of Y Est	5.071687		Std Err of Y Est	5.689688		Std Err of Y Est	1.802532	
R Squared	0.382053		R Squared	0.414107		R Squared	-0.08044	
No. of Observations	3		No. of Observations	3		No. of Observations	3	
Degrees of Freedom	2		Degrees of Freedom	2		Degrees of Freedom	2	
X Coefficient(s)	0.972327		X Coefficient(s)	0.851281		X Coefficient(s)	0.39355	
Std Err of Coef.	0.11784		Std Err of Coef.	0.131675		Std Err of Coef.	0.073633	

Table C6 - Linear Regressions for Total Phenolics Removal Factors (K2)

Total Phenolics Design Criteria

Linear Regression for: 2000 BPD
Wetland Cell

Regression Output:

Constant	0
Std Err of Y Est	0.027789
R Squared	-0.93057
No. of Observations	3
Degrees of Freedom	2

X Coefficient(s)	0.000653
Std Err of Coef.	0.00085

Linear Regression for: 4000 BPD
Wetland Cell

Regression Output:

Constant	0
Std Err of Y Est	0.017831
R Squared	-0.07175
No. of Observations	4
Degrees of Freedom	3

X Coefficient(s)	0.00023
Std Err of Coef.	0.000143

Linear Regression for: 6000 BPD
Wetland Cell

Not Enough Data for Regression

Slope = 0.000437

Linear Regression for: 8000 BPD
Wetland Cell

Not Enough Data for Regression

Slope = 0.0000715

Table C7 - Calculation of Bicarbonate Reduction Factors and Treatment Ratios

Design Criteria - Bicarbonate

Terraced, 3% Grade, Gravel Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	0.867	867	5.00
2000	0.254	508	2.50
3000	0.163	489	1.67
4000	0.106	424	1.25

Planar, 3% Grade, Gravel Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	0.535	535	5.00
2000	0.155	310	2.50
4000	0.073	292	1.25

Planar, 3% Grade, Soil Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	0.666	666	5.00
2000	0.210	420	2.50
3000	0.079	237	1.67
4000	0.034	136	1.25

Table C8 - Calculation of Radium 226 Reduction Factors and Treatment Ratios

Design Criteria - Radium

Terraced, 3% Grade, Gravel Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	2.450	2450	5.00
2000	0.892	1784	2.50
4000	0.361	1444	1.25

Planar, 3% Grade, Gravel Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	1.610	1610	5.00
2000	0.840	1680	2.50
4000	0.176	704	1.25

Constructed Wetland Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
2000	0.543	1086	16.50
4000	0.453	1812	8.25
6000	0.191	1146	5.50

Table C9 - Calculation of Sulfide Reduction Factors and Treatment Ratios

Design Criteria - Sulfide

Terraced, 3% Grade, Gravel Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	2.660	2660	5.00
2000	1.950	3900	2.50
3000	1.500	4500	1.67
4000	0.972	3888	1.25

Planar, 3% Grade, Gravel Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
1000	0.729	729	5.00
2000	1.450	2900	2.50
4000	0.651	2604	1.25

Planar, 3% Grade, Soil Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
2000	1.460	2920	2.50
3000	0.960	2880	1.67
4000	0.393	1572	1.25

Table C10 - Calculation of Phenolics Reduction Factors and Treatment Ratios

Design Criteria - Total Phenolics

Constructed Wetland Cell

Flow Rate (BPD)	Removal Factor K2 (Cred/Loading)	Reduction Factor K1 (K2 * BPD)	Treatment Ratio R1 (sqft/BPD)
2000	6.53E-04	1.306	16.50
6000	4.37E-04	2.622	5.50
8000	7.15E-05	0.572	4.13

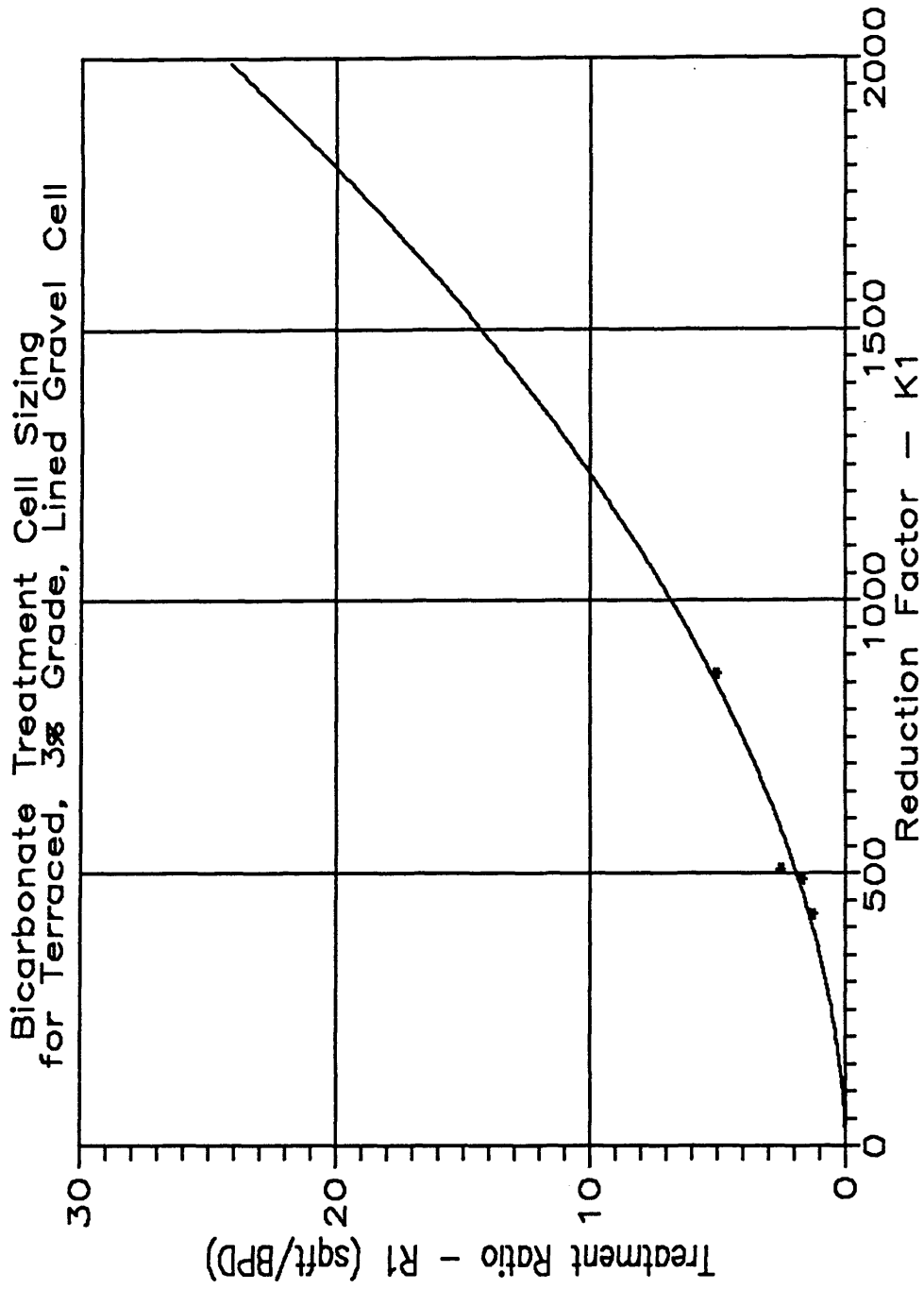


Figure C11 - Bicarbonate Treatment Cell Sizing for Terraced, 3% Grade, Gravel Cell

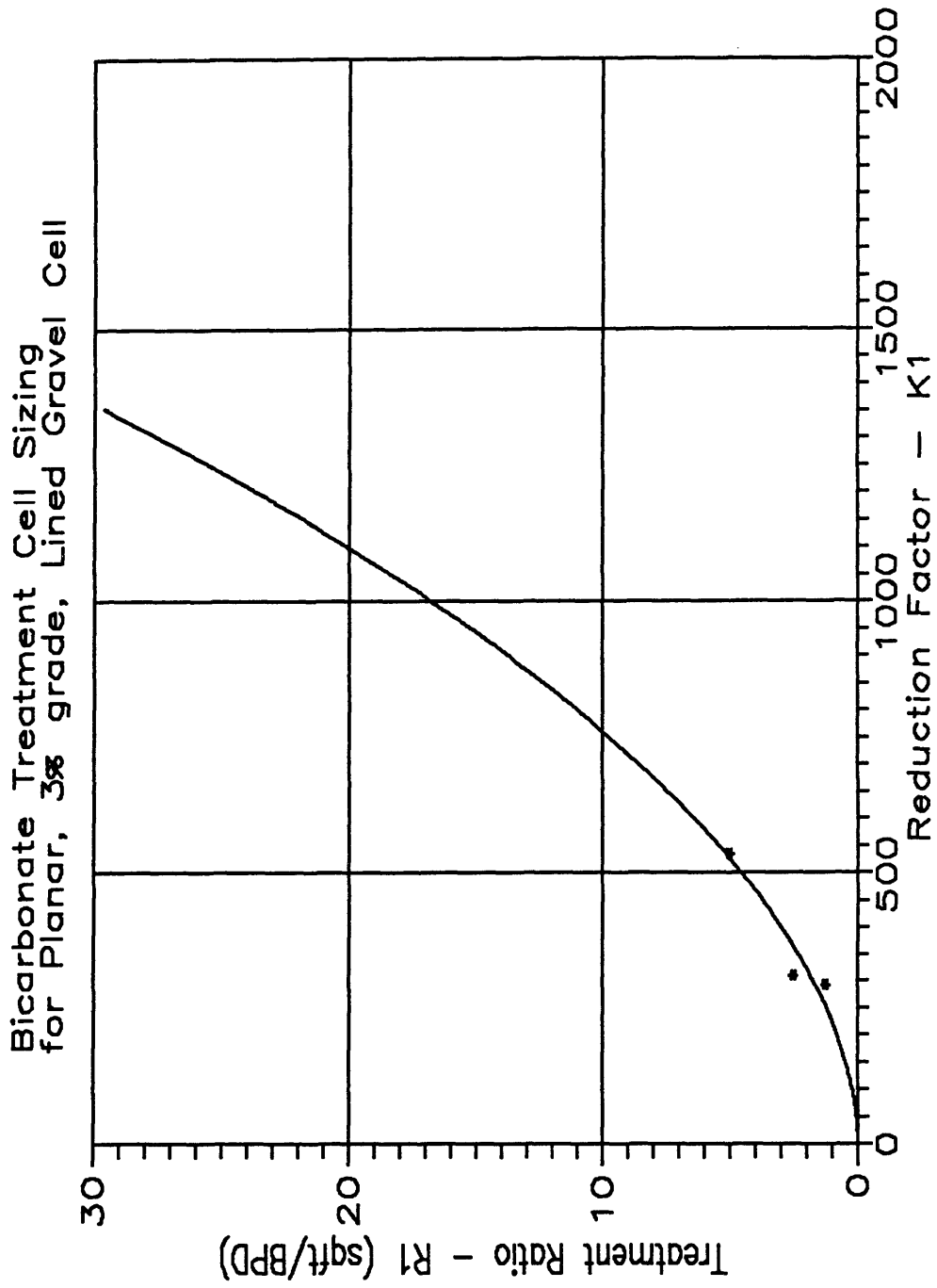


Figure C12 - Bicarbonate Treatment Cell Sizing for Planar, 3% Grade, Gravel Cell

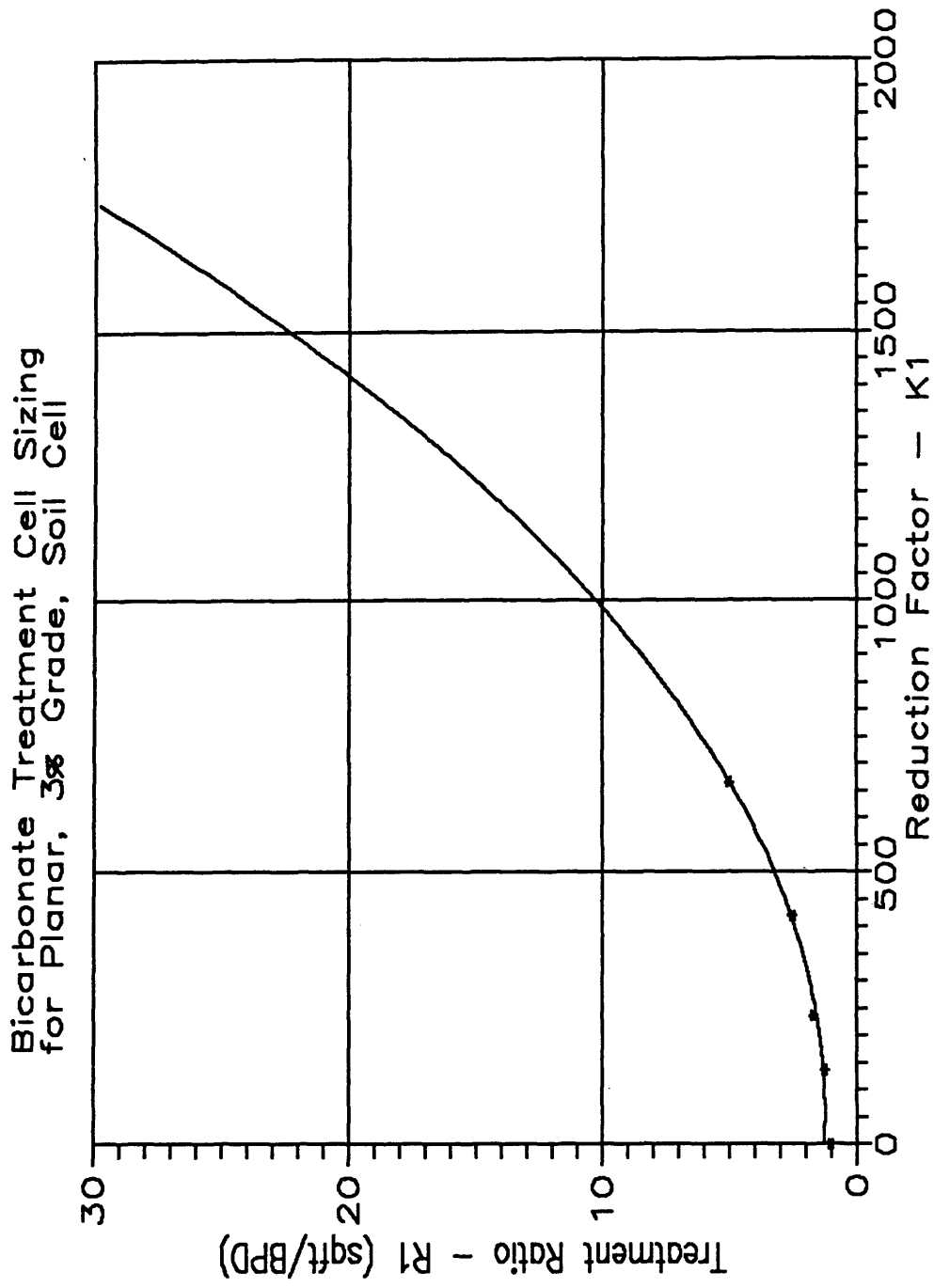


Figure C13 - Bicarbonate Treatment Cell Sizing for Planar, 3% Grade, Soil Cell

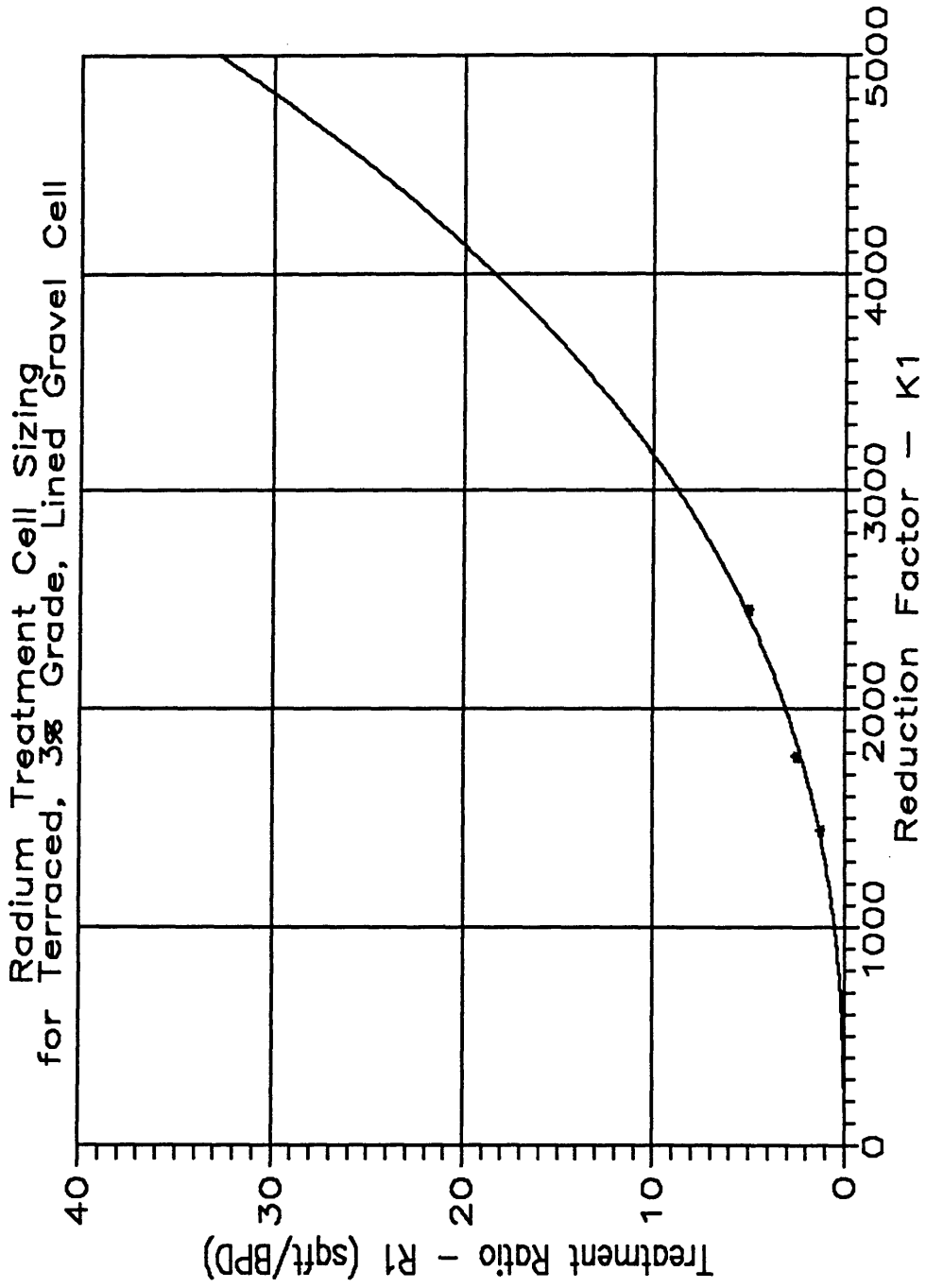


Figure C14 - Radium 226 Treatment Cell Sizing for Terraced, 3% Grade, Gravel Cell

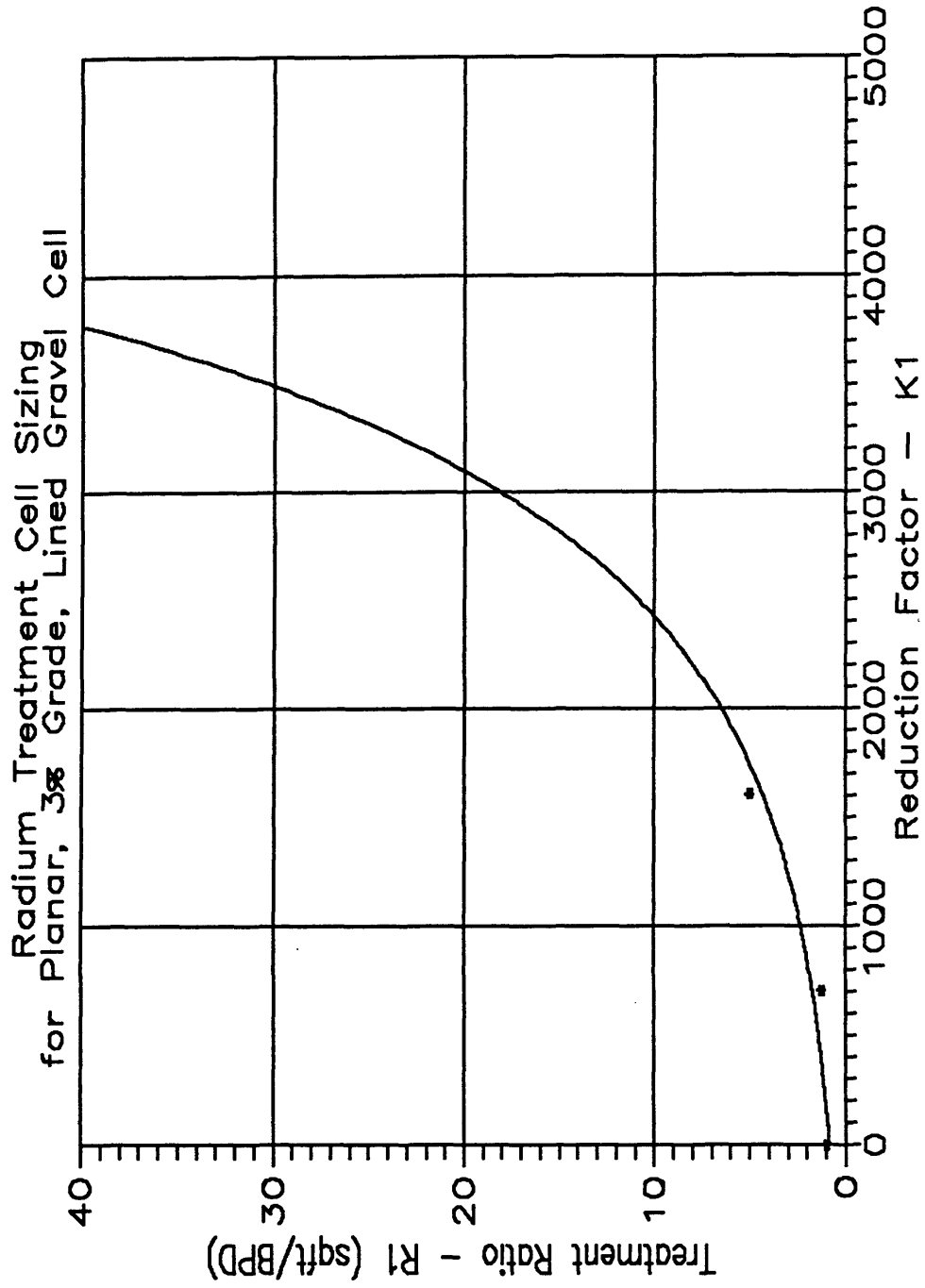


Figure C15 - Radium 226 Treatment Cell Sizing for Planar, 3% Grade, Gravel Cell

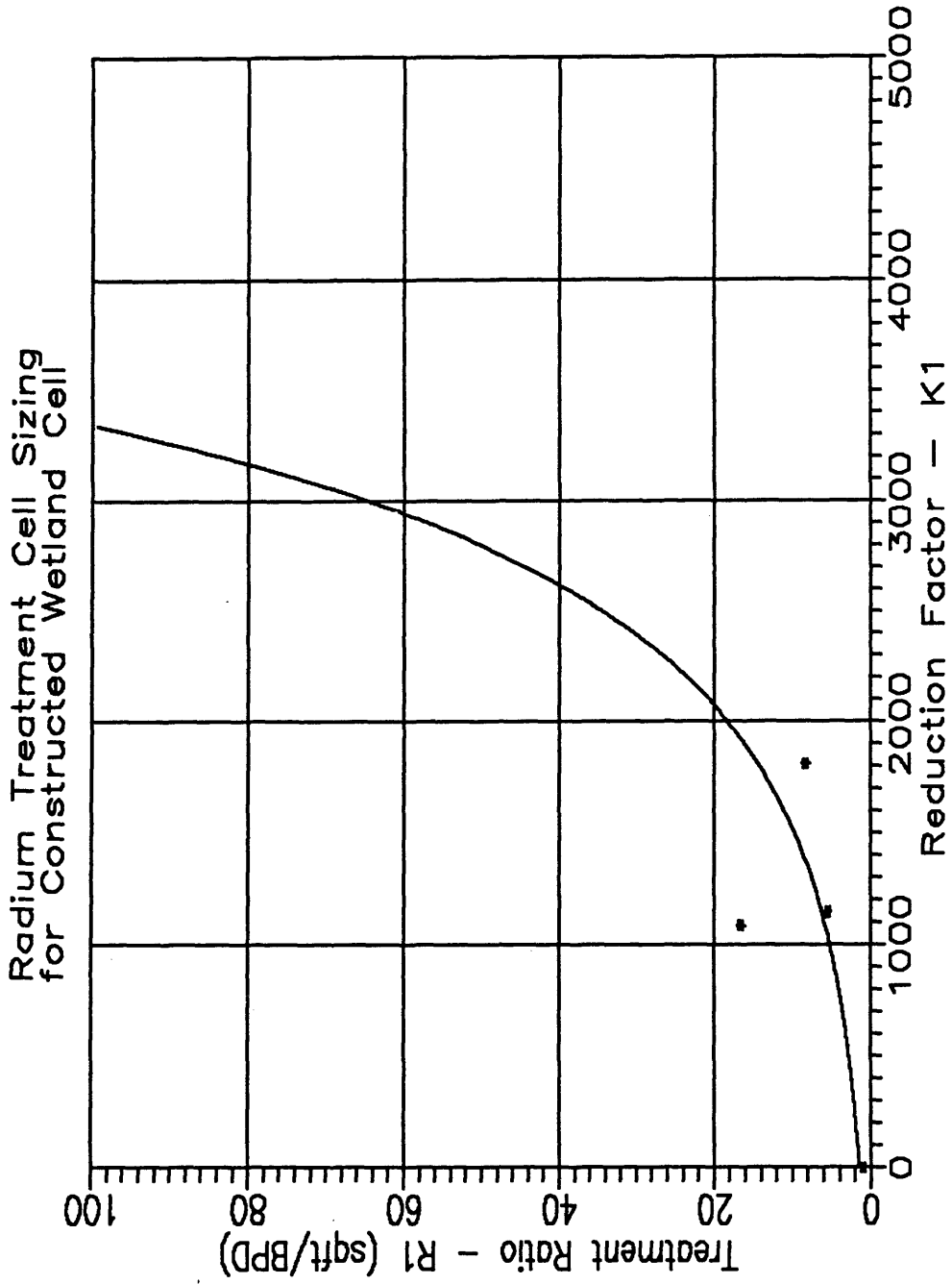


Figure C16 - Radium 226 Treatment Cell Sizing for Constructed Wetland Cell

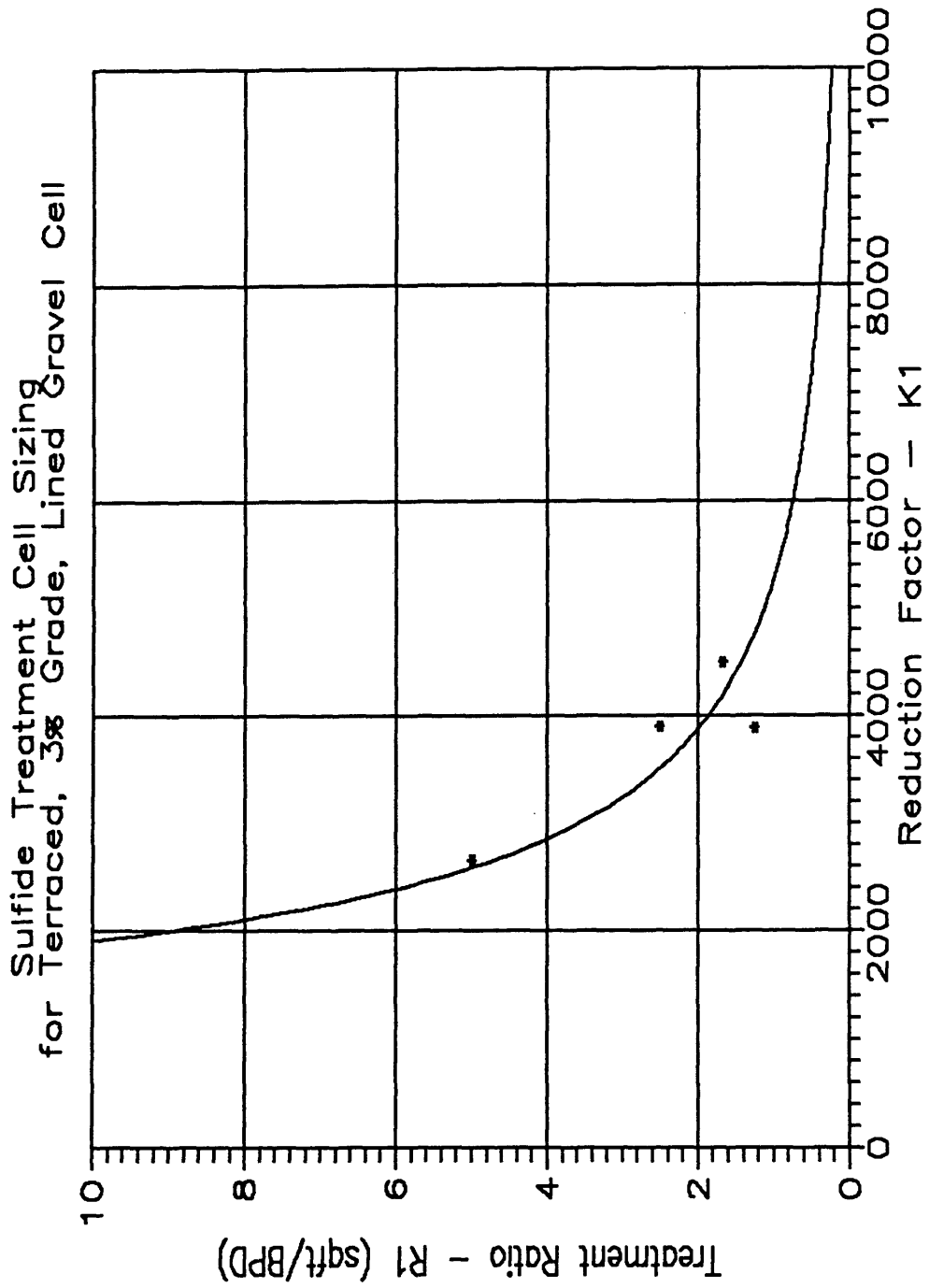


Figure C17 - Sulfide Treatment Cell Sizing for Terraced, 3% Grade, Gravel Cell

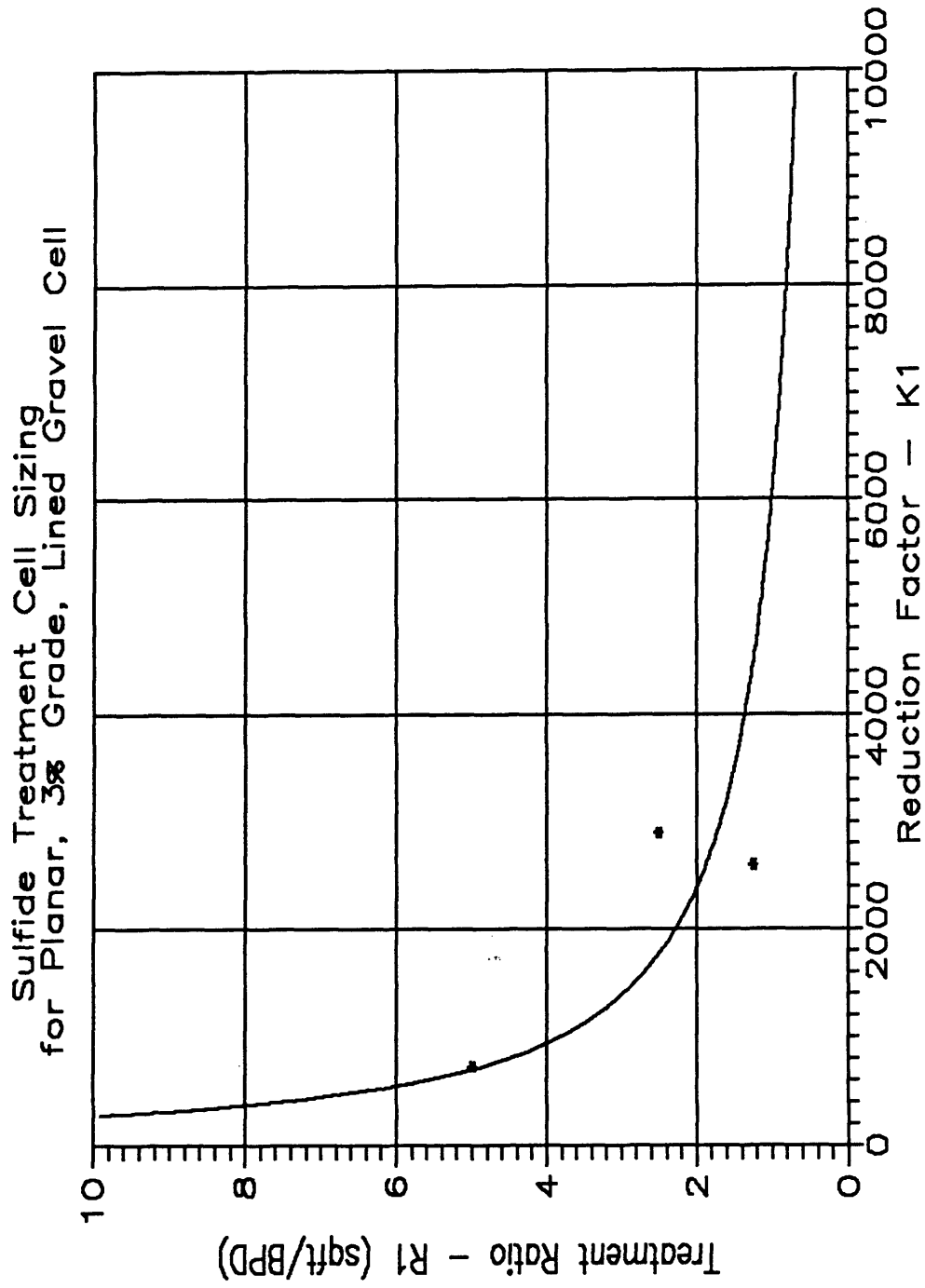


Figure C18 - Sulfide Treatment Cell Sizing for Planar, 3% Grade, Gravel Cell

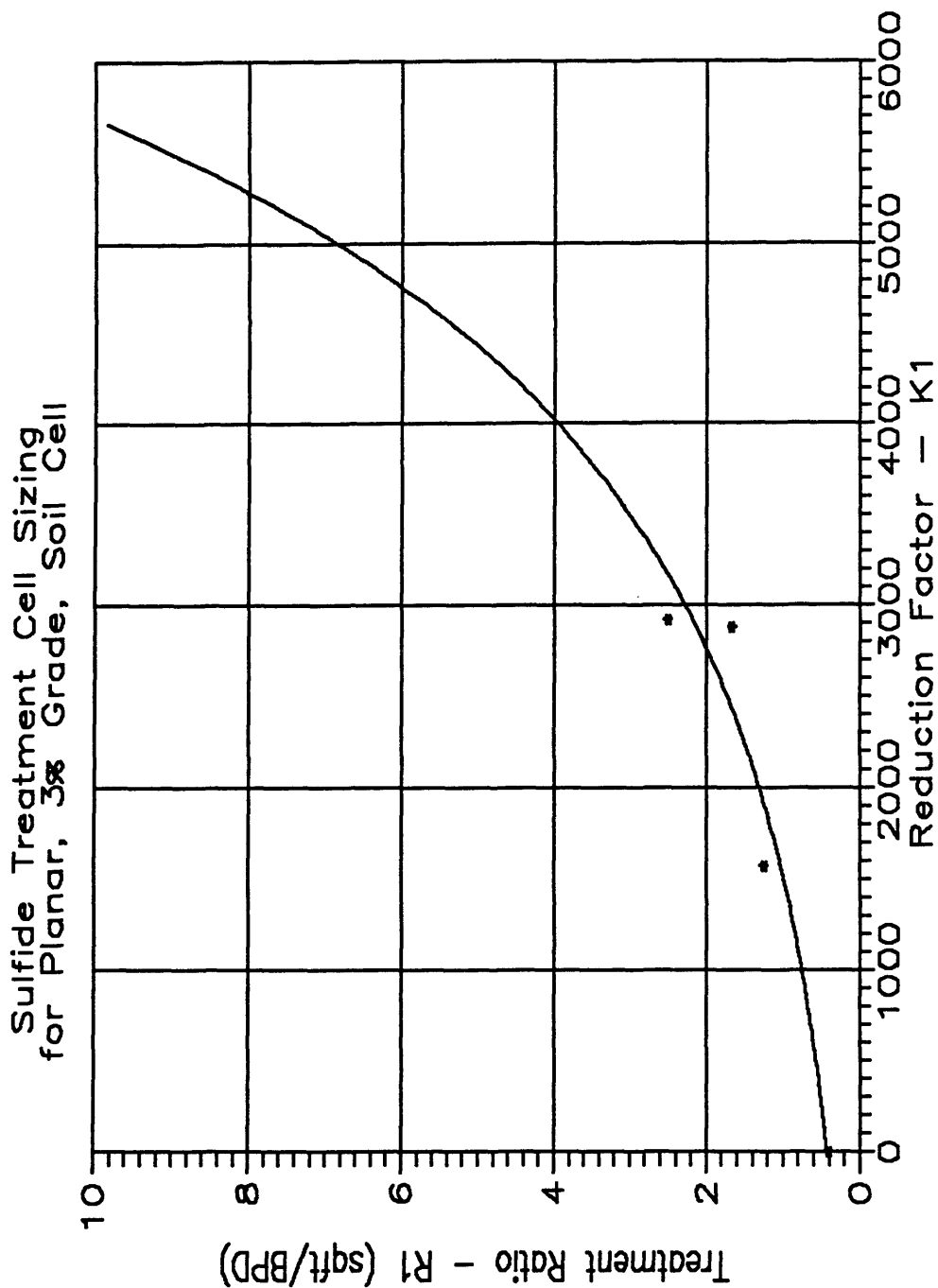


Figure C19 - Sulfide Treatment Cell Sizing for Planar, 3% Grade, Soil Cell

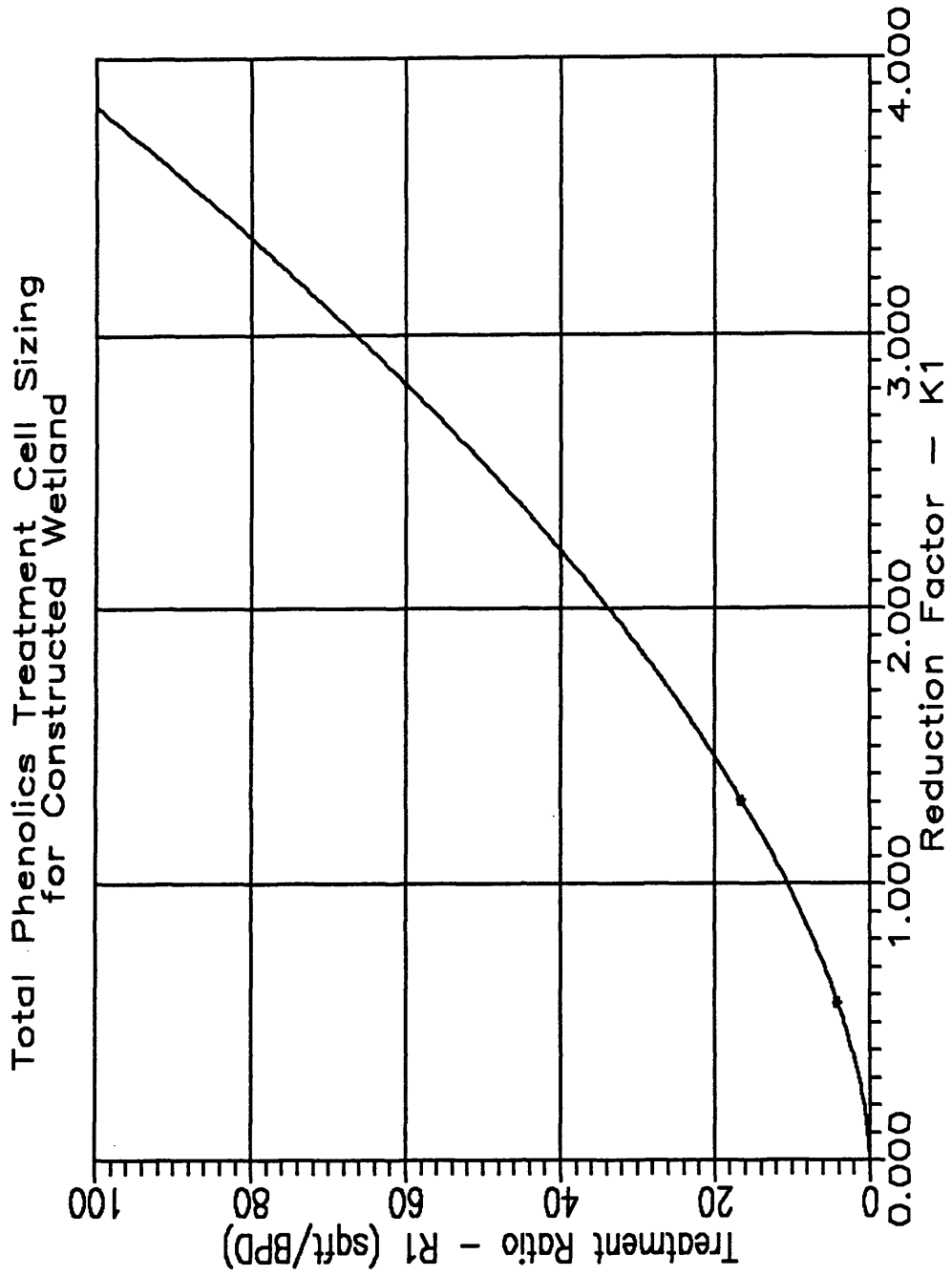


Figure C20 - Total Phenolics Treatment Cell Sizing for Constructed Wetland Cell

Table C11 - Design Example for Radium 226

Constituent to be removed: radium 226
 Flow rate: 5,000 BPD
 Cell Type: 3% grade, terraced, lined gravel cell

<u>Design Procedure</u>	<u>Radium 226</u>	<u>Procedure Description</u>
Maximum inflow concentration	10 pCi/l	from untreated effluent analysis
Required Conc. Reduction	5 pCi/l	(maximum inflow conc. - allowable discharge)
Daily mass loading	7.9 uCi/day	(max inflow conc * flow rate * conversion factor)
Removal factor, K2	0.633	(Req'd conc. red. (pCi/l) / Mass loading (uCi/day))
Reduction factor, K1	3165	(K2 * Flow rate (BPD))
Treatment ratio, R1 for terraced, lined gravel cell	10	Figures C11 - C20
Required treatment area for terraced, lined gravel cell	50,000 sqft	(R1 * Flow rate in BPD)
Cell width	125 ft	((Flow rate (BPD) / 2000) * 50 ft)
Cell length	400 ft	(Treatment area (sqft) / Cell width (ft))
Number of terraces required	16	(Cell length (ft) / 25 ft)
Excavated site grade required	7 %	$\frac{[(\text{cell length}(\text{ft}) * 3\%) + (1\text{ft} * \text{No. of terraces})]}{(\text{cell length}(\text{ft}))} * 100$