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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY  
REGION 5  
77 WEST JACKSON BOULEVARD  
CHICAGO, IL 60604-3590

REPLY TO THE ATTENTION OF  
SR-6J

August 30, 2004

Ms. Jill Kupcak  
Bosch Braking Systems  
3737 Red Arrow Highway  
St. Joseph, MI 49085-9217

RE: Distribution of Five-Year Report  
Bendix/Bosch Superfund Site  
St. Joseph, MI

Dear Ms. Kupcak:

Enclosed is a color copy of the Bendix Five Year Report with attachments. Let me know when you would like to meet and discuss the findings, along with your thoughts on the recommendations contained in this report.

Call me if you have questions prior to the meeting.

I have also sent a color copy to each on the cc list. A black and white version of this report is also available if requested.

If there are requests for further information concerning this report I will let you know

Sincerely,

A handwritten signature in black ink, appearing to read "Ken Glatz".

Kenneth Glatz, P.E.

cc with enclosure

Mark Henry DEQ  
Karl Kasper -W&C

Ruben Slone-Churchill Farms  
John Tielsch - ORC  
Luanne Vanderpool-EPA  
John Wilson- EPA, Ada OK  
Maude Preston Palenske Memorial Library-St Joseph, MI  
Lincoln Township Public Library-Stevensville, MI  
EPA Region 5 Records Center -Chicago IL 7<sup>th</sup> floor  
Office of Superfund, Region 5-Chicago IL 6<sup>th</sup> floor

# **Five-Year Review Report**

**Bendix/Bosch Automotive Group  
Berrien County  
St. Joseph, Michigan**

**August, 2004**

**PREPARED BY:**

**U.S. EPA REGION 5  
Chicago, Illinois**

Approved by:

Date:

Richard C Karl

8-23-04

Richard C. Karl, Acting Director  
Superfund Division

# Five-Year Review Report

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## List of Acronyms

<u>ACRONYM</u>	<u>NAME OR TERM</u>
AOC	Administrative Order on Consent
ARARs	Applicable or Relevant and Appropriate Requirements
BGWDCP	Baseline Groundwater Data Collection Program
CERCLA/SARA	Comprehensive Environmental Response, Compensation and Liability Act/Superfund Amendments and Reauthorization Act of 1986 (Superfund)
CD	Consent Decree
DNAPL	Dense Non Aqueous Phase Liquid (a source area)
GSI	Groundwater Surface Water Interface
HSL	Hazardous Substance List
MDNR	Michigan Department of Natural Resources
MDEQ	Michigan Department of Environmental Quality
MSL	Mean Sea Level
NPL	National Priorities List
O&M	Operation and Maintenance
POC	Point of Compliance
ppb	Parts per Billion concentration
PRP	Potential Responsible Parties
ROD	Record of Decision
RD/RA	Remedial Design/Remedial Action
RI/FS	Remedial Investigation/ Feasibility Study
SOW	Statement of Work
TBC	To Be Considered
U.S. EPA	United States Environmental Protection Agency
VAS	Vertical Aquifer Sampling
VOC	Volatile Organic Compound

## **Executive Summary**

The purpose of a statutory five-year review is to evaluate whether a completed remedial action remains protective of human health and the environment where hazardous waste remains on-site at levels that do not allow for unlimited use and unrestricted exposure. The methods, findings, and conclusions of reviews are documented in Five-Year Review reports. In addition, Five-Year Review reports identify issues found during the review, if any, and identify recommendations to address them.

U. S. EPA conducted this statutory five-year review under Section 121 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the National Contingency Plan (NCP). The next five year report is due by June, 2009.

This review will be placed in the Site files and local repositories for the Bendix/Bosch Superfund Site at the following locations and be available for viewing during normal business hours:

**Maud Preston Palenske Memorial Library**  
500 Market Street  
St. Joseph, MI 49085  
(269) 983-7167

**Lincoln Township Public Library**  
2099 West John Beers Road  
Stevensville, MI 49127  
(269) 429-9575

**U. S. Environmental Protection Agency**  
Region 5 Records Center- Seventh floor  
77 W. Jackson Blvd-7th floor.  
Chicago, IL 60604

**Michigan Department of Environmental Quality**  
Remediation and Redevelopment Division  
Superfund Section  
525 W. Allegan  
PO Box 30426  
Lansing, MI 48909



## Five-Year Review Summary Form

SITE IDENTIFICATION		
Site name (from WasteLAN): Bendix/Bosch Site		
EPA ID (from WasteLAN): MID005107222		
Region: 5	State: MI	City/County: St. Joseph/Berrien County
SITE STATUS		
NPL status: <input checked="" type="checkbox"/> Final <input type="checkbox"/> Deleted <input type="checkbox"/> Other (specify)		
Remediation status (choose all that apply): <input type="checkbox"/> Under Construction <input checked="" type="checkbox"/> Operating <input type="checkbox"/> Complete		
Multiple OUs? <input type="checkbox"/> YES <input checked="" type="checkbox"/> NO	Construction completion date: December 3, 2001	
Has site been put into reuse? <input checked="" type="checkbox"/> YES <input type="checkbox"/> NO		
REVIEW STATUS		
Lead agency: <input checked="" type="checkbox"/> EPA <input type="checkbox"/> State <input type="checkbox"/> Tribe <input type="checkbox"/> Other Federal Agency		
Author name: Kenneth Glatz		
Author title: Remedial Project Manager	Author affiliation: Superfund-2, Section 6	
Review period:** June 1999 - June 2004		
Date(s) of site inspection: Several, jointly by U.S. EPA and MDEQ, in conjunction with supplemental Site studies and groundwater monitoring events.(2000-2003). SVE system-August 17, 2004		
Type of review: <input checked="" type="checkbox"/> Post-SARA <input type="checkbox"/> Pre-SARA <input type="checkbox"/> NPL-Removal only <input type="checkbox"/> Non-NPL Remedial Action Site <input type="checkbox"/> NPL State/Tribe-lead <input type="checkbox"/> Regional Discretion		
Review number: <input checked="" type="checkbox"/> 1 (first) <input type="checkbox"/> 2 (second) <input type="checkbox"/> 3 (third) <input type="checkbox"/> Other (specify)		
Triggering action: <input checked="" type="checkbox"/> Actual RA Onsite Construction at OU # 1__ <input type="checkbox"/> Actual RA Start at OU#____ <input type="checkbox"/> Construction Completion <input type="checkbox"/> Previous Five-Year Review Report <input type="checkbox"/> Other (specify)		
Triggering action date (from WasteLAN): Remedial Action Start , June 17, 1999		
Due date (five years after triggering action date): June 17, 2004		

**Issues:**

The Site remedy is MNA for the west plume and MNA/SVE for the east plume. At issue is whether the remedy as functioning meets U.S. EPA MNA guidance. A three year monitoring study (BGWDCP) was completed in September 2003. The data analysis using GEOS groundwater simulation programs (see appendix) indicates that the mass and concentration of VOC's is increasing in the west plume, and that the boundaries are expanding in both plumes. Data analysis also indicates that the conversion of Vinyl Chloride to non-chlorinated hydrocarbons or carbon dioxide is not completed before the plume vents to Lake Michigan. These findings are contrary to the expectations of MNA, even though risk calculations indicate that there is no unacceptable health risk from exposure to Lake Michigan water, or an ecological problem caused by the venting of VOCs at the shoreline.

**Recommendations and Follow-up Actions:**

The analysis of the BGWDCP data (Volpe and GEOS Reports attached) indicate that the following work needs to be initiated by the PRPs.

- 1 Plume boundaries need to be re-established. Current institutional controls/restrictions need to be reviewed to insure that institutional controls/deed restrictions apply to all property with access to the contaminated groundwater.
- 2 Quarterly monitoring/reporting must be continued until further notice. Lake water sampling must be added to the sampling program.
- 3 Replacement wells need to be installed at all locations that do not permit Low Flow sampling procedures to be practiced.
- 4 A better understanding of the VOC plume path and discharge of VOCs to Lake Michigan is necessary. This will necessitate additional VAS sampling and installation of multi-level groundwater micro-samplers along the beach area between POCW-2 and POCW-4, and additional sampling of Lake Water. Tracer studies should be considered to identify plume movement.
- 5 All historical and current site data needs to be consolidated and used to better identify the location of the west plume TCE source, in the event additional remedial activity is warranted for the source area.
- 6 The PRPs need to prepare a report that identify the specifics of alternate treatments/enhancements to MNA, including cost estimates and a time line schedule,

should they be required. At a minimum two enhancements should be considered 1) injection of specific TCE destroying microbes near the TCE source area, and 2) chemical release into the plume to enhance conversion of vinyl chloride to ethane/ethene, without upsetting the "natural" biogeochemical process now operating. The work plan should also suggest pilot studies for these or other alternates. The work plan should be delivered by January 2005. Additional recommendations from the PRPs are encouraged.

- 7 Alternate concentration limits or GSI values must be selected for both the east and west plumes.

**Protectiveness Statement:**

The remedy is currently protective of human health and the environment, and was constructed in accordance with the Record of Decision. Capping and SVE treatment of the contaminated soils has removed the possibility of human contact with the east source material and institutional controls are in place that restrict use of contaminated groundwater for both the east and west plumes. However for the remedy to be protective in the long-term an assessment of the MNA activity in both plumes must be conducted. Pilot studies for improving the effectiveness of MNA and sampling along the beach and in the Lake waters need to be considered to insure that human health risk continues to be acceptable.

## **Five-Year Review Report**

### **I. Introduction**

#### **The Purpose of the Review**

The purpose of a statutory five-year review is to evaluate whether a completed remedial action remains protective of human health and the environment at sites where hazardous waste remains on-site at levels that do not allow for unlimited use and unrestricted exposure. The methods, findings, and conclusions of reviews are documented in Five-Year Review reports. In addition, Five-Year Review reports identify issues found during the review, if any, and identify recommendations to address them.

#### **Authority for Conducting the Five-Year Review**

U. S. EPA is preparing this Five-Year Review pursuant to CERCLA Section 121 and the National Contingency Plan (NCP). CERCLA Section 121 states:

*If the President selects a remedial action that results in any hazardous substances, pollutants, or contaminants remaining at the site, the President shall review such remedial action no less often than each five years after the initiation of such remedial action to assure that human health and the environment are being protected by the remedial action being implemented. In addition, if upon such review it is the judgement of the President that action is appropriate at such site in accordance with section 104 or 106, the President shall take or require such action. The President shall report to the Congress a list of facilities for which such review is required, the results of all such reviews, and any actions taken as a result of such reviews.*

U.S. EPA interpreted this requirement further in the NCP; 40 Code of Federal Regulations (CFR) Section 300.430(f)(4)(ii) which states:

*If a remedial action is selected that results in hazardous substances, pollutants, or contaminants remaining at the site above levels that allow for the unlimited use and unrestricted exposure, the lead agency shall review such action no less often than every five years after the initiation of the selected remedial action.*

#### **Who Conducted the Five-Year Review**

Mr. Kenneth Glatz, Remedial Project Manager, U.S. EPA Region 5, performed this five-year review. The Five-Year Review was based, in part, on the ongoing oversight of monitoring activities at the Site from December 2000 to September 2003, and the interpretation of that data. In addition the Project Manager reviewed documents, including the ROD, SOW, Consent Decree, Construction Completion Report and results of supplemental studies conducted at the Site. U.S. EPA completed this Five-Year Review based upon the information obtained from

these sources and activities.

### Other Review Characteristics

This is the first five-year review for the Bendix/Bosch Site. The triggering action for this review is the date of RA on-site construction mobilization, June, 1999. The review is necessary since hazardous substances, pollutants and contaminants are left on Site above levels that allow unlimited and unrestricted exposure.

## **II. Site Chronology**

<u>Event</u>	<u>Date</u>
NPL RP Search	June 1988
AOC	March, 1989
Community relations Plan	August 1989
NPL Listing	February 1990
Special Notice issued	September 1996
RI Report	September 1997
Public Comment	August - September 1997
ROD	September 1997
PRP Remedial Design	June 1999
RA Start	June 17, 1999
Consent Decree	October 1999
Lake Study Data Report	November 1999
SVE Final Inspection	August 2000
Construction Completion Report	November 2001

Preliminary Close Out Report

December 2001

Ecological Risk Assessment

January 2002

### III. Background

#### Physical Characteristics

The Bendix/Bosch Superfund Site is located in Lincoln Township, Berrien County, Michigan, approximately four miles south of the City of St. Joseph. The Bendix/Bosch Site address is 3737 Red Arrow Highway, approximately one-half mile from the eastern shore of Lake Michigan, and approximately one-third mile west of Hickory Creek, and bordered to the west by Red Arrow Highway (Fig. 1). Contaminants have migrated from the Site to Lake Michigan and Hickory Creek (Fig. 2).

The Bendix/Bosch Site's topography is generally flat and the land surface is mostly covered by manufacturing buildings and pavement. The land surface rises slightly to the west of the Bendix/Bosch Plant to the lake bluff. The land surface to the east gently slopes toward Hickory Creek falling steeply away at the creek. Groundwater flows from the Bendix/Bosch Site toward Hickory Creek to the east, and toward Lake Michigan to the west. Hickory Creek and Lake Michigan are used for recreational purposes. The entire area adjacent to the Bendix/Bosch Site is supplied with drinking water from the City of St. Joseph municipal water supply. The source of the drinking water is Lake Michigan, three and a half miles north of the site.

Directly beneath the Bendix/Bosch Site, there are three distinct hydrogeologic units, the unconfined water table aquifer; a series of aquicludes (semi-confining layers) consisting of interbedded silts and sands; and the lower clay unit acting as an aquatard (confining layer).

The uppermost soil at the Bendix/Bosch Site is a fine to medium sand. This sand extends from the surface to approximately 40 to 50 feet below ground surface. This medium to fine sand unit allows rain water to infiltrate the subsurface and recharge the groundwater. This uppermost soil also has the greatest hydraulic conductivity, which has been measured in the  $10^{-3}$  to  $10^{-4}$  cm/sec range, and provides the path for contaminant transport. These fine to medium sands grade to fine silty sands with depth.

At an elevation of between 580 and 560 feet above MSL, the soil type changes to interlayered clayey silts and silty sands with occasional gravel. This unit is discontinuous and is most prevalent below the eastern side of the Bendix/Bosch Site. When present, this fine-grained unit ranges in thickness from a few feet to approximately 20 feet. The hydraulic conductivity values of the silt/clay layers are generally  $10^{-5}$  cm/sec with occasional  $10^{-6}$  cm/sec values in the clay units. The interlayered silty sands have hydraulic conductivity values ranging from  $10^{-4}$  to  $10^{-5}$

cm/sec. Groundwater movement through this interlayered unit will occur principally within the more conductive thin silty sand layers.

Below the interlayered clayey silt sand is a stiff clay to silty clay. This clay unit is most prevalent at the center of the Bendix/Bosch Site near the plant. The hydraulic conductivity value of this unit was measured at  $10^{-6}$  cm/sec. This unit has a significantly lower permeability than the sands located stratigraphically above it, and will act as a hydraulic barrier to the vertical migration of groundwater and/or contaminants.

Regional groundwater flow is toward Lake Michigan with a nominal Lake elevation of 580 feet above MSL. The maximum groundwater elevation in the vicinity of the plant is approximately 605 feet above MSL. Superimposed on this regional flow are the localized effects of Hickory Creek. Hickory Creek has incised the sandy surface soils to a current creek elevation of 586 feet above MSL. This elevation difference between the groundwater and the creek causes the localized groundwater to flow toward Hickory Creek. This has created a groundwater divide in the vicinity of the Bendix/Bosch plant. Groundwater on the east side of this divide flows toward and discharges to Hickory Creek, while groundwater on the west side of this divide flows toward and discharges to Lake Michigan ( Fig. 2).

#### Land and Resource Use

Currently, land use in the vicinity of the Bendix/Bosch Site is a mixture of commercial, residential, and industrial. Churchill Farms is a residential development between the Site and Lake Michigan. Commercial and industrial facilities are located between the Bendix/Bosch Site and Hickory Creek. Areas north and south of the Bendix/Bosch Site are a mixture of commercial and residential properties.

#### History of Contamination

The Bendix/Bosch Site was originally farmland but was developed in 1939 by the Nylen Products Corporation. The 36-acre facility consisted of an iron casting foundry and a machine shop. The Bendix Corporation (Bendix) purchased the property in 1952 that was later acquired by Allied Chemical in 1983. Its successor, AlliedSignal Inc. sold the facility to Bosch, current owner, in 1996. The facility currently contains a foundry and a manufacturing plant.

Oil-based cutting fluids were used at the facility during the 1950s and 1960s. Water-soluble cutting fluids were used beginning in 1967. Chlorinated solvents were reportedly used in the 1960s and 1970s. From 1965 to 1975, foundry dust and machine shop oily waste waters were disposed into three former unlined lagoons: (1) foundry "A" lagoon, (2) south lagoon, and (3) the loading dock lagoon. The foundry "A" lagoon and the loading dock lagoon were closed and their contents disposed into the south lagoon. The south lagoon was closed in 1978 with the installation of a MDNR-approved clay cap. Bendix used an on-site liquid incinerator, lagoons,

and off-site commercial disposal facilities until the mid 1970s. A landfill (Maiden Lane Landfill) was also used from 1966 to 1979 for the disposal of foundry residues, asbestos in brake shoes, and encapsulated asbestos pellets. Environmental investigations began at the Bendix Site in 1975 when three groundwater wells were installed around the south lagoon. Since that time numerous investigations have been conducted to evaluate the nature and distribution of industrial chemicals in soil, groundwater, surface water, and sediments associated with the Bendix Site and neighboring properties. Industrial chemicals identified in the environment include both organic and inorganic compounds associated with the manufacture of braking systems.

### Initial Response

The Bendix/Bosch site was placed on the NPL of hazardous waste sites on February 21, 1990. Offsite contamination was found in residential wells to the west of the plant (west plume), and in a commercial business well to the east of the plant (east plume). Preliminary sampling and analysis of groundwater in the plant area indicated the presence of high concentrations of organic HSL compounds.

In response to a release or a substantial threat of a release of hazardous substances at or from the Site, the Bendix Corporation initiated RI/FS work at the site under an AOC issued in March, 1989. Bendix completed the RI Report in September 1997, and the FS report in January 1998. U.S. EPA published a notice of the completion of the FS and Proposed Plan for the groundwater remedial action on August 31, 1997.

### Basis for Taking Action

Industrial chemicals identified at the Site included both organic compounds and inorganic elements associated with the manufacture of braking systems. The most frequently detected organic contaminants at the Bendix Site are trichloroethene (TCE) and 1,1,1-trichloroethane (1,1,1-TCA), along with their degradation products, cis-1,2-dichloroethene (cis-1,2-DCE) and trans-1,2-dichloroethene (trans-1,2-DCE), 1,1-dichloroethane (1,1-DCA) and vinyl chloride (VC). These contaminants accounted for the majority of health-based risk posed at the Site. As a result of the industrial activities at the Bendix Site, and the natural groundwater divide, two VOC Plumes were identified (eastern and western plumes). The eastern plume capillary fringe source is a buried lagoon in the vicinity of the loading dock, creating a plume that extends northeast to its primary discharge zone along Hickory Creek. The western plume DNAPL source (assumed, since it was never identified) originates in the area of the north parking lot and creates a plume that extends to the northwest where it discharges to Lake Michigan (see Fig. 3 and Fig. 4). The closed south lagoon is located over the groundwater divide and continues to release low levels of industrial cutting oil residuals to the groundwater.



## **IV Remedial Actions**

### Remedy Selection

The response action selected in the September 29, 1997 ROD is a combined SVE treatment/MNA remedy for the east plume, MNA for the west plume and deed restrictions on the use of contaminated groundwater until the remedy is complete. The selected remedial alternative for the eastern and western plumes and their source areas acknowledges the natural biodegradation processes occurring within the plumes. U.S. EPA's Kerr Laboratory scientists concluded at that time that the contaminants causing the risk in the western plume were being naturally degraded to below harmful concentrations prior to discharge to Lake Michigan. Environmental monitoring continues to be conducted to evaluate the effectiveness of natural attenuation processes. The ROD remedy includes the following components:

- Environmental monitoring with protective contingency plans;
- Institutional controls restricting use of contaminated groundwater;
- Natural attenuation of dissolved organics;
- Five-year Site Reviews;
- Eastern plume source area cover maintenance and;
- Installation/operation of an SVE vapor treatment system.

These remedial actions prevent the potential for future human health risks associated with exposure to VOCs in the groundwater plumes and the air through volatile emissions by (1) reducing VOC concentrations in the eastern plume source area (2) reducing volatile emissions in the vadose zone over the eastern plume, and (3) reducing concentrations of VOCs in groundwater associated with the eastern and western plumes. Contingency plans will be implemented in the event that monitoring shows confirmed, statistically significant exceedences of groundwater contamination above (yet to be) established values, prior to the discharge of the plume to Lake Michigan. This will prevent release of contaminants into surface water bodies that would cause unacceptable human health or ecological risk concerns.

### Remedy Implementation

The Preliminary Close-Out Report for the Bendix/Bosch Site documents that all construction activity has been completed at the Site. The initial SVE system used ultra violet contaminant destruction but was replaced with a thermocatalytic system when the ultraviolet unit failed to produce design destruction efficiency. The final inspection for the thermocatalytic SVE system was made on August 30, 2000. The SVE system was last inspected on August 17, 2004 and continues to perform as designed. The BGWDCP monitoring wells were completed in the fall of 2000.

The Remedial Action shall restore the plumes to: Drinking Water Standards; a cumulative excess

cancer risk below  $10E-4$ ; and a cumulative Hazard Index below one (i.e., Cleanup Standards) throughout the east and west plumes; and deed restrictions on the use of contaminated groundwater until groundwater goals have been met.

### System Operation/O & M

#### Existing Cover System:

The cover system above the eastern plume source area consists of asphalt, concrete slab, and existing buildings. The cover system is visually inspected quarterly and repaired as necessary (e.g., resurfaced, patched). This cover system will continue to minimize infiltration to vadose zone soils, thereby reducing the amount of contaminants released to groundwater, and will also reduce potential access/direct contact to these soils by on-site workers.

#### Operation of the SVE System:

The modified Operation and Maintenance Plan (O&M) for the SVE system was approved in August 2000. The SVE treatment system is an in-situ vadose zone treatment technology that operates via application of a vacuum to promote vapor flow through the vadose zone. Contaminants volatilize from soil and are swept by air flow to extraction wells located throughout the contaminated area. Extracted air is treated using thermocatalytic oxidation to destroy contaminants and achieve air emission requirements. System operating parameters (temp, pressure and flow) are taken weekly. This system is instrumented with a variety of alarms. These alarms are responded to by Bosch plant personnel as required. Summa canister testing procedures are used on a quarterly basis to collect influent and effluent samples from the SVE system. The results of the summa canister data is reported quarterly, and summarized in an annual report. Calculations indicate that over 1900 pounds of VOCs have been removed from the soils since the system was put into operation in 2000.

#### Monitoring Well Systems:

Groundwater at the Site is not being used as a source of drinking water and is not likely to be used in the future because of groundwater use restrictions on the Site and the availability of municipal water. Monitoring well systems for both plumes were completed in late 1999. These well systems contain POC wells, plume centerline wells, sentinel wells (perpendicular to centerline wells), plume boundary wells and background wells (upgradient of the plumes). These wells were sampled quarterly using Low-Flow sample techniques from December 1999 to September 2003. The results were reported quarterly, summarized in two annual reports and in the Final BGWDCP Report issued in February 2004.

## **V Progress since the last Five Year Review.**

This is the first Five Year Review for the Site.

## **VI Five Year Review Process**

### Administrative Components

This Five-Year Review was based, in part, on Site visits conducted from December 2000 to March 2004, during oversight of the BGWDCP monitoring events, and the analysis of the data contained in the Final BGWDCP Report. The Final BGWDCP Report consisted of two volumes. Volume I includes a summary of all 12 rounds of data, PRP data analysis, PRP development of ACLs, the Human Health Risk Assessment update and conclusions/recommendations. Volume II contains all Appendices referred to in Vol I.

The monitoring events were frequently attended by the Settling Defendants, Settling Defendants contractor, representatives from MDEQ and the U.S. EPA Project Manager.

### Community Involvement

A meeting was held at the Site in June, 2003, with representatives from the Churchill Farms Homeowners Association, MDEQ, and representatives from U.S. EPA, to review the status of venting of contaminants into Lake Michigan just off the beach area of the Churchill Farms property. Risk calculations indicate that there is no unacceptable risk posed by recreational use of the beach area, but the concentration and quantity of contaminants being vented to the Lake needs to be monitored on a regular schedule. U.S. EPA indicated during the meeting that the five year review report would be issued in the summer of 2004.

A news release was made in the St. Joseph Herald Palladium October, 2003, to announce the start of the Five Year Review for the Bendix/Bosch Site.

### Interviews.

No interviews were conducted in connection with this five year review, since the primary interest was from the Homeowners Association, mentioned above.

### Site Inspection

As indicated, this Five-Year Review was based, in part, on Site visits conducted from December 2000 to March 2004, during oversight of the BGWDCP monitoring events. The SVE system is

located within the plant gates proper, and the SVE system was inspected by U.S. EPA and MDEQ on two occasions. The system was operating as designed during these visits.

#### Document and data review

The Project Manager reviewed documents, including the ROD, Construction Completion Report, Churchill Farms beach area Ecological Survey, data from supplemental studies conducted by MDEQ and Bosch, SVE data, and data evaluation of the BGWDCP. U.S. EPA completed this Five-Year Review based upon the information obtained from these sources and activities. The documents and data reviewed in preparing this Five Year Review are listed in the "List of Documents Reviewed", and the attachments.

### **VII. Technical Assessment**

**Question A: Is the remedy functioning as intended by the decision documents? Indeterminate**

#### Remedial Action Performance

U.S. EPA's Kerr Laboratory conducted extensive evaluations of the conditions at the Bendix Site, and indicated that the most important natural degradation mechanism is reductive dechlorination. This mechanism involves microbially catalyzed reactions caused by the replacement of chlorine atoms on the organic solvent molecules with hydrogen atoms. Reductive dechlorination of TCE results in the formation of daughter products, most significantly cis-1,2-DCE and vinyl chloride. Vinyl chloride, in turn, is degraded either aerobically or anaerobically to carbon dioxide or ethene, respectively (see Fig. 5).

All biodegradation reactions require an electron donor and an electron acceptor. In reductive dechlorination reactions, the contaminants (i.e., TCE, DCE) serve as electron acceptors rather than the primary food source (electron donor) for microbes. Thus, a primary organic substrate (food source) is necessary to serve as the electron donor for microbial energy and reproduction. A number of low molecular weight organic compounds can serve as electron donors. Data from the Bendix Site suggests that one source of the primary substrate (electron donors) used by anaerobic microorganisms to drive the dechlorination reactions originates from the former south lagoon. The low levels of soluble cutting oil residuals and other non-chlorinated organic compounds are being released into the groundwater from the former south lagoon.

The model for the destruction of TCE in both the western and eastern plumes occurs in two steps:

Anaerobic reduction of TCE to cis-1,2-DCE, vinyl chloride, and finally to ethene.

Aerobic oxidation of any remaining vinyl chloride to carbon dioxide.

The data analysis of the BGWDCP was completed in June 2004. GEOS Groundwater simulation programs (attachment 1), indicate that the mass and volume of TCE is statistically increasing in the west plume. The mass of TCE is not statistically increasing in the east plume but the volume is. The data analysis also indicates that the conversion of Vinyl Chloride to non-chlorinated hydrocarbons or carbon dioxide is not proceeding to completion before being vented into Lake Michigan. The mass of the other chlorinated VOCs show no statistical trends, but have not decreased in overall mass in either plume during the study. These findings are inconsistent with the expectations of the ROD remedy for MNA and is the basis for the "Indeterminate" answer above.

### System Operation and Maintenance

#### Existing Cover System:

The cover system above the eastern plume source area consists of asphalt, concrete slab, and existing buildings. The cover system is visually inspected quarterly and repaired as necessary (e.g., resurfaced, patched). This cover system will continue to minimize infiltration to vadose zone soils, thereby reducing the amount of contaminants released to groundwater, and will also reduce potential access/direct contact to these soils by on-site workers.

#### Operation of the SVE System:

The modified Operation and Maintenance Plan (O&M) for the SVE system was approved in August 2000. The SVE treatment system is an in situ vadose zone treatment technology that operates via application of a vacuum to promote vapor flow through the vadose zone. Contaminants will volatilize from soil and be swept by air flow to air extraction wells located throughout the contaminated area. Extracted air is treated using catalytic oxidation to destroy contaminants and achieve air emission requirements. System operating parameters (temp, pressure and flow) are taken weekly. This system is instrumented with a variety of alarms. These alarms are responded to by Bosch plant personnel as required. Summa canister procedures are used on a quarterly basis to collect influent and effluent samples from the SVE system. The results of the summa canister data is reported quarterly, and summarized in an annual report. Calculations indicate that over 1900 pounds of VOCs have been removed from the soils since the system was put into operation in 2000.

#### Monitoring Well Systems:

Groundwater at the Site is not being used as a source of drinking water and is not likely to

be used in the future because of groundwater use restrictions on the Site. Monitoring well systems for both plumes were completed in late 1999. These well systems contain POC wells, plume centerline wells, sentinel wells (perpendicular to centerline wells), plume boundary wells and background wells (upgradient of the plumes). These wells were sampled quarterly using Low-Flow sample techniques from December 1999 to September 2003. The results were reported quarterly and all data summarized in the Final BGWDCP Report issued in January 2004.

#### Implementation of Institutional Controls and Other Measures

Institutional controls are in place that restrict the use of contaminated groundwater for all uses until the groundwater meets the clean-up goals.

**Question B: Are the exposure assumptions, toxicity data, cleanup levels, and remedial action objectives used at the time of the remedy still valid? YES**

#### Changes in Standards and To Be Considered Criteria

The state has indicated that vinyl chloride and trichloroethane groundwater concentrations are above state GSI criteria at two POCW monitoring locations. The U.S. EPA is currently reviewing whether the current GSI criteria for these compounds are applicable or relevant and appropriate to the remedy at the Site. Based on the decision, the appropriate action will be taken in accordance with the provisions in the ROD and Consent Decree. There are no other standards identified in the ROD which have been revised, no newly promulgated standards and no TBC used in selecting the cleanup levels at the Site that have changed and could affect the protectiveness of the remedy.

#### Changes in Exposure Pathways

Contaminants are venting into Lake Michigan in shallow water just off the Churchill Farms beach. This presents an exposure pathway for recreational exposure not considered in the ROD. To date the risk calculations based on the surface water quality in this area are well below risk based concerns. Additional O&M provisions will be implemented to insure that the recreational exposure stays minimal, and that there is no unacceptable risk to recreational use of the beach. There have been no land use changes at the Site nor are any expected in the near future.

#### Changes in Toxicity and Other Contaminant Characteristics

Neither the toxicity factors for the contaminants of concern nor other contaminant characteristics have changed in a way that could affect the protectiveness of the remedy.

### Changes in Risk Assessment Methods

Standardized risk assessment methods have not changed in a way that could affect the assessment of the protectiveness of the remedy. Risk calculations will be updated as necessary.

### Expected Progress Toward Meeting Remedial Action Objectives

The remedy for the Site is progressing through MNA processes, primarily biological activity. Progress toward the Remedial Action Objectives continues to be made at the Site, although there are concerns as indicated in the "Issues" section of this report. The monitoring program will continue to ensure that any changes in contaminant levels will be detected and addressed as necessary.

**Question C: Has any other information come to light that could call into question the protectiveness of the remedy? YES**

### Technical Assessment Summary

Post-ROD information suggested that the western plume may be discharging to Lake Michigan nearer to the shoreline than believed (*Effects of the Lake-Ground Water Interactions on the Transport and Bioremediation of Chlorinated Solvents Discharging to the Great Lakes*; University of Michigan Doctoral dissertation by S.M. Dean (1998)). S.M. Dean's paper indicated that TCE may be venting at the shore line into the lake well above earlier modeling projections. Scientists from the U.S. EPA Kerr Laboratories verified this in April, 1998, by collecting samples just off the beach area in shallow water. MDEQ has also conducted independent pore water studies in the beach area with the intent of defining and monitoring the area of the plume discharge. (Pore water is defined as the interstitial water contained in the sand beneath the Lake surface. The pore-water sample is taken six to 12 inches deep into this sand layer). Bosch submitted a Lake Study Work Plan to U.S. EPA Region 5 as part of the RD/RA for the Bendix/Bosch Superfund Site to explore this concern. This proposed Work Plan detailed additional sampling activities to be conducted to support a supplemental Human Health and Ecological Risk Evaluation of surface water, sediment, and shallow groundwater associated with the western plume and Lake Michigan at the location where the western plume discharges to Lake Michigan. The Work Plan was incorporated into the CD and SOW for the RD/RA signed by Bendix/Bosch and U.S. EPA in March, 1999. The requirements included post-design studies for further characterization of the cross-sectional area of the plumes directly upgradient of their discharge points and additional evaluation of the potential human health and ecological risk completed during the 1997 RI.

The results of the Lake study were submitted to U.S. EPA by Bosch entitled "Lake Study Data Report", November 1999. The conclusions presented in this report indicate that the plume venting into Lake Michigan does not present an unacceptable risk to Human Health. The

Ecological Survey was conducted by Bosch in September 2001. The Ecological Survey Report indicated that at that time there was no ecological risk presented from the groundwater plume venting into Lake Michigan. Since then over 100 samples have been taken in the pore-water and surface waters just off the Churchill Farms' beach area. There is some indication from MDEQ data that the pore-water and surface water contaminant concentrations are increasing, but the surface water data does not present an unacceptable risk to recreational users of the beach.

Plume characterization work was also conducted at the bluff along with the Lake Study as a requirement of the RD/RA. A total of 52 groundwater samples were collected along the lake bluff utilizing a Hydropunch and bailer. These data sets provided a detailed cross-sectional view of the western plume transverse to its discharge to Lake Michigan. U.S. EPA's evaluation of the recently completed BDWDCP study indicates that the west plume concentration centerline shifts slightly to the north and south, and perhaps the plume does as well. There is some concern that this plume concentration centerline movement may influence the data taken from the POCW wells. U.S. EPA believes that several exploratory wells will need to be installed between POCW-2 and POCW-4 to complete the characterization of the plume and study the plume movement trends. Vertical Aquifer Sampling to clay will be used to select the location of multi-level groundwater micro-samplers screens for future sampling.

In addition the BGWDCP data indicates that the MNA remedy is deficient in three areas. The first is that the plumes are expanding, in volume and mass in the west plume, and in volume in the east plume. The second is that the data indicates that the mass of chlorinated contaminants is increasing in the middle of the plume. Data analysis also indicates that the conversion of Vinyl Chloride to non-chlorinated hydrocarbons and carbon dioxide is not completed before the plume vents to Lake Michigan. These findings are contrary to the expectations of MNA, and raises the concern with MNA as a sole remedy, even though there is no unacceptable calculated health risk from exposure to Lake Michigan water, or an observed ecological problem from the venting of VOCs at the shoreline. The PRPs will be required to consider remedy refinements.

There have been no newly identified human health or ecological risks, impacts from natural disasters, or any other information that has been identified that could affect the protectiveness of the remedy for the Site.

## **VIII. Issues**

The Site remedy is MNA for the west plume and MNA/SVE for the east plume. At issue is whether the remedy as functioning meets U.S. EPA MNA guidance. A three year monitoring study (BGWDCP) was completed in September 2003. The data analysis using GEOS groundwater simulation programs (see attachment 1) indicates that the mass and concentration of VOC's is increasing in the west plume, and that the boundaries are expanding in both plumes. Data analysis also indicates that the conversion of Vinyl Chloride to non-chlorinated



hydrocarbons or carbon dioxide is not completed before the plume vents to Lake Michigan. These findings are contrary to the expectations of MNA, even though risk calculations indicate that there is no unacceptable health risk from exposure to Lake Michigan water, or an ecological problem caused by the venting of VOCs at the shoreline.

## **IX. Recommendations and Follow-Up Actions**

The analysis of the BGWDCP data (Volpe and GEOS Report attachments) indicate that the following work needs to be initiated by the PRPs.

- 1 Plume boundaries need to be re-established. Current institutional controls/restrictions need to be reviewed to insure that institutional controls/deed restrictions apply to all property with access to the contaminated groundwater.
- 2 Quarterly monitoring/reporting must be continued until further notice. Lake water sampling must be added to the sampling program.
- 3 Replacement wells need to be installed at all locations that do not permit monitoring well Low Flow sampling procedures to be practiced.
- 4 A better understanding of the VOC plume path and discharge of VOCs to Lake Michigan is necessary. This will necessitate additional VAS sampling and installation of multi-level groundwater micro-samplers along the beach area between POCW-2 and POCW-4, and additional sampling of Lake Water. Tracer studies should be considered to identify plume movement.
- 5 All historical and current site data needs to be consolidated and used to better identify the location of the west plume TCE source, in the event additional remedial activity is warranted for the source area.
- 6 The PRPs need to prepare a report that identifies the specifics of alternate treatments/enhancements to MNA, including cost estimates and time line schedule, should they be required. At a minimum two enhancements should be considered 1) injection of specific TCE destroying microbes near the TCE source area, and 2) chemical release into the plume to enhance conversion of vinyl chloride to ethane/ethene, without upsetting the "natural" biogeochemical process now operating. The work plan should also suggest pilot studies for these or other alternates. Additional recommendations from the PRPs are encouraged.
- 7 Alternate concentration limits or GSI values must be selected for both the east and west plumes.

## **X. Protectiveness Statement**

The remedy is currently protective of human health and the environment, and was constructed in accordance with the Record of Decision. Capping and SVE treatment of the contaminated soils has removed the possibility of human contact with the east source material and institutional controls are in place that restrict use of contaminated groundwater for both the east and west plumes. However for the remedy to be protective in the long-term an assessment of the MNA activity in both plumes must be conducted. Pilot studies for improving the effectiveness of MNA need to be considered, and O&M provisions made for the beach area to insure human health risk continues to be acceptable.

The statutory and regulatory requirements for the remedial action at the Bendix Site as described in the ROD are to:

- Reduce/eliminate the potential risks to human health associated with exposure to chlorinated VOCs in the Western and Eastern Plumes;
- Reduce the concentrations of VOCs in the Western and Eastern Plumes to drinking water standards;
- Reduce/control the VOC source of contaminants; and Satisfy ARARs.

The major components of the selected remedial action as described in the ROD are:

- Environmental monitoring to evaluate the effectiveness of natural attenuation processes in the Plumes
- Deed restrictions to prohibit future ground water use
- Land use restrictions to restrict access to Bendix Site-related VOCs in vadose zone soils
- Natural attenuation of ground water Plumes to continue destruction of ground water contaminants
- Five-year site reviews

In addition the following three components will be implemented to address the Eastern Plume source area:

- Maintenance of existing cover system to minimize infiltration of precipitation to VOCs in vadose zone soils and restrict access to/direct contact with those soils
- Installation and Operation of SVE vapor phase treatment system to remove VOCs from the vadose soils

## **XI. Next Five-Year Review**

The second five-year review will be conducted by August, 2009, which is five years from the signature of this five-year review.

Table 1

List of Documents Reviewed

- 1 Record of Decision, Bendix Superfund Site, St. Joseph Michigan, U.S. EPA, September 1997
- 2 Final Report for the BGWDCP by Woodard & Curran for Robert Bosch Corporation. Volume I and Volume II, February 2004
- 3 Lake Study Data Report by Woodard & Curran for Robert Bosch Corporation, November 1999
- 4 Feasibility Study by Woodard & Curran for Robert Bosch Corporation, July 1997
- 5 Remedial Investigation by Woodard & Curran for Robert Bosch Corporation, July 1997
- 6 Ecological Risk Assessment by Woodard & Curran for Robert Bosch Corporation, April 2002
- 7 Consent Decree, U.S. EPA vs Robert Bosch Corporation, October 1999
- 8 MDEQ Technical Memorandum on plume discharge, July 2004 (Draft)

Figures:

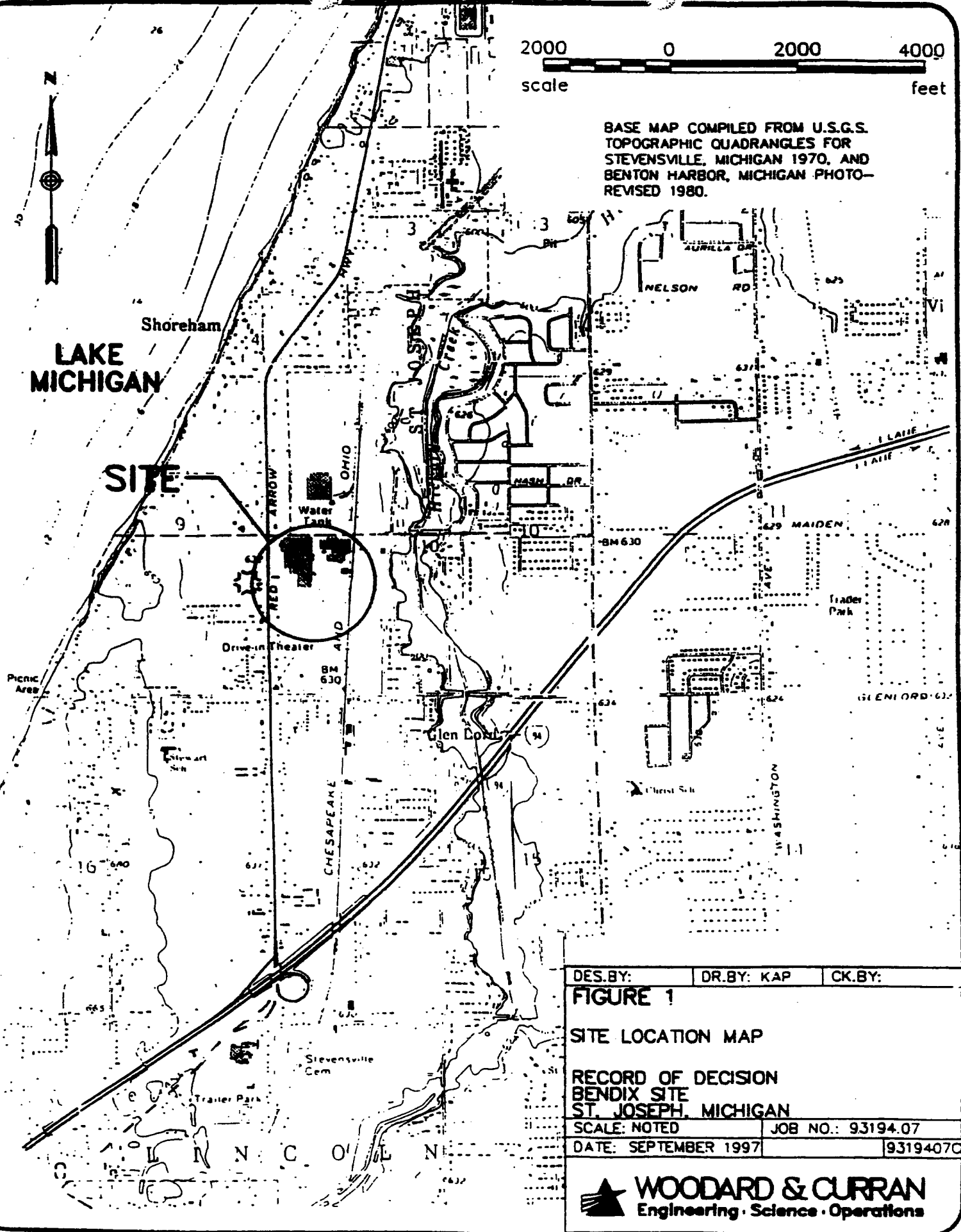
- Figure 1 Site Location Map
- Figure 2 Schematic Topographic Overview of Site Plumes
- Figure 3 Cross Section West Plume in 1997
- Figure 4 Cross Section East Plume in 1997

Attachments:

- 1 Analysis of Plume Data prepared by Subterranean Research, Inc. for U.S. EPA Region 5, August 2004.
- 2 Bendix Corporation Statistical Analysis Report (Abridged Version) prepared by Volpe National Transportation System Center for the U.S. EPA Region 5, February, 2004.

2000 0 2000 4000  
 scale feet

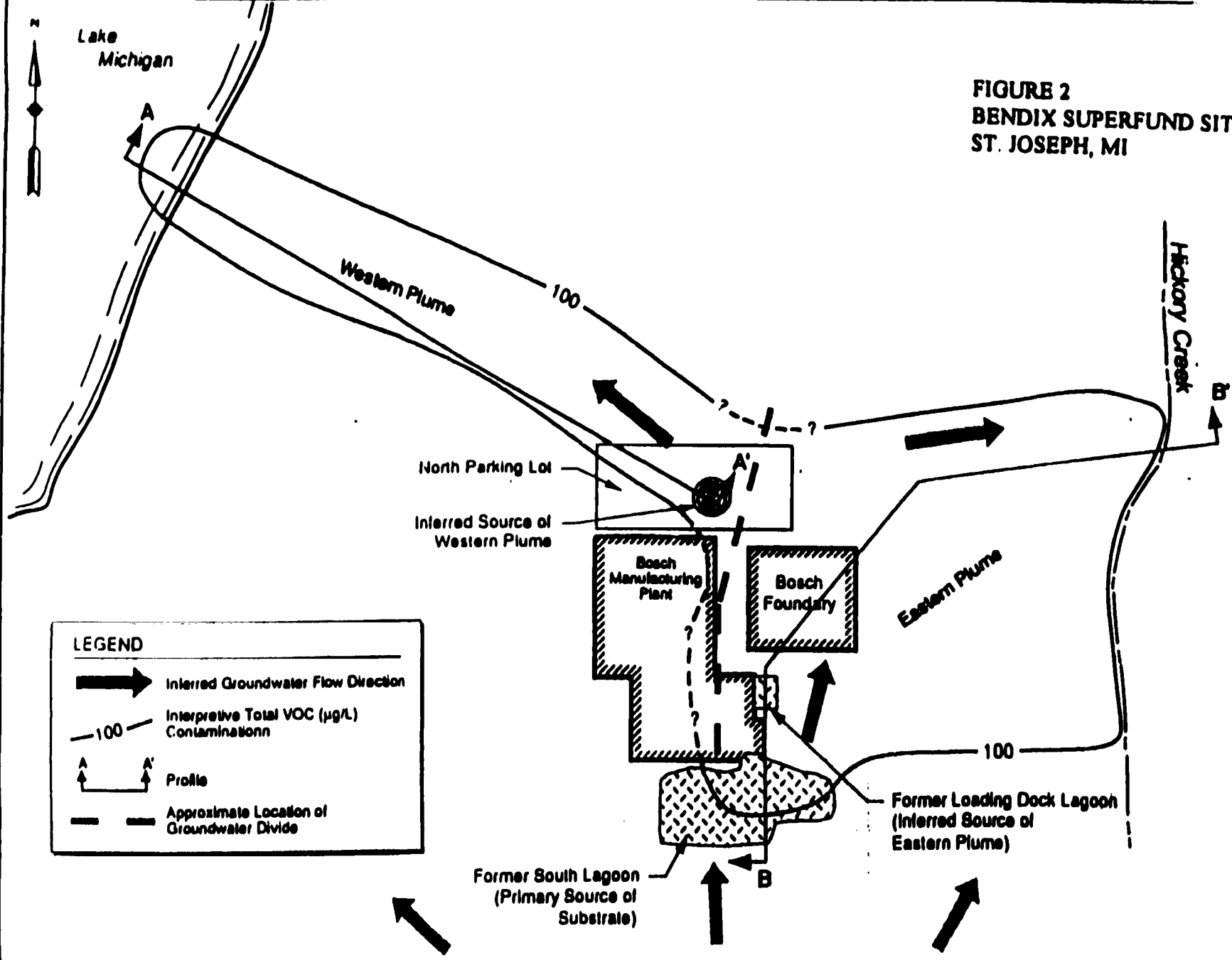
BASE MAP COMPILED FROM U.S.G.S.  
 TOPOGRAPHIC QUADRANGLES FOR  
 STEVENSVILLE, MICHIGAN 1970, AND  
 BENTON HARBOR, MICHIGAN PHOTO-  
 REVISED 1980.



DES. BY:	DR. BY: KAP	CK. BY:
<b>FIGURE 1</b>		
SITE LOCATION MAP		
RECORD OF DECISION BENDIX SITE ST. JOSEPH, MICHIGAN		
SCALE: NOTED	JOB NO.: 93194.07	
DATE: SEPTEMBER 1997	9319407C	

**WOODARD & CURRAN**  
 Engineering · Science · Operations

**FIGURE 2  
BENDIX SUPERFUND SITE  
ST. JOSEPH, MI**



**LEGEND**

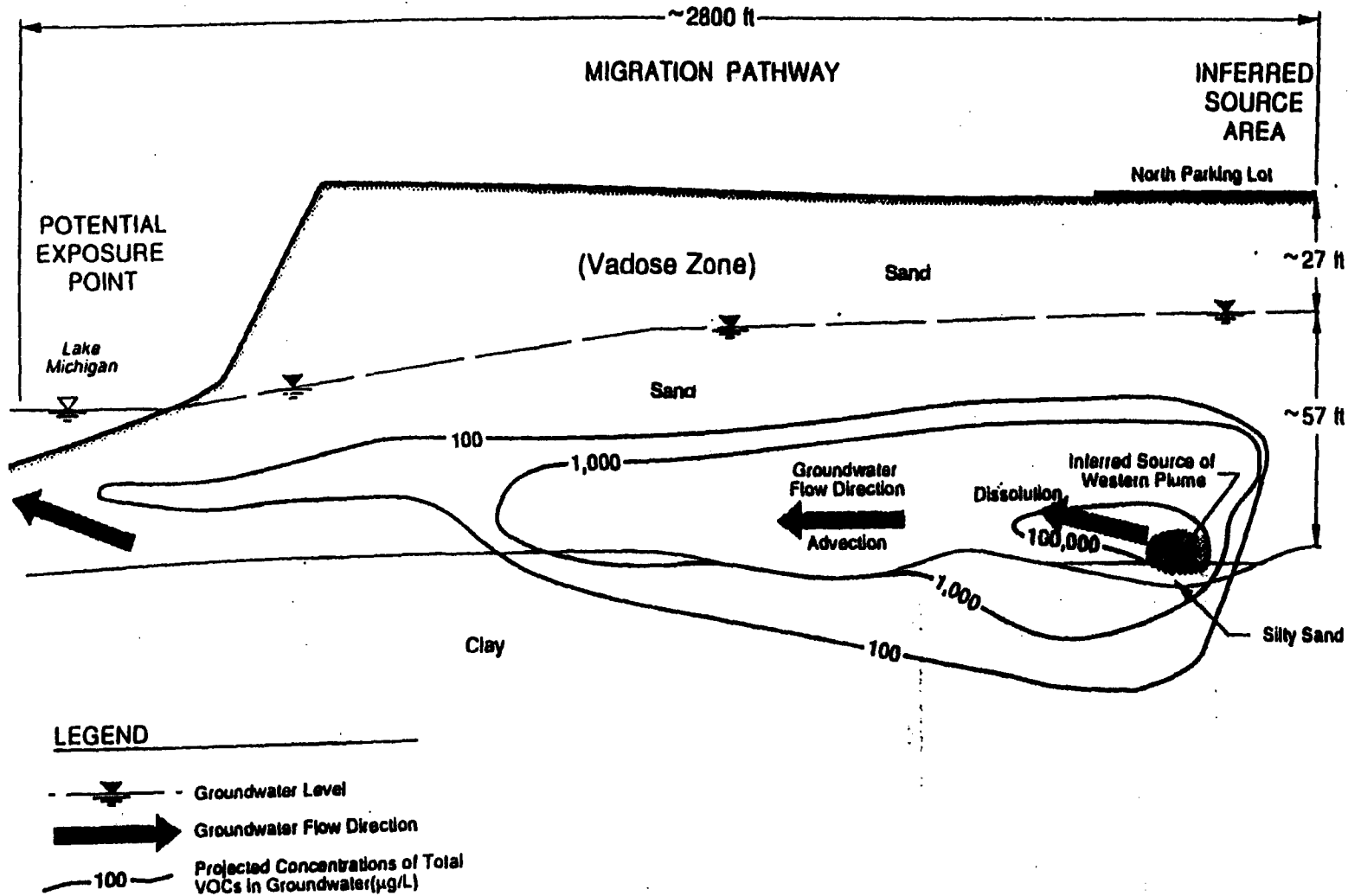
- Inferred Groundwater Flow Direction
- Interpretive Total VOC (µg/L) Contamination
- Profile
- Approximate Location of Groundwater Divide

Not to Scale

**FIGURE 3  
BENDIX SUPERFUND SITE  
ST. JOSEPH, MI**

**A**  
Northwest

**A'**  
Southeast

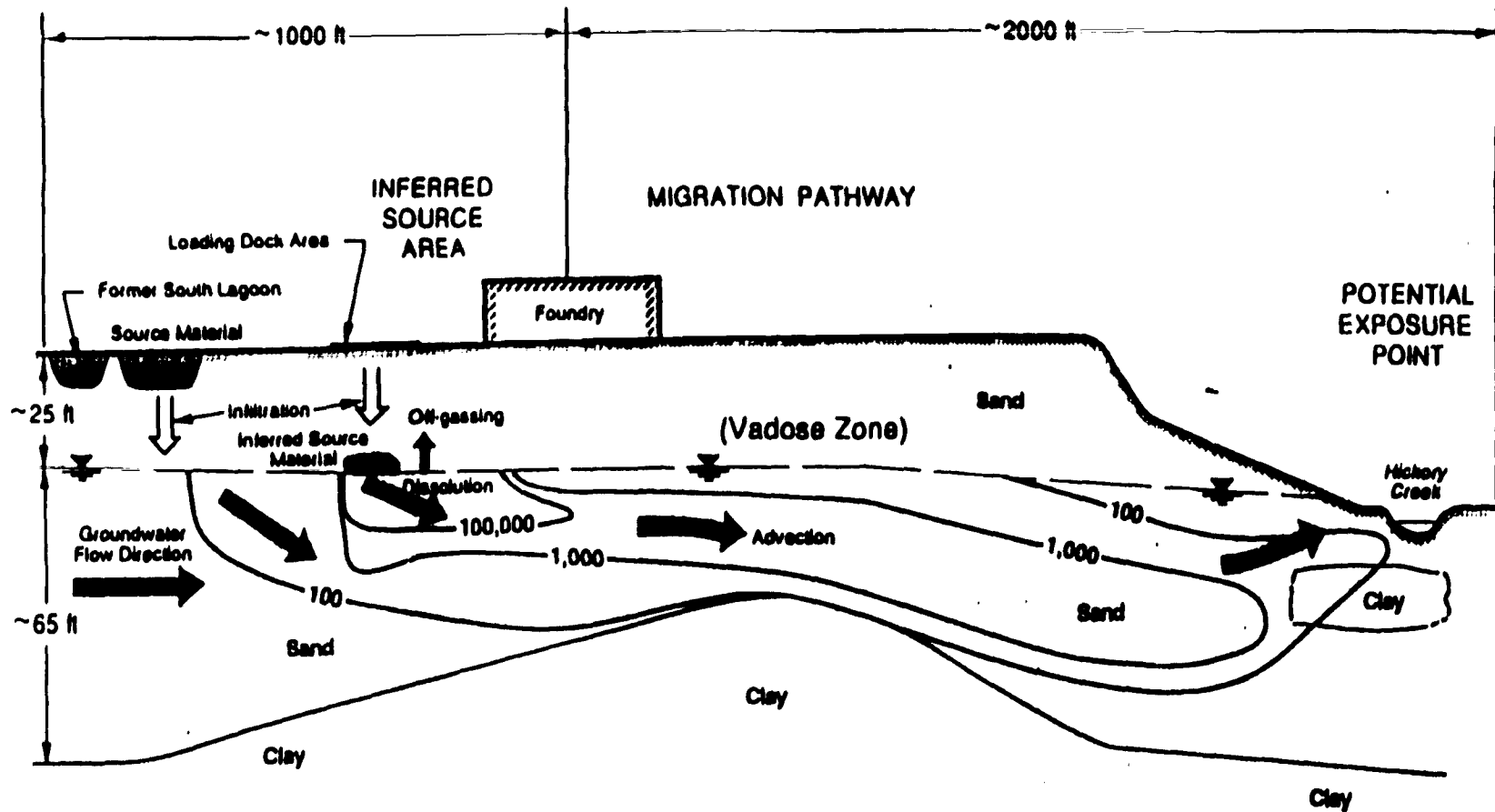


Not to Scale

**FIGURE 4**  
**BENDIX SUPERFUND SITE**  
**ST. JOSEPH, MI**

**B**  
 South

**B'**  
 North



**LEGEND**

- - - - - Groundwater Level
- Groundwater Flow Direction
- 100 — Projected Concentrations of Total VOCs in Groundwater (µg/L)

Not to Scale



## **ANALYSIS OF PLUME DATA**

**Bendix Corporation/Allied Automotive/Bosch**

St. Joseph, Berrian County, Michigan

EPA ID: MID005107222

PREPARED FOR

U. S. Environmental Protection Agency, Region 5  
Groundwater Evaluation and Optimization System



and  
Volpe National Transportation Systems Center  
and  
EG&G Technical Services

Order No. DTRS57-03-P-80206

Reference No. 33-4187

PREPARED BY

Subterranean Research, Inc., Duxbury, MA



July 2004

## 1. PURPOSE

This report documents an observation-based review and analysis for the Bendix Corporation/Allied Automotive site (Bendix), located in St. Joseph, Berrien County, Michigan. The site is sometimes called the Bosch site, named for the current owner of the site.

This report was prepared in support of the first five-year review of activities at the site, triggered by the completion of the remedy construction in 1999. This analysis focuses on groundwater chemistry data for the period December 2000 to October 2003, as contained in a database provided by United States Environmental Protection Agency (USEPA) Region 5 via Volpe National Transportation Systems (Volpe). For the sake of brevity, a very short background section is presented here based on the USEPA National Priorities List Fact Sheet for the site [USEPA, 2003]; refer to other site documents for greater depth and detail.

The objective is to review the data to determine, if possible, whether the remedy for groundwater at Bendix is working as intended. As a result of waste emplacement locations and subsurface hydrology, there are two plumes at the site. One, moving west-northwest toward Lake Michigan—the west plume, utilizes monitored natural attenuation. The other, migrating east-northeast toward Hickory Creek—the east plume, uses monitored natural attenuation as well as soil vapor extraction near the original location of waste. The primary focus of this study is the west plume.

Multiple lines of evidence are investigated, in accordance with USEPA [2002, 2004]. This approach is necessary because environmental data can be noisy, are sparse, and must be interpreted rather than simply collected. The following lines are considered in this report to determine whether they are consistent with adequate remedy:

- What are the groundwater flow directions? How do they compare to the anticipated directions?
- Is there evidence that the state of groundwater contamination at the site has improved? Are the plumes stable or shrinking?
- Is there evidence that trichloroethene (TCE) is degrading through a chain to nonchlorinated ethene and/or CO<sub>2</sub>, as expected when the remedy was selected? Is there any interruption of the decay chain? In particular, by the time the western plume vents (discharges) into Lake Michigan, has the plume been sufficiently degraded or attenuated?
- Is the monitoring network adequate to accomplish its purpose for the next five years? Are any adjustments needed?

Some of the data analyses have been performed by others and, rather than duplicate those efforts, are integrated here.

July 2004

Section 2 presents a background of the site, contamination, and record of decision. Methods used in this study are described in Section 3, which is followed in Section 4 by a discussion of the evaluations. The several lines of evidence are brought together in Section 5. Our conclusions and recommendations are presented in Section 6. The key data and analysis sources used in this are listed in Section 7, along with other references. A list of abbreviations and acronyms is included as Section 8. The document also includes one appendix. Note that some of the figures in this report are best viewed in color.

## 2. BACKGROUND

### 2.1 Site

The Bendix plant is located in St. Joseph, Michigan, at 3737 Red Arrow Highway in a residential/light industry setting. The site is situated on a topographic divide, with Lake Michigan approximately one half mile to the west and the Hickory Creek about one third mile to the east. There are approximately 750 homes within three miles of the site, but the majority receive water from a municipal water system that is unaffected by this site. During the plant's history, tetrachloroethene and trichloroethene (as well as other wastes) were disposed in unlined lagoons at the plant [ASTDR, 1998]. The soils in this area are composed of unconsolidated glacial deposits. These coarse-grained soils allowed vertical migration down into the groundwater and lateral migration across- and off-site. The plant is located near a groundwater divide, and the locations of the disposal lagoons relative to the groundwater flow system has led to two lobes of contaminant plumes, one of which is discharging (or "venting") into Lake Michigan and the other to Hickory Creek.

A map of the region is provided in Figure 1, annotated with several features of interest. Figure 1 also includes the locations of monitoring wells across the site.

The Remedial Investigation and Feasibility Study (RI/FS) was completed under an Administrative Order by Consent, signed in February 1989. USEPA's Kerr Laboratory in Ada, Oklahoma, the University of Michigan, Stanford University, and others have intensively studied the groundwater flow (e.g., Tiedeman and Gorelick [1993]) and groundwater plumes discharging to Lake Michigan. They have presented strong evidence that natural biological degradation and other forms of natural attenuation have been occurring, mitigating the discharge of contaminants into Lake Michigan (e.g., Weaver *et al.* [1996a], Lendvay *et al.* [1998], and Stiber *et al.* [1999, 2004]). Based on the RI the chemistry noted in west plume was also noted in the the east plume, indicating that biological activity was also present in the east plume. However, an additional Remedial Action (RA) was planned for the eastern plume. Final RI and FS reports were issued and a Record of Decision was signed on September 30, 1997, calling for monitored natural attenuation (MNA) of both the western and eastern plumes with an additional soil vapor extraction (SVE) system RA for the east plume.

The results of a packed tower biological treatment pilot study, conducted at the plant under a Superfund Innovative Technology Evaluation Program, eliminated this process from further consideration in the FS. Soil vapor extraction was selected to augment the MNA for the east plume, and the SVE system started in the summer of 1999. Through the end of December 2002, it is estimated that the SVE system had removed 1,800 pounds of volatile organic compounds (VOCs) from the source area soils.

Point-of-compliance wells have been installed for both the east and west plumes. A supplemental Human Health Assessment was conducted along the Lake Michigan beach in 1999. A follow-up ecological survey was conducted in Lake Michigan in 2001 and indicated that there was no ecological risk at the site. Sampling of selected monitoring wells to establish alternate concentration limits (ACL) for the point of compliance wells has been occurring quarterly since fall 2000.

Interpretations of data collected during the remedial investigation, such as the map view and cross-section produced by Woodward and Curran [1999, 2000], repeated here as Figures 2 and 3, indicate that the core of the plume is narrow—perhaps 150 feet wide—and thin—highly concentrated in a <10 foot thick “tongue”. The clay layer defining the bottom of the aquifer undulates, so vertical fluctuations of groundwater flow along the aquifer bottom will affect the vertical location plume, even though groundwater flows that carry dissolved contaminants are generally horizontal until discharging into the lake.

Discharge to Lake Michigan has been an ongoing concern. Monitoring data from on-shore groundwater wells have been supplemented by samples obtained from sediments located below Lake Michigan. A vertical aquifer sampling (VAS) event from a barge was performed by USEPA in June 1996. Negligible contamination was found in the study area, which was offshore (west) of a row of wood pilings about 50 feet from shore. In June 1999, the Michigan Department of Environmental Quality (MDEQ) conducted off-shore sampling along a transect parallel to the lake shore and inferred that the groundwater plume was venting into the Lake approximately 25 feet off-shore, on the east side of the wood pilings and near the location of the 1996 VAS.

MDEQ performed additional investigations in Fall 1999 and Spring 2000. These two investigations extended the June 1999 transect, sampled along an axial transect (oriented in the direction the axis of the west plume) that extended beyond a line of pilings that parallels the shore, and sampled a transect parallel to shore and further off-shore than the June 2000 transect. MDEQ's fourth sampling event examined pore water and surface water at two clusters of sampling points from beneath the ice pack on Lake Michigan. A fifth event was performed in Summer 2003, in which pore water from sub-lake sediments was sampled on a grid-like pattern across the main part of the previously established plume discharge area. Pore water samples acquired by MDEQ were obtained from small-volume syringe-based samplers. A draft memorandum describing the methods and results has been prepared by MDEQ [2004]. These small-scale samples yielded concentrations with substantially higher peak values than were observed in 1999, with the aqueous concentration of total volatile organic chemicals ranging upwards of 50,000 µg/L. These 2003 results suggest that the discharge area is located between the shore and pilings west-northwest of point-of-compliance well POCW-3. Although these concentrations are significant and may have great utility for mapping the plume discharge into Lake Michigan, these data were not obtained from groundwater monitoring wells and, as a

result of the differences in sampling volume and protocol, were not included in the following evaluation of monitoring well data.

## 2.2 Standards

The 1997 Record of Decision (ROD) provides allowable concentrations of chemicals of concern at point-of-compliance (POC) wells limited to the more restrictive of alternate concentration limits (ACLs) or the Michigan mixing-zoned-based Groundwater/Surface water Interface Criteria (GSI).

The Part 2001 Generic Cleanup Criteria and Screening Levels for Groundwater, Residential and Commercial Drinking Water Criteria, Attachment A, follow:

1,1,1-Trichloroethane (1,1,1-TCA)	200 µg/L
1,1-Dichloroethane (1,1-DCA)	—
1,1-Dichloroethene (1,1-DCE)	7 µg/L
cis-1,2-Dichloroethene (cDCE)	70 µg/L
trans-1,2-Dichloroethene (tDCE)	100 µg/L
Trichloroethene (TCE)	5 µg/L
Vinyl Chloride (VC, chloroethene)	2 µg/L.

The Michigan GSI for key chemicals of concern at the points of compliance (POC) in this study follow:

Trichloroethene (TCE)	2200 µg/L
cis-1,2-Dichloroethene (cDCE)	6800 µg/L
Vinyl Chloride (VC, chloroethene)	170 µg/L.

Note that the POC wells for the western plume, indicated by labels beginning "POCW", are located on-shore and not in the groundwater-lake interface *per se*.

## 2.3 Data Available

This study has utilized a database of groundwater monitoring well sampling results provided by USEPA and Volpe. These data span the December 2000 to October 2003 timeframe, and include 8199 values of concentrations at wells for 28 different analytes. The database is Earthsoft's EQulS [Earthsoft, 2004], using Microsoft Access as the data store.

### 3. METHODS

Multiple lines of evidence are used in this analysis. The methods associated with each line of evidence are introduced in this section.

#### 3.1 Line of Evidence: Groundwater Heads

Groundwater heads have been observed and reported in a MDEQ draft report [2004]. Variability in these heads has been reviewed in that report, as have changes in the inferred groundwater head gradients, which are proportional to and in the same direction as inferred groundwater flows, by fitting a plane to heads observed at three wells (POCW-3, POW-4, and MWW-2).

#### 3.2 Line of Evidence: Intrawell Concentrations

Intrawell concentration time series were statistically analyzed and reported by Volpe [2004]. The analysis used the *CARStat* version 2.1.1 software [Discerning Systems, 2003]. The main statistical methods employed in the evaluation of these data follow.

##### 3.2.1 Comparison to standard

The “comparison to standard” test compares historical data in a time series to a cleanup standard; the four most recent data were used in this evaluation. If the upper confidence level (UCL) of this time series, based on a statistical confidence of 95%, is greater than the cleanup standard then an exceedance is recorded. The data are first checked to determine whether a normal, lognormal, or nonparametric distribution best fit the data. For a normally distributed set of data, the UCL is the mean of the data plus the product of the standard error of the mean (square root of sample variance divided by the number of data,  $m$ ) times the upper critical value of the one-sided Student-t distribution with  $m-1$  degrees of freedom and significance ( $\alpha = 1 - \text{confidence}$ ). Further information, including procedures for lognormal and nonparametric distributions, may be found in Gibbons and Coleman [2001].

##### 3.2.1 Comparison to baseline

Later data are compared to earlier data in a time series in a test called “comparison to baseline”. Using this test, one can determine whether concentrations in a well are getting better or worse. *CARStat* version 2.1.1 [Discerning Systems, 2003] was used to perform these tests. As described in Gibbons and Coleman [2001], this involves selecting a time interval of baseline data in the well, evaluating a concentration interval defined by the lower and upper prediction levels (LPL and UPL) of the data excluding the most recent datum for a specified (here 95%) confidence level. Then, the most recent datum is compared to the the LPL/UPL interval; if the latest datum exceeds the UPL, then

conditions are worse than the baseline and if it is less than the LPL, then conditions are better than the baseline.

### ***3.2.2 Trends***

Detection of trends was performed using the software package *CARStat* version 2.1.1 [Discerning Systems, 2003]. *CARStat* version 2.1.1 tests for the presence of trends in a time series of concentrations at a well using Sen's method. The test is run at the 99% confidence level, meaning that one must be 99% certain before declaring that a time series exhibits a trend. The confidence level of this test cannot be changed by a *CARStat* user.

### **3.3 Line of Evidence: Spatial Moments**

The monitoring well data were used to determine the overall status of the plume of dissolved contaminants for the different monitoring events using spatial moments. The term "spatial moments" applies to several common measures of a volume or mass; in fact, some use the word "volumetrics" instead. Common spatial moments include volume and mass (zeroth moments), centers of volume and mass (first moments), and second moments of volume and mass. Note that the volume of the plume is the volume of water in the saturated zone in which the plume is located; it excludes the volume of the solid aquifer matrix. Similarly, the mass of contaminant in a plume is the dissolved mass only.

For each monitoring event, the locations and concentrations at the monitoring wells are used to make a "snapshot" of the plume. Each snapshot is quantified using spatial moments.

For this project, volume and mass calculations were performed using *MVS* (Mining Visualization Software) Version 7.5 [C-Tech, 2004], a three-dimensional visualization and analysis tool that layers groundwater related tools on top of the *AVS* visualization software. Because *MVS* Version 7.5 currently does not provide a method to calculate second moments, Subterranean Research's *PAM*<sup>™</sup> (Plume Assessment Method) Version 0.1 software was used. As in the *MAROS 2.0* software produced by the U. S. Air Force Center for Environmental Excellence and Groundwater Services Inc. [AFCEE, 2004], the *PAM*<sup>™</sup> Version 0.1 calculations are limited to two spatial dimensions; that is, a representative concentration is selected to represent a vertically variable concentration distribution.

#### ***3.3.1 Volume and mass of plume***

For a given monitoring event and a given analyte, the locations and concentrations are input to a spatial interpolation method to determine the spatial distribution of contaminants based on the observation data. Once this distribution of concentration,



$c(x, y, z, t)$ , is known one can determine the volume of water occupied by the plume above some threshold concentration at the particular time  $t$ .

The volume and mass calculations involve evaluating integrals over a three-dimensional volume of space within which the plume exists. Since concentration, aquifer thickness, and other data observations are often based on discrete, small-scale samples (e.g., screened intervals of borehole), evaluating these integrals requires first that a distribution of concentrations at every spatial location by interpolation. Then, these integrals are evaluated using approximations that are based on the spatial interpolation method used.

In *MVS* Version 7.5, the upper and lower surfaces of the aquifer are interpolated from boring and well log data using kriging. Concentration data are also interpolated with kriging after first taking their logarithms and, after kriging, by taking the antilogarithms. Porosity is assumed constant. The *MVS* Version 7.5 computational module for volume and mass allows the selection of lower and upper concentration values, so that the volume and mass within a “band” or “doughnut” of concentration values are obtained.

Once the volume and mass have been calculated for a given analyte for each of the monitoring events, they comprise a time series of derived data (since they are calculated from observed data but are not directly observed themselves). These time series can be the subject of statistical testing as described in Section 3.2.2.

### ***3.3.2 Center of mass of plume***

The center of mass of the plume at the time of a given monitoring event is calculated by *MVS* Version 7.5 in a manner much like the mass itself, but it results in the  $x$  (easting),  $y$  (northing), and  $z$  (elevation) location of the center of the plume as inferred in a way consistent with the calculation of volume and mass. The  $x$ -component of the center of mass is obtained by summing the product of porosity, thickness, concentration, and the  $x$ -coordinate of each small volume in the plume and then dividing by the mass of the plume. (That is, we multiply the contribution to mass for each small volume by a moment arm measured from  $x=0$ .) The  $y$ -component and  $z$ -component of center of mass simply require substituting the  $y$ - and  $z$ -coordinate, respectively, instead of the  $x$ -coordinate.

### ***3.3.3 Spreads and orientation of plume***

As mentioned previously, *MVS* Version 7.5 currently does not calculate second moments of volume and mass. Because the second moments and plume orientation are important, the *PAM*<sup>TM</sup> Version 0.1 software has been used. Details of the *PAM*<sup>TM</sup> Version 0.1 calculations for are given in Appendix I. They are developed from the same integrals, evaluated over a three-dimensional volume of space within which the plume exists, that were used to develop the *MVS* volume and mass module. *PAM*<sup>TM</sup> Version 0.1 assumes that there is no vertical variation of porosity and concentration (or that a representative

value is selected), so that the required volume integrals can be converted into an area integrals. Horizontal variations of porosity, thickness, and concentration are allowed.

Since concentration, aquifer thickness, and other data observations are often based on discrete, small-scale samples (e.g., screened intervals of borehole), evaluating these integrals requires first that a distribution of concentrations at every spatial location by interpolation. Then, these integrals are evaluated using approximations that are based on the spatial interpolation method used. *PAM*<sup>TM</sup> Version 0.1 obtains the spatial interpolation by first creating a triangulation (specifically a Delaunay triangulation) using the locations at which data are available for a given monitoring event, and by second interpolating the logarithms of concentration linearly across each triangle. The volume (or mass) is calculated by summing up, over the volume of interest, the product of porosity and thickness (and concentration, for mass) for all of the small volumes within the plume.

If more than one sample result exists at a single monitoring point at a given monitoring event (i.e., duplicate samples), then the maximum of these is selected. (Other alternatives are allowed by the *PAM*<sup>TM</sup> Version 0.1 software. They will lead to different, but conservative, magnitudes of mass and volume.) If there are multiple samples from the same monitoring event and the same map (areal) location, but from different elevations (such as a monitoring well nest), then it is necessary to select a representative value from these overlapping samples (as described above). For this study, the median of overlapping samples is used.

The spread of the plume is not used as widely as center of mass, but is not much more complicated. If we think of the center of mass in the  $x$ -direction as the mass-weighted average  $x$ -coordinate of the plume, then the second moment can be thought of as a mass-weighted variance (square of the standard deviation). The second moment involves multiplying the contribution to mass for each small volume by two moment arms. The moment arms are different than for the center of mass calculation—here we use the distance from the center of mass, not from the origin of the coordinate system. We can multiply by the  $x$ -moment arm twice, by the  $y$ -moment arm twice, or by the product of the  $x$ - and  $y$ -moment arms (which is the same as the product of the  $y$ - and  $x$ -moment arms; the order doesn't matter). As a result, there are 3 second moments involving the  $x$  and  $y$  coordinates.

If the second moments of mass were calculated in terms of distance from a particular set of rotated coordinates, then 1 of the 3 moments will exactly equal zero. These special rotated axes centered at the plume center of mass are the principal coordinate axes; their origin is the center of mass, one axis is oriented parallel to the long axis of the plume, and the second axis is perpendicular to the first.

The rotation needed to find the principal axes from the  $x$  and  $y$  axes can be calculated once the 3 second moments of mass are calculated in terms of  $x$  and  $y$ . This gives the orientation of the plume. In addition, the two non-zero second moments for the principal axes can be calculated. These are the principal values of the second moment. Once the principal values are computed, they are divided by the plume mass and then their square roots are taken. The larger of the two is the longitudinal plume spread and the smaller is the transverse plume spread. The plume spreads have units of length.

*PAM*<sup>TM</sup> Version 0.1 calculates the plume spreads and orientation for each monitoring event. Multiple monitoring events leads to a time series of spreads and orientation that can be analyzed statistically, as described in Section 3.2.2. It should be noted that, because *MVS* Version 7.5 and *PAM*<sup>TM</sup> Version 0.1 have different interpolation, integration, and geometric assumptions, the computed masses and volumes will not (and should not) be equal.

### **3.4 Line of Evidence: Biologically-Mediated Attenuation Indicators**

The groundwater plume remedies at the Bendix site were selected with the intention that biological activity would cause TCE to be degraded by dechlorination into daughter products: DCE isomers, VC, and ethene or CO<sub>2</sub>. Dechlorination from TCE to DCE and VC has been shown in several studies to occur at the site (e.g., Weaver *et al.* [1996a], Lendvay *et al.* [1998], and Stiber *et al.* [1999, 2004]). The transformation of TCE to DCE and VC occurs under anaerobic conditions by the process of methanogenesis. The cis-isomer of DCE (cDCE or cis-1,2-DCE) is much more prevalent than the trans-isomer (tDCE or trans-1,2-DCE). Conversion of VC to ethene occurs much more rapidly under aerobic conditions. It should be noted that the end points can be produced by other reactions, so the presence of ethene or CO<sub>2</sub> is not sufficient to indicate complete biotransformation. Measurements of dissolved oxygen (DO) are not available in the 2000-2003 dataset reviewed. Methane measurements were available.

If the source of TCE has been controlled such that it no longer provides contaminants to the groundwater and if biologically-mediated attenuation occurs, then it should be possible to look at the ratios of TCE to DCE, DCE to VC, and VC to ethene to observe evidence of the degradation process. These ratios can be computed for each well for each monitoring event, forming time series.

## 4. LINES OF EVIDENCE

### 4.1 Groundwater Heads

MDEQ [2004] reviewed twelve groundwater head monitoring events from 10/2000 through 11/2003. The data are reproduced in Table 1; missing data are indicated by blanks in the table. One apparently incorrect head datum at STW-2B for 9/23/2001 is highlighted: the error was determined by visual “buddy checking”—that is, by comparing other values at the same well and the variations observed at other wells. (The cause of this apparent error is not known.) The MDEQ interpretations, excluding this point, about temporal variations indicate that at least in the vicinity of POCW-2, POCW-3, and STW-2 flow directions vary by only a couple of degrees. While it is true that a shift of groundwater flow by  $\pm 2^\circ$  across the entire plume could lead to oscillations of the location of the plume core axis by as much as  $\pm 70$  feet, it should be noted that this amount of variability in plume location maintains the plume location within the region traversed by the six POCW wells. This is discussed further in Section 4.3.

### 4.2 Intrawell Concentrations

Volpe [2004] prepared intrawell statistical analysis of the 2000-2003 dataset using *CARStat* version 2.1.1 [Discerning Systems, 2003]. Table 2 reproduces Volpe's Table 5, which summarizes results. It was found that a number of wells continue to demonstrate exceedances of standards (as indicated by the upper confidence limits of each time series) for TCE, cDCE, 1,1-DCE, and VC (and some other CVOCs). The contaminants with the most exceedances were VC (21 locations, 7 in the East Plume and 14 west), cDCE (14 locations, 5 east and 9 west), and TCE (14 locations, 4 east and 10 west), and 1,1-DCE (9 locations, 2 east and 7 west). Comparison of the 10/2003 datum to the first 8 samples in the 3-year monitoring dataset for various location-chemical combinations showed that the latest datum is worse than the baseline data for 18 location-chemical pairs and better for 2. (The analysis was limited to 1,1,1-TCA, 1,1-DCA, 1,1-DCE, cDCE, tDCE, TCE, and VC.) Trends were found to be upward for 4 location-contaminant pairs and downward for 12 pairs. The results were, therefore, mixed.

Volpe [2004] reports that the greatest upper confidence limit (UCL) concentration reported at any well and for any contaminant is cDCE at MWW-2 at 67,123  $\mu\text{g/L}$ ; the UCL for TCE at MWW-2 is about 680  $\mu\text{g/L}$  while for VC it is 4,717  $\mu\text{g/L}$ . Perusal of Table 4 of the Volpe report indicates that this result can be generalized across the site—the greatest UCL concentrations observed are generally for cDCE, followed by VC, and then by TCE. Since PCE and TCE were believed to be major emplaced wastes, these results suggest dechlorination has occurred. The fact that cDCE and VC persist at higher UCL concentrations indicates that the dechlorination is not complete and suggests that earlier estimates of net degradation rate of cDCE and VC [Weaver *et al.*, 1996b],

particularly in the region from 400 feet onshore to the lake discharge area, may have been optimistic.

The UCL for concentrations of cDCE at MWW-2 approach 1 percent of aqueous solubility. As stated in many literature sources, such as the National Research Council [1994, pg. 204], aqueous concentration of 1% or greater of solubility is highly suggestive that there may be separate phase DNAPL residuals upgradient of MWW-2.

### 4.3 Spatial Plume Moments

Unlike intrawell statistics, which examine one well independent of another for a given contaminant, the spatial plume moments look at all wells for a given contaminant at each monitoring event. That is, plume moments give information about the plume as a whole. In response to earlier results, this section focuses on TCE, cDCE, and VC.

#### 4.3.1 Volume and Masses

Concentration data were analyzed using *MVS* Version 7.5 to find the volume and mass, as described in section 3.2.2,. In addition to examining the plumes in their entirety, they were found for several "concentration bands". (Only values exceeding 5 µg/L were used in the calculations to hedge against interpolation errors at low concentrations.) The time series of each resulting volume and mass were analyzed using *CARStat* version 2.1.1 to determine whether there was a trend.

Figure 4 shows the volume and mass versus time for dissolved TCE, cDCE, and VC in the west plume. TCE volume and mass are increasing with 99% confidence, according to the statistical trend test; no significant trends were found for cDCE or VC.

Figure 5 repeats the plot, but for the east plume. The volume of the TCE plume is increasing, but its mass shows no trend. No significant trends were found for cDCE or VC.

To explain the information in these data, the volume and mass calculations were repeated for several concentration bands (see the first paragraph of this subsection). Figures 6 through 11 show the results for TCE, cDCE, and VC for the west and east plumes, respectively.

- Figure 6, for TCE in the west plume, shows increasing volumes and masses, driven by increases for regions where concentrations are less than 50 µg/L.
- For the east plume of TCE, Figure 7 shows an increased volume driven by concentrations less than 100 µg/L, while the overall mass shows no trend, even though the masses of regions with concentrations less than 100 µg/L are increasing.

- The west plume for cDCE, shown in Figure 8, has no overall trends in mass and in volume, and there is no trend in any of the bands. Looking at the volume and mass corresponding to concentrations greater than 1000 µg/L, it is evident that a region of high concentration and low volume (one or more “hot spots”) exists. (Note: The April 2002 mass plot, which shows little mass at concentrations above 1000 µg/L, should in fact show a larger amount of mass—the plotted result is an artifact of the applied *M/S* volume-and-mass module.)
- The cDCE plume to the east plume shows no trends for either mass or volume in any of the concentration bands or for the plume overall. Figure 9 shows that a significant fraction of the mass appears to be due to high concentration regions, as was found for cDCE in the west plume..
- In Figure 10, VC for the west plume shows no statistically significant trend upward or downward for mass and concentration. The distributions among the various concentration bands also show no trends. A comparison of the mass and volume plots for the bands above 100 µg/L indicates that a large portion of the VC mass is found in a relatively small portion of the plume.
- Similarly, in Figure 11, the east VC plume shows no trends in mass or volume for any of the concentration bands. The mass estimates sometimes fluctuate a great deal, which appears to be a combined result of concentration fluctuations and the *M/S* volume and mass calculation procedure employed.

TCE volume and mass in the dissolved west plume are increasing. The increased volumes and masses of TCE are driven by lower concentrations, and not by peak concentrations. The mass in the highest concentration band (>1000 µg/L) has too few data to apply the trend test, but appears to have decreased. This implies that the TCE is attenuating in the high concentration regions, but the lower concentration portions of the plume may be expanding. In the east plume, the volume is increasing but the mass is not, which similarly suggests that high concentrations of TCE are attenuating, but are accumulating in a larger diffuse plume.

For cDCE, the west plume shows a stable volume and mass, as a whole and for the different concentration bands. The majority of cDCE volume is for concentrations less than 100 µg/L, while most of the cDCE mass is due to concentrations above 1000 µg/L. This is driven by the concentrations at MWW-2, which during the 12/2000 to 10/2003 time frame were observed at concentrations up to 1% of its aqueous solubility.

The eastern cDCE plume shows similar characteristics. Most of the volume is occupied by concentrations less than 100 µg/L, while most of the mass is in regions with concentrations greater than 1000 µg/L. The mass and volume in the east plume are about half of the west plume values.

Vinyl chloride mass and volume in the west and the east plumes show no trends, unlike the increasing TCE. The preponderance of mass for VC is due to concentrations above 100 µg/L, unlike the TCE result. This may be indicative of the breakdown of TCE or cDCE into VC, with low rates of VC breakdown.

Ethene is generally not present in high concentrations in shallow groundwater systems in the absence of contamination, and it is often used as an indicator that biodegradation of chlorinated ethenes has occurred. Unfortunately, there are insufficient measurements to perform volume and mass analysis of ethene. However, those ethene data available do not generally show high ethene concentrations, except at POCW-3 and STW-2B. The available ethene data do not demonstrate that complete dechlorination to ethene has occurred.

On the basis of this analysis, it appears that there is degradation of TCE to DCE and of DCE to VC. There appears to be an accumulation in the cDCE and VC stages of the degradation "chain", indicating that oxidation to ethene is not occurring at a sufficient rate at most locations. Some high concentrations observed for cDCE, up to 1 percent of the solubility limit, may indicate the presence of residual DNAPL that is acting as a continuing source of dissolved contamination. Given the site's waste disposal history and the documented biological activity at the site, it is believed that such residual DNAPL would be TCE, although there is no direct evidence.

#### ***4.3.2 Center of Mass***

The center of mass for the key constituents was determined using the *PAM*<sup>TM</sup> Version 0.1 software. This subsection focuses on the west plume. The locations of the centers of mass for the TCE, cDCE, and VC plumes are quantified in Table 3 and illustrated in Figures 12 through 14.

The centers of mass for the 12/2000 monitoring event are most different from others; subsequent monitoring events yielded centers of mass that, between monitoring events, have varied less than the distance between MWW-2 and MWW-3. The centers of mass are all located near MWW-2. The location of the center of mass of TCE began near MWW-3 and migrated southeast toward MWW-2 over the first four monitoring events and subsequently has fluctuated around MWW-2 (Figure 12). Its amount of fluctuation is clearly greater than that of cDCE which, other than the initial monitoring event, has had a center of mass very close to MWW-2 (Figure 13). After the first monitoring event, the VC center of mass location has been near MWW-2 and has varied by an intermediate amount. Figure 14 illustrates that there appears to be a slow migration of the VC center of mass to the northwest over the last six monitoring events available for this study.

The migration of the TCE center of mass over four monitoring events toward the original source area for the chlorinated solvents is consistent with the attenuation of the low-

concentration portion of the TCE plume by hydrodynamic dispersion and biological attenuation. The cDCE center of mass is, except for the first monitoring event, quite stable—this reflects the persistently very high concentrations of cDCE found at MWW-2. The center of mass location for the VC plume indicates that the VC concentration at MWW-2 is not as dominant as for cDCE. The VC data suggests a slow migration of the center of mass in a west-northwest direction; this could be consistent with partial dechlorination of cDCE to VC and subsequent migration with the groundwater flow or, because the distance migrated is less than the distance between MWW-2 and MWW-3, may simply be coincidental result of random fluctuations in the monitoring data.

#### ***4.3.2 Spreads and Orientation: Second Moments***

This section discusses the spreads and orientation, focusing on the west plume because of implications for discharge to Lake Michigan. Second moments quantify the spread of the concentration plume along different directions and the orientation of the “long” axis of the plume at a specified time. The major spread is the distance found by taking the square root of the mass-normalized second moment of mass along the “long axis” of the plume; the minor spread is similar but uses the second moment of mass perpendicular to the “long axis” of the plume. Once the major spread, minor spread, and orientation are determined for each monitoring event, trends are assessed.

For TCE in the western plume the median value of the major spread is about 687 feet and of the minor (or transverse) spread is about 188 feet. The major axis of the plume oriented about 29° north of west, ranging from 25.5° to 37.3° and the time series of TCE plume orientations does not indicate a trend. For cDCE in the west plume the median major spread is 240 feet, the minor spread is 76 feet, and the median orientation is 25.4° north of west, ranging from 22.8° to 26.9° with no trend. For VC in the west, the median major spread is 351 feet, the minor is 106 feet, and the median orientation is 29.8°. The plume orientation varies between 25° to 39.4° north of west and does not exhibit a trend.

The implication of these “whole plume” analyses is that the plumes for these three contaminants have similar orientations, that there are natural variations in plume orientation that are observed in the concentration data, and there is no consistent trend in the orientations. These results do not suggest a significant trend, meaning that none of these 3 plumes is rotating toward the south, contrary to MDEQ's analysis of three groundwater heads [MDEQ, 2004].

The major spreads of TCE, cDCE, and VC are 687, 240, and 351 feet, respectively. These do not indicate that the actual extent of the VC plume is less than TCE, but reflects the distribution concentrations. For example, the cDCE spread is shortest because the maximum cDCE concentration MWW-2 exceeds cDCE values in other wells by such a large amount.



Figures 15, 16, and 17 show for each monitoring event the center of mass and a 2000 foot long line emanating from that center of mass and pointing in the direction obtained from the second moment analysis for the west plume for TCE, cDCE, and VC, respectively. (The length was not based on plume size; it was selected to visualize where the plume axis would cross the lake shore.) The rays are color-coded, ranging from light to dark in correspondence with 12/2000 to 10/2003. In addition, each figure shows the median value of the center of mass and a ray corresponding the median direction, using a dashed black and white ray. (The median is selected to avoid making assumptions about the underlying probability distributions.)

These "ray" figures show clearly that there is variation in the location of center of mass and the plume orientations inferred from the monitoring data. They also show that these variations lie within the region covered by the existing POCW wells, and that the rays pass between POCW-2 and POCW-4. These inferred plume axes are consistent with Figure 3 [Woodward and Curran, 2000]. This suggests that transverse shifts of the plume for the key contaminants can be detected by the monitoring network, if future shifts are consistent with the past. This does not necessarily imply that the resolution of the network is sufficient, particularly in the discharge area, or that the core (highest concentrations) of the plume is being adequately sampled.

Figures 18 to 20 repeat the ray figures for TCE, cDCE, and VC, respectively, but the scale has been changed to focus on where the rays pass through the area of the POCW wells. To enhance interpretation, the lines remain color-coded by date, but with randomized coloring, and the date corresponding to each ray is indicated on the plot. Figure 18, for TCE, shows that the interpreted plume axis passes in most cases through or within 50 feet of POCW-3 with similar directions, that there are three cases in which the interpreted axis is between POCW-3 and POCW-4, and that there is no temporal trend in axes. Figure 19, for cDCE, shows the plume axes are oriented in essentially the same direction and show lateral shifts in position among events. All but two rays lie south of POCW-3. Again, there does not appear to be a temporal trend in the lateral shifts. Figure 20 for VC shows the most variability in the ray orientations and lateral locations. All but one ray lie north of POCW-3 and no temporal trend is evident.

The terminal ends of the TCE rays (at the northwest ends of the line segments in Figure 15) are readily seen to be more scattered than those of either cDCE or VC. This reflects the variability of the centers of mass obtained from the TCE data. The centers of mass for cDCE and VC are less variable than TCE because their locations are dominated by high concentrations at MWW-2. Note also that there is little variation among the cDCE ray orientations (Figure 16) compared to either TCE or VC. For VC (Figure 17), the ray orientations show the greatest variation and the median ray apparently sits in the middle of early and late rays, suggesting no trend in the orientation of the plume.

#### 4.4 Biologically-Mediated Attenuation Indicators

Table 4 presents west plume data for all west plume wells and all monitoring events for TCE, cDCE, VC, and ethene. These should comprise the natural biodegradation chain. Nondetects are replaced with the detection limit (e.g., for ethene the detection limit is 10 µg/L). In addition, ratios of various parent-to-decay-product quantities are presented; when lack of data prevents a ratio calculation, a dashed line is present. One obvious observation is the paucity of ethene data. If the ratio data are all decreasing then either there is dechlorination or advective processes are sweeping out all contaminants. If some ratios (e.g., TCE to cDCE) decrease and others increase (e.g., cDCE to VC), then the ratios may indicate some dechlorination (e.g., of TCE), but a lower rate of degradation of other members of the decay chain family (e.g., of cDCE or VC).

- At BDW-1, the ratio of TCE to cDCE is increasing. There are no ethene data.
- At POCW-1A, cDCE has shown a step increase from nondetect to about 20 µg/L, while no similar behavior exists for the other chlorinated ethenes.
- At POCW-2A, all of the ratios appear to be decreasing, suggestive of effective dechlorination. More recent ethene data would be desirable.
- Meanwhile, at POCW-2B all contaminants are at low levels and the ratios are not particularly informative.
- Although TCE is essentially at nondetect levels at POCW-3A, cDCE, VC, and ethene persist though trending downward.
- At POCW-3B, the only apparent trend is a decrease in ethene, although this is a visual observation using only three ethene samples.
- The shallower POCW-3C initially had two significant ethene concentrations (over 300 µg/L), but two later samples are nondetects. At the same time, TCE, cDCE, and VC showed a V-shaped trend; the lack of similar behavior for ethene suggests oxidation of VC has been inhibited in some way. As indicated in Table 2, TCE, cDCE, and VC are all in exceedance at POCW-3C.
- STW-2A shows no downward trend in any of TCE, cDCE, VC, or ethene. Based on the very limited ethene data it appears that the ratios of cDCE and VC to ethene are increasing slightly, suggesting net production rate of VC exceeding production of ethene.
- STW-2B initially had a detectable ethene concentration, but the other two available samples are nondetects. Concentrations of TCE, cDCE, and VC have shown both increases and decreases during the 2000-2003 time interval, with the last two VC concentrations at nondetect levels. The TCE and cDCE concentrations have varied significantly in a sawtooth pattern. This may be indicative of the lateral variation of the margin or flank of the plume.
- Looking at vertical variations in well nests, the screen of STW-2A is deeper than STW-2B. TCE is greater in the shallower well, both STW-2A and STW-2B have about the same cDCE, and VC is greater in the deeper STW-2A well. The same basic pattern may exist in the data from POCW-4A, POCW-4B, and POCW-4C. At POCW-3 a similar pattern is seen, although the cDCE concentrations are a little higher in the

POCW-3B well than in the shallower POW-3C well. POW-2 shows higher concentrations of all these ethenes in the deeper "A" screen, but the elevation of the POW-2A screen lies between that of the POW-3B and POW-3C screens. On the other hand, POW-1 shows the highest concentrations of all of these ethenes in the deeper screen (the "A" screen) rather than in the shallow one, even though the elevation of the "A" screen is about the same elevation as the deep POW-3A screen. (Note that the peak concentration at POW-1 is 37 µg/L of cDCE, substantially less than at STW-2, POW-2, and POW-3.) These data suggest that TCE remains at shallower depths, which typically are more aerobic than deeper in aquifers, and has been substantially attenuated at depth. They also suggest that cDCE and VC are present at greater depths and are not being as effectively removed.

## 5. SUMMARIZING LINES OF EVIDENCE

Previous sections of this report have discussed four lines of evidence that have been investigated to determine whether, in particular, the western plume is being satisfactorily affected by monitored natural attenuation.

- Groundwater heads fluctuate, but consistently show groundwater flows in the direction anticipated, plus or minus a few degrees. This amount of variability is relatively small. Therefore, the first line is supportive of being consistent with intentions.
- Statistical analysis of intrawell concentration data show most wells are improving, but during the 2000-2003 timeframe some monitoring wells showed increasing concentrations and exceedances (see Volpe [2004]). Examination of TCE, cDCE, VC, ethene, and methane traces indicate that partial dechlorination of TCE has occurred through methanogenesis in the core of the plume. Other traces suggest that some aerobic degradation of vinyl chloride to ethene may be occurring near the Lake discharge area. Complete mineralization is limited, however, and that there may be a relative increase of cDCE. Lendvay *et al.* [1998] suggested that in shallow zones this may be due to higher rates of co-oxidation of VC by methanotrophs than for cDCE. In summary, this line of evidence suggests that the intended degradation mechanisms are operative, but they are not operating at a rate sufficient to degrade contaminants before their discharge to the Lake.
- The high concentrations observed at MWW-2 of cDCE are about 1% of the solubility limit in water. Increasing concentrations of cDCE and VC at MWW-3 have also been observed. These high concentrations are suggestive of (but not direct evidence for) contamination in a dense non-aqueous phase liquid (DNAPL), perhaps in residual amounts. It is believed that that cDCE and VC are degradation products of TCE, but no residual DNAPL source has been characterized. This line of evidence suggests that there may be a need for additional characterization of the source of increasing cDCE.
- The intrawell concentration records for STW-2 show erratic increases and decreases in concentrations of TCE, cDCE, and VC, which are particularly noticeable in STW-2B. Given the location of the STW-2 wells relative to the inferred main body of the plume (e.g., Figure 3), these fluctuations may be indicative of back-and-forth (lateral) "sloshing" of the flank of the narrow plume.
- The moment analyses show that there is a statistically significant increasing trend of TCE volume and mass in the western plume, and an increasing TCE volume in the eastern plume, though there is no increasing TCE mass. The volumes and masses for cDCE and VC in the east and west show no trends.

The centers of mass of TCE and cDCE have fluctuated over the 3-year monitoring dataset. The centers and orientations for these plumes have been quite consistent, with plume axis orientation fluctuating within only a few degrees, consistent with line of evidence 1. The interpreted plume axes for TCE, cDCE, and VC all appear to be straddled by the existing POCW wells. As described below, this does not mean that the data produced by the POCW wells are necessarily sufficient, as the three-

dimensional components of groundwater flow and contaminant distribution and the subsurface heterogeneity may cause peak concentrations to occur elsewhere.

- Looking to ethene data for the 2000-2003 data for evidence of complete dechlorination shows that elevated ethene concentrations exist at POCW-2A (deep), POCW-3 (all 3 monitored elevations), and STW-2A; other ethene observations are below the detection limit. Ethene concentrations at POCW-3 show decreasing trends of ethene (now undetected at the shallowest "C" level). Examining TCE, cDCE, and VC concentrations at these locations indicates that TCE is being attenuated.

***Result:*** We conclude that the observation data presented and supporting information indicate that natural biologically-mediated attenuation is occurring, but at a lower rate than expected. This means that the dechlorination of the dissolved chlorinated solvents is not complete by the time the plume discharges. There is an indication that there is increasing mass of TCE in the west plume during the 2000-2003 period, although the estimated mass of TCE in the west plume is substantially less than was interpreted (using a different methodology) based on 1996 data (see Weaver *et al.* [1996b]). Some of the 2000-2003 data suggest that there may be a need for additional work to characterize the near-discharge behavior of the western plume; for example, the MDEQ small-volume samples showed very high concentrations of TCE, cDCE, and VC. High concentrations of cDCE at MWW-2 may be indicative of residual DNAPL, and additional characterization may be needed if supplemental remedial actions (such as biostimulation or air-sparging) are investigated for the future.

## 6. CONCLUSIONS AND RECOMMENDATIONS

Following are conclusions and remarks drawn from our assessment of these data:

1. Contaminants continue to migrate in the east and west plumes.
2. Natural biologically-mediated attenuation is occurring at the site. Multiple degradation processes are occurring. Anaerobic dechlorination of TCE appears to be occurring through methanogenesis in the higher TCE concentration areas, and aerobic mineralization of VC to ethene appears to be occurring near the Lake Michigan discharge area. There is some evidence that suggests zones near the Lake that have alternately experienced both conditions (e.g., see Lendvay *et al.* [1998]).
3. Natural attenuation is incomplete. cDCE and VC concentrations in the venting (discharge) zone are especially excessive, at least locally.
4. The volume and mass of dissolved TCE in the western plume are increasing. Most of the increase appears to be at concentrations of less than 50 µg/L. The volume of the eastern TCE plume appears to be increasing also, though the mass apparently has no trend. There is no trend in volume or mass for cDCE or VC in either the eastern or western plume.
5. Consistently very high concentrations of cDCE have been observed at MWW-2. The concentrations have been roughly 1% of the solubility limit for cDCE. Concentrations this high are “highly suggestive of NAPL presence” [National Research Council, 1994] somewhere hydraulically up-gradient of MWW-2. The existence of DNAPL, or more likely DNAPL residues, has not been directly observed in the monitoring wells. There is some evidence that may suggest that a “train” of pulses of contaminant is being transported; this may be indicative of vadose zone DNAPL residuals. Additional characterization of the plume in this area may be warranted if additional remedial action alternatives, such as biostimulation or air-sparging, are considered for the future.
6. Offshore sampling by MDEQ in 2002, performed using small-bore needles pressed into lake sediments and having 4 cm-long perforated ends, recovered in some cases high concentrations of cDCE, TCE, and VC in areas where groundwater is discharging into the Lake. Yet, onshore monitoring wells near the Lake during 2000 to 2003 do not show concentrations approaching the offshore observations. There are several possible explanations for these differences. One factor is the difference in sample size—the offshore samples are drawn from cylinder 3 mm in outside diameter and 4 cm high, while the monitoring wells are typically 4 inches in diameter and more than 5 feet high. Second, the core of the plume has previously been interpreted as narrow [Woodward and Curran, 1999], so it is possible that the core of the plume could be induced by natural subsurface heterogeneities to travel in paths that do not intercept the monitoring wells. (The irregularity of the top of clay forming the base of the aquifer is an example heterogeneity.) Third, high concentrations of contaminant could be released into the groundwater at an upstream source area in a “train” of discrete pulses, so that there are gaps between high concentration areas (see #4 above). A fourth factor considered is that it takes time for groundwater contamination to travel

from onshore to offshore; that is, the MDEQ samples in 2002 were representative of onshore concentrations at a previous time determined by groundwater velocity. The cDCE concentrations at POCW-3B may be consistent with this hypothesis, but in that case we would expect a correspondence with TCE and VC data, which is not observed. The cause has not been resolved.

Resolution of the onshore/offshore differences can only occur with additional characterization. Detailed investigations, say using a GeoProbe, would help determine the best locations for additional onshore monitoring wells. We suggest that several locations be probed, along a line roughly perpendicular to groundwater flow and extending from between POCW-1 and POCW-2 and extending parallel to the lakeshore (approximately N30°E) about 150 feet beyond POCW-4. Selection of map locations and sampling elevations would be selected on the basis of probe results.

7. To evaluate natural biologically-mediated attenuation, it is necessary to monitor the appropriate analytes with sufficient frequency. For example, there are too few sampling results for ethene and dissolved oxygen. More regular sampling, particularly near the discharge area near the Lake, is needed to understand whether complete mineralization of TCE is occurring and the conditions that affect this. If TCE, cDCE, or VC are analyzed, so too should be ethene, DO, and methane, among a number of biologically-mediated-attenuation-related parameters.
8. If and when sampling protocols change, say from high- to low-volume sampling, the resulting datasets must clearly identify that such a change has occurred. Keeping such notices in the dataset will reduce the chance for misinterpretation of the data.
9. There is a need to establish a sample size for determining concentrations that allows fair comparisons of different samplers and is consistent with protection of human and environmental well-being. For example, a single needle sample (such as has been used in Lake Michigan sediment sampling) seems too small relative to the cross-sectional area of the plume.
10. Chemical and geohydrologic sampling results and supporting information (e.g., well locations, construction details, and sampling protocols) from the site should be consolidated into a database that can be used for ongoing evaluations.

## 7. DATA SOURCES AND REFERENCES

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## **8. ABBREVIATIONS AND ACRONYMS**

<b>ATSDR</b>	<b>Agency for Toxic Substances and Disease Registry</b>
<b>cDCE</b>	<b>cis-1,2-dichloroethene</b>
<b>cis-1,2-DCE</b>	<b>cis-1,2-dichloroethene</b>
<b>CO<sub>2</sub></b>	<b>carbon dioxide</b>
<b>DO</b>	<b>dissolved oxygen</b>
<b>MDEQ</b>	<b>Michigan Department of Environmental Quality</b>
<b>TCE</b>	<b>trichloroethene</b>
<b>tDCE</b>	<b>trans-1,2-dichloroethene</b>
<b>trans-1,2-DCE</b>	<b>trans-1,2-dichloroethene</b>
<b>USEPA</b>	<b>United States Environmental Protection Agency</b>
<b>VC</b>	<b>vinyl chloride (chloroethene)</b>

Table 1: Water level elevations (elevation above mean sea level, in feet) for the Bendix monitoring wells closest to Lake Michigan. Water level data extracted from draft MDEQ report [2004]. Missing data are indicate by blanks. Apparent error at STW2B is underlined and italicized.

<u>TOC</u> <u>elev.</u>		<u>12/1/00</u>	<u>4/4/01</u>	<u>6/21/01</u>	<u>9/23/01</u>	<u>12/1/01</u>	<u>4/4/02</u>	<u>6/22/02</u>	<u>9/26/02</u>	<u>12/4/02</u>	<u>4/2/03</u>	<u>6/5/03</u>	<u>9/30/03</u>
634.53	POCW1A	579.05	578.87	579.31	579.40	579.91	579.35	580.03	579.97	579.53	578.74	579.05	579.39
634.46	POCW1B	579.14	578.95	579.43	579.51	580.00	579.44	580.09	579.99	579.63	578.84	579.08	579.49
635.06	POCW2A	580.04	579.45	579.79	580.56	580.80	579.88	580.47	580.89	580.16	579.31	579.10	580.06
635.11	POCW2B	579.98	579.47	579.82	580.57	580.77	579.89	580.49	580.90		579.31	579.55	580.04
633.87	POCW3A	580.66	580.24	580.61	581.07	581.61	580.77	581.29	581.74	581.11	580.13	580.16	580.81
634.01	POCW3B	580.88	580.46	580.83	581.33	581.86	581.01	581.51	581.99	581.37	580.38	580.43	581.10
633.99	POCW3C	580.94	580.44	580.86	581.33	581.84	581.01	581.49	581.93	581.34	580.37	580.53	581.12
629.25	POCW4A	582.20	581.65	581.97	582.73	582.97	582.18	582.55	583.10	582.31	581.47	581.48	582.21
629.34	POCW4B	582.26	581.88	581.91	582.62	583.07	582.14	582.52	583.16	582.58	581.41	581.50	582.18
629.31	POCW4C	582.33	581.65		582.72	582.93	582.22	582.59	583.26	582.66	581.52	581.62	582.26
635.6	POCW5A	580.00	579.48	580.04	580.41	580.49	580.16	580.45	580.73	580.57	579.39	579.64	580.35
635.55	POCW5B	579.84	579.40	579.94	580.27	580.37	580.00	580.49	580.72	580.32	579.27	579.59	580.23
634.89	POCW6	580.01	579.53	580.00	580.47	580.53	580.06	580.62	581.00	580.38	579.38	579.64	580.39
633.74	STW1	586.44	585.51	585.97	586.55	586.98	585.94	586.24	587.16	586.88	585.51	585.11	586.20
633.78	STW2A	584.95	584.15	584.58	585.20	585.59	584.84	585.02	585.68	585.45	584.18	583.86	584.81
633.97	STW2B	585.01	584.25	584.68	<u>576.77</u>	585.84	584.86	585.09	585.90	585.52	584.24	583.97	584.87
635.16	STW3	584.24	583.56	583.94	584.35	584.85	584.00	584.44	585.09	584.74	583.58	583.37	583.99

Table 2. Summary of intrawell statistical evaluation performed by Volpe [2004]. This table replicates Table 5 of the Volpe report. For representative concentration values see Table 4 of Volpe report. ✓ = upper confidence level (UCL) exceeds cleanup standard. B = most recent sample below lower prediction level. W = most recent sample above upper prediction level. ↑ = increasing trend, and ↓ = decreasing trend.

Well	1,1,1-Trichloroethane	1,1-Dichloroethane	1,1-Dichloroethene	Cis-1,2-Dichloroethene	Trans-1,2-Dichloroethene	Trichloroethene	Vinyl Chloride
BDE-1							B
BDE-2							✓ ↑
BGE-1							
MWE-1		W	✓	✓	✓	✓ ↓	✓ W
MWE-2						✓	
POCE-1							
POCE-2							✓
POCE-3		W		✓			✓
POCE-4							
POCE-5							
POCE-6				✓			✓
POCE-7							
STE-1						W	
STE-2			✓	✓		✓	✓
STE-3				✓ ↓	↓	✓ ↑	✓ ↓
OW-17							
OW-25							
BDW-1		W ↑		✓		✓ W ↑	✓
BDW-2		W					✓
BGW-1							
MWW-1		↓				✓	✓
MWW-2			✓	✓	✓	✓	✓
MWW-3			✓ W	✓ W	W		✓ W
POCW-1A			B	W	W	✓	

<i>Well</i>	<i>1,1,1-Trichloro-ethane</i>	<i>1,1-Dichloro-ethane</i>	<i>1,1-Dichloro-ethene</i>	<i>Cis-1,2-Dichloro-ethene</i>	<i>Trans-1,2-Dichloro-ethene</i>	<i>Trichloro-ethene</i>	<i>Vinyl Chloride</i>
POCW-1B							
POCW-2A				✓	↓	✓	✓ W
POCW-2B							
POCW-3A			✓	✓	↓		✓ ↓
POCW-3B		W	✓	✓		✓	✓
POCW-3C			✓	✓		✓	✓ ↓
POCW-4A							✓
POCW-4B							✓
POCW-4C						✓	
POCW-5A							
POCW-5B							
POCW-6							↓
STW-1				W			
STW-2A			✓	✓			✓
STW-2B			✓	✓		✓	✓
STW-3						✓	✓

Table 3. Center of mass coordinates in the west plume for TCE, cDCE, and VC obtained from P.A.M.<sup>™</sup> analysis. Note that coordinates are given in feet.

EventDate	TCE		cDCE		VC	
	Easting ft	Northing ft	Easting ft	Northing ft	Easting ft	Northing ft
12/2000	539945.5	4655828.4	540083.1	4655789.1	540047.4	4655792.8
4/2001	539985.8	4655808.2	540180.1	4655730.3	540153.2	4655739.9
5/2001	540069.2	4655748.9	540189.4	4655726.5	540185.6	4655718.6
9/2001	540175.4	4655704.4	540188.1	4655726.0	540175.1	4655727.8
12/2001	540146.8	4655739.2	540192.7	4655720.5	540185.7	4655721.5
4/2002	540143.5	4655740.6	540180.4	4655730.2	540156.2	4655734.4
5/2002	540181.4	4655724.9	540195.8	4655719.1	540169.6	4655728.0
9/2002	540161.2	4655733.6	540193.0	4655718.2	540174.8	4655714.8
12/2002	540145.0	4655742.4	540192.9	4655719.6	540160.0	4655731.5
4/2003	540201.4	4655659.4	540190.0	4655721.7	540112.9	4655714.6

Location	Sample Date	TCE, ug/L	cis12DCE, ug	VC, ug/L	Ethene, ug/L	TCEtoDCE	TCEtoVC	DCEtoVC	DCEtoEthene	VC toEthene
HDW-1	12/08/00	19		20			0.9500	0.0000		
HDW-1	12/08/00	20	260	21		0.0769	0.9524	12.3810		
HDW-1	04/07/01	15	250	30		0.0600	0.4167	6.9444		
HDW-1	08/22/01	27	220	44		0.1227	0.6136	5.0600		
HDW-1	09/24/01	22	380	54		0.0679	0.4074	7.0370		
HDW-1	11/29/01	23	100	62		0.1211	0.3710	3.0645		
HDW-1	04/03/02	30	220	62		0.1564	0.4836	3.0484		
HDW-1	08/24/02	26	380	68		0.0684	0.4483	6.5517		
HDW-1	09/24/02	29	240	26		0.1208	1.1154	9.2368		
HDW-1	12/05/02	29	220	19		0.1518	1.5263	11.5789		
HDW-1	04/03/03	33	230	16		0.1438	2.0828	14.5780		
HDW-1	08/07/03	42	250	22		0.1680	1.9091	11.3636		
HDW-1	10/01/03	48	220	22		0.2182	2.1818	10.0000		
MWW-1	12/08/00	140	92	61		1.5217	2.2951	1.5082		
MWW-1	04/07/01	240	77	64		3.1189	3.7500	1.2031		
MWW-1	08/22/01	400	66	620		6.0606	0.6452	0.1085		
MWW-1	09/24/01	440	56	1200		7.8571	0.3667	0.0467		
MWW-1	11/29/01	290	54	590		5.3704	0.4915	0.0913		
MWW-1	04/03/02	190	40	150		4.7500	1.2667	0.2667		
MWW-1	08/22/02	200	68	230		2.2727	0.8696	0.3826		
MWW-1	09/24/02	180	75	200		2.1333	0.8000	0.3750		
MWW-1	12/05/02	150	66	120		2.2727	1.2500	0.5500		
MWW-1	04/03/03	190	59	57		3.2203	3.3333	1.0351		
MWW-1	08/07/03	97	35	21		2.7714	4.6190	1.6667		
MWW-1	08/07/03	98	38	22		2.5789	4.4545	1.7273		
MWW-1	10/01/03	130	58	120		2.3214	1.0833	0.4667		
MWW-1	10/01/03	140	59			2.3729				

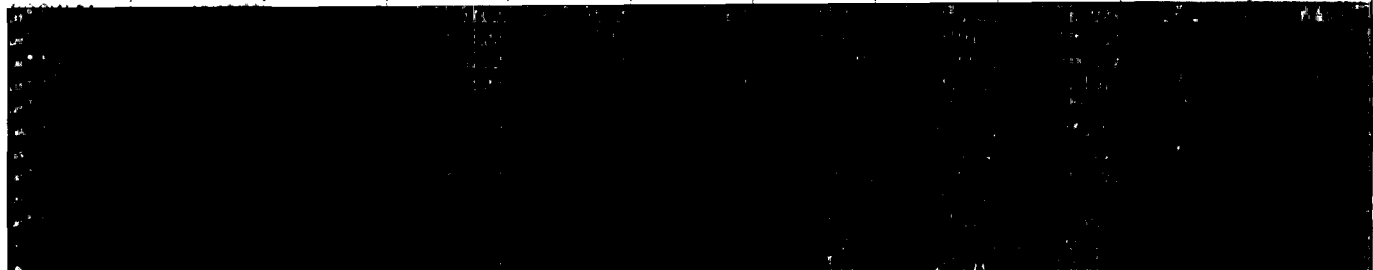
Table 4. Summary of data for TCE, cDCE, VC, and ethene for western plume, sorted by location and date. Ratios of among members of the TCE degradation chain are also shown. Nondetects are replaced by detection limit; missing data are blank; ratios that cannot be calculated are marked "--".

Location	Sample Date	TCE, ug/L	Ch12DCE, ug	VC, ug/L	Ethene, ug/L	TCEtoDCE	TCEtoVC	DCEtoVC	DCEtoEthene	VC toEthene
MWW-3	12/08/00	5	430	120		0.0118	0.0417	3.5833		
MWW-3	04/08/01	5	390	150		0.0143	0.0333	2.3333		
MWW-3	04/08/01			160						
MWW-3	08/22/01	1	180	110		0.0056	0.0091	1.6364		
MWW-3	09/23/01	1	390	310		0.0028	0.0052	1.8613	..	..
MWW-3	11/29/01	1	190	130		0.0053	0.0077	1.4618	..	..
MWW-3	04/03/02	2	240	190		0.0083	0.0108	1.2652	..	..
MWW-3	06/24/02	2	330	260		0.0081	0.0089	1.1379	..	..
MWW-3	09/26/02	2	240	230		0.0083	0.0087	1.0458	..	..
MWW-3	12/04/02	2	220	280		0.0061	0.0071	0.7857	..	..
MWW-3	04/03/03	2	340	2800		0.0059	0.0008	0.1308	..	..
MWW-3	06/05/03	20	920	3000		0.0217	0.0067	0.3087	..	..
MWW-3	09/30/03	50	8400	4800		0.0080	0.0109	1.8261	..	..

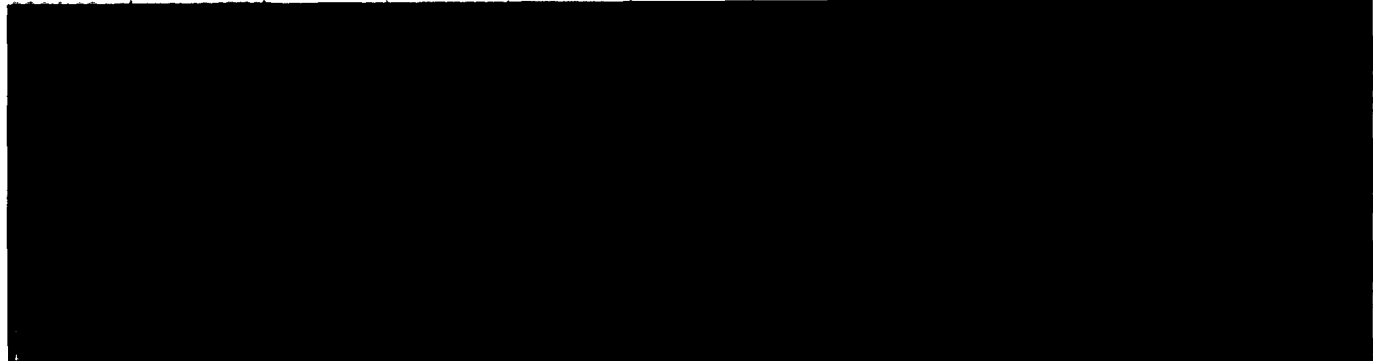
POCW-1B	12/10/00	1	1	2	10	1.0000	0.5000	0.5000	0.1	0.2
POCW-1B	04/04/01	1	1	2		1.0000	0.5000	0.5000	..	..
POCW-1B	06/21/01	18	4	2		4.5000	9.0000	2.0000	..	..
POCW-1B	09/23/01	1	1	2	10	1.0000	0.5000	0.5000	0.1	0.2
POCW-1B	11/29/01	1	1	2		1.0000	0.5000	0.5000	..	..
POCW-1B	04/03/02	1	1	2		1.0000	0.5000	0.5000	..	..
POCW-1B	06/24/02	1	1	2	10	1.0000	0.5000	0.5000	0.1	0.2
POCW-1B	09/26/02	1	1	2		1.0000	0.5000	0.5000	..	..
POCW-1B	12/04/02	1	1	2		1.0000	0.5000	0.5000	..	..
POCW-1B	04/02/03	1	1	2		1.0000	0.5000	0.5000	..	..
POCW-1B	06/05/03	2	1	2		2.0000	1.0000	0.5000	..	..
POCW-1B	09/30/03	1	1	2		1.0000	0.5000	0.5000	..	..



Location	Sample Date	TCE, ug/L	Cis12DCE, ug	VC, ug/L	Ethene, ug/L	TCEtoDCE	TCEtoVC	DCFtoVC	DCEtoEthene	VC toEthene
POCW-2B	12/03/00	7	1	2	10	7.0000	3.5000	0.5000	0.1	0.2
POCW-2B	04/04/01	8	2	2		3.0000	3.0000	1.0000		
POCW-2B	08/19/01	10	1	2		16.6667	5.0000	0.3000		
POCW-2B	09/23/01	8	3	2	10	2.6667	4.0000	1.5000	0.3	0.2
POCW-2B	11/28/01	1	1	2		1.0000	0.5000	0.5000		
POCW-2B	04/04/02	2	1	2		2.5000	1.0000	0.4000		
POCW-2B	06/24/02	3	1	2	10	3.3333	1.5000	0.4500	0.09	0.2
POCW-2B	09/24/02	5	1	2		7.1429	2.5000	0.3500		
POCW-2B	12/04/02	1	1	2		0.9000	0.4500	0.5000		
POCW-2B	04/02/03	1	1	2		1.0000	0.5000	0.5000		
POCW-2B	06/05/03	3	1	2		3.0000	1.5000	0.5000		
POCW-2B	09/30/03	2	1	2		2.0000	1.0000	0.5000		



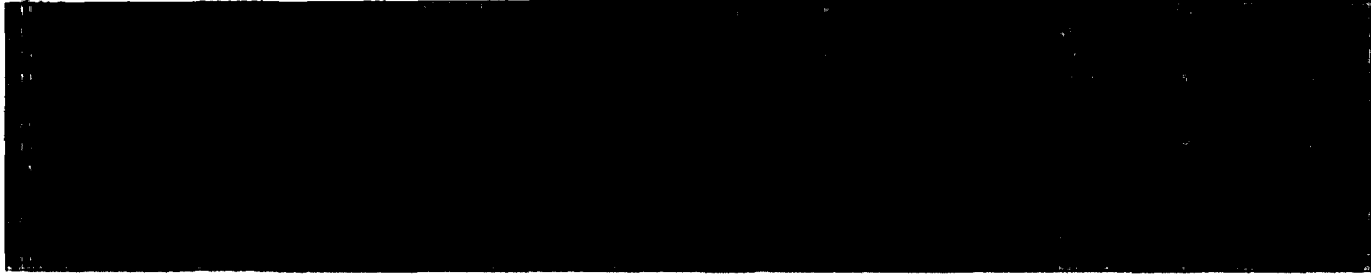
POCW-3B	12/10/00	1800	3100	2200	1100	0.5808	0.8182	1.4091	2.82	2
POCW-3B	04/04/01	1200	1700	1400		0.7059	0.8571	1.2143		
POCW-3B	08/19/01	2300	2800	1900		0.8214	1.2105	1.4737		
POCW-3B	09/23/01	1600	3200	2000	500	0.5000	0.8000	1.6000	6.4	4
POCW-3B	11/28/01	880	1900	1400		0.4632	0.8286	1.3571		
POCW-3B	04/04/02	1100	1700	1000		0.6471	1.1000	1.7000		
POCW-3B	04/04/02		1800	990				1.8182		
POCW-3B	06/24/02	580	3200	1600	190	0.1813	0.3625	2.0000	16.84	8.42
POCW-3B	09/24/02	870	1000	500		0.8700	1.7400	2.0000		
POCW-3B	12/04/02	1400	1300	450		1.0769	3.1111	2.8889		
POCW-3B	04/01/03	1400	1100	610		1.2727	2.2951	1.8033		
POCW-3B	04/01/03		1200	640				1.8750		
POCW-3B	06/05/03	980	940	740		1.0426	1.3243	1.2703		
POCW-3B	09/29/03	520	1400	830		0.3714	0.6286	1.6667		



Location	Sample Date	TCE, ug/L	Cis12DCE, ug	VC, ug/L	Ethene, ug/L	TCEtoDCE	TCEtoVC	DCEtoVC	DCEtoEthene	VC toEthene
POCW 4A	12/09/00	1	1	3	10	1 0000	0 3333	0 3333	0 1	0 3
POCW 4A	04/04/01	1	1	3		1 0000	0 3333	0 3333		
POCW 4A	08/16/01	1	1	2		1 0000	0 5000	0 5000		
POCW 4A	09/20/01	1	1	4	10	1 0000	0 2500	0 2500	0 1	0 4
POCW 4A	11/28/01	1	1	4		1 0000	0 2500	0 2500		
POCW 4A	04/04/02	1	1	2		1 0000	0 5000	0 5000		
POCW 4A	06/24/02	1	1	4	10	1 0000	0 2500	0 2500	0 1	0 4
POCW 4A	09/24/02	1	1	4		1 0000	0 2500	0 2500		
POCW 4A	12/04/02	1	1	4		1 0000	0 2500	0 2500		
POCW 4A	04/01/03	1	1	2		1 0000	0 5000	0 5000		
POCW 4A	06/05/03	2	1	4		2 0000	0 5000	0 2500		
POCW 4A	09/29/03	1	1	4		1 0000	0 2500	0 2500		
POCW 4C	12/09/00	13	11	2	10	1 1818	6 5000	5 5000	1 1	0 2
POCW 4C	04/04/01	17	13	2		1 3077	6 5000	6 5000		
POCW 4C	08/16/01	12	4	2		3 0000	6 0000	2 0000		
POCW 4C	09/23/01	1	1	2	10	1 0000	0 5000	0 5000	0 1	0 2
POCW 4C	11/28/01	1	7	3		0 1429	0 3333	2 3333		
POCW 4C	04/04/02	17	5	2		3 4000	6 5000	2 5000		
POCW 4C	06/24/02	14	9	2	10	1 5556	7 0000	4 5000	0 9	0 2
POCW 4C	09/24/02	12	7	2		1 7143	6 0000	3 5000		
POCW 4C	12/04/02	13	8	2		1 6250	6 5000	4 0000		
POCW 4C	04/01/03	18	10	2		1 6000	6 0000	5 0000		
POCW 4C	06/05/03	18	10	2		1 6000	9 0000	5 0000		
POCW 4C	09/29/03	10	5	2		2 0000	6 0000	2 5000		

Location	Sample Date	TCE, ug/L	Cis-1,2-DCE, ug	VC, ug/L	Ethene, ug/L	TCE to DCE	TCE to VC	DCE to VC	DCE to Ethene	VC to Ethene
POCW 5B	12/00/00	1	1	2	10	1.0000	0.5000	0.5000	0.1	0.2
POCW 5B	04/08/01	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	06/18/01	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	09/20/01	1	1	2	10	1.0000	0.5000	0.5000	0.1	0.2
POCW 5B	11/27/01	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	04/02/02	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	06/21/02	1	1	2	10	1.0000	0.5000	0.5000	0.1	0.2
POCW 5B	09/23/02	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	12/03/02	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	03/31/03	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	06/03/03	1	1	2		1.0000	0.5000	0.5000		
POCW 5B	09/29/03	1	1	2		1.0000	0.5000	0.5000		
STW 1	12/11/00	1	6	2	10	0.2000	0.5000	2.5000	0.5	0.2
STW 1	04/06/01	1	6	2		0.1667	0.5000	3.0000		
STW 1	06/21/01	1	6	2		0.1667	0.5000	3.0000		
STW 1	09/24/01	1	6	2	10	0.1667	0.5000	3.0000	0.6	0.2
STW 1	11/30/01	1	4			0.2500				
STW 1	04/02/02	1	4	2		0.2500	0.5000	2.0000		
STW 1	04/02/02	1	5							
STW 1	06/25/02	1	6	2	10	0.1667	0.5000	3.0000	0.6	0.2
STW 1	09/27/02	1	4	2		0.2500	0.5000	2.0000		
STW 1	12/05/02	1	4	2		0.1750	0.3500	2.0000		
STW 1	04/04/03	1	4	2		0.2500	0.5000	2.0000		
STW 1	06/06/03	1	7	2		0.1429	0.5000	3.5000		
STW 1	10/03/03	1	7	2		0.1429	0.5000	3.5000		

Location	Sample Date	TCE, ug/L	Cis12DCE, ug	VC, ug/L	Ethene, ug/L	TCEtoDCE	TCEtoVC	DCEtoVC	DCEtoEthene	VC toEthene
STW 2B	12/11/00	370	1600	240	26	0.2113	1.5417	n non?	61.54	0.21
STW 2B	04/06/01	800	240	38		3.3333	21.0526	6.3158		
STW 2B	05/21/01	2200	360	78		5.6410	28.2051	5.0000		
STW 2B	09/24/01	5400	1100	310		4.6691	17.4104	3.6484		
STW 2B	09/24/01		070	320	10		0.0000	3.0313	67	32
STW 2B	11/30/01	160	60	2		3.2000	80.0000	28.0000		
STW 2B	04/02/02	160	16	73		8.4211	2.1918	0.2603		
STW 2B	06/25/02	180	30	130	10	6.0000	1.3848	0.2308	3	13
STW 2B	09/27/02	1300	1500	130		0.8667	10.0000	11.8388		
STW 2B	12/07/02	1100	1200	87		0.8187	12.6437	13.7831		
STW 2B	04/04/03	100	44	4		2.2727	28.0000	11.0000		
STW 2B	06/06/03	19	8	1		2.3750	18.0000	8.0000		
STW 2B	10/03/03	61	34	2		1.7941	30.0000	17.0000		



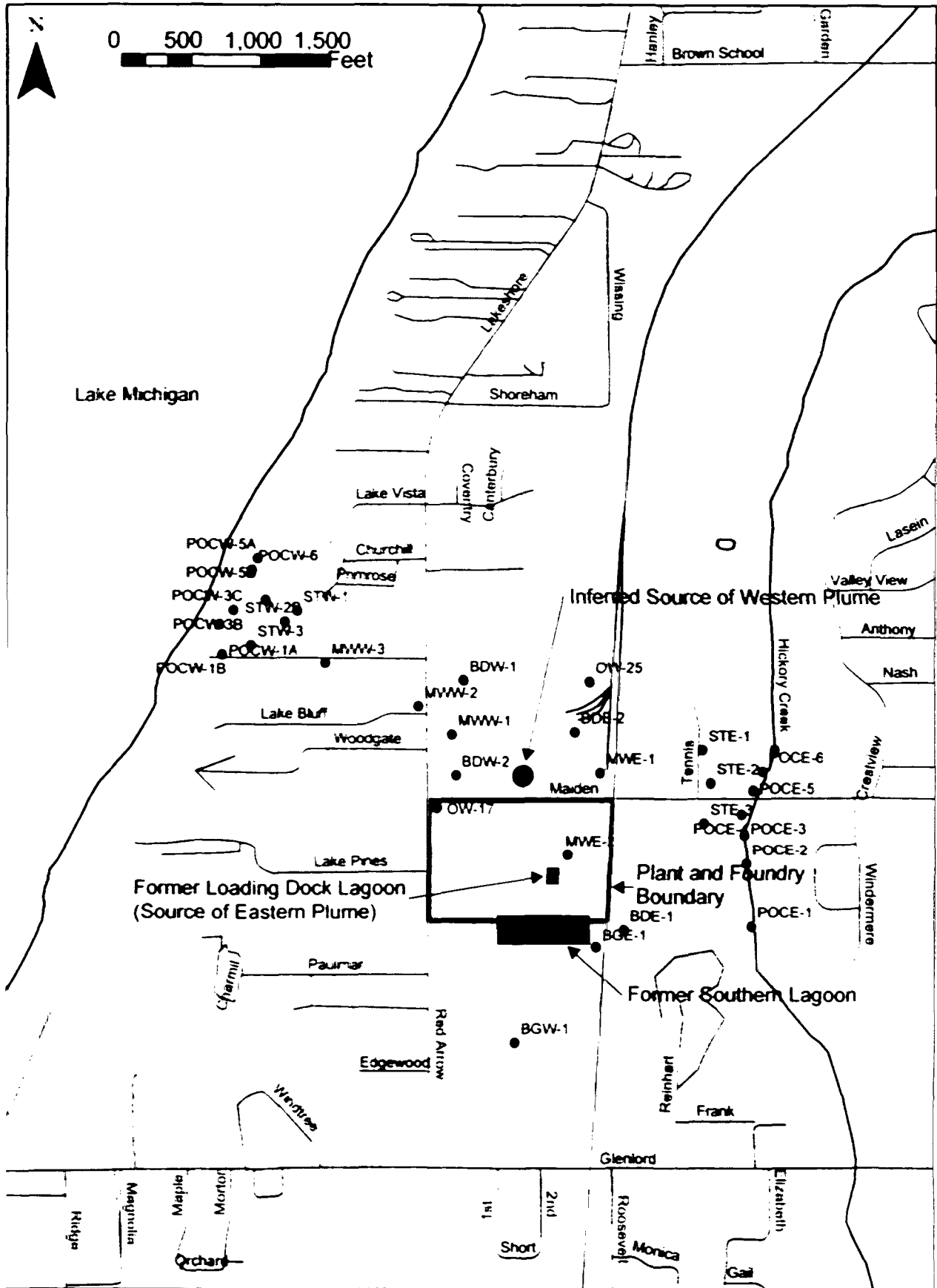


Figure 1. Map of the Bendix site and its vicinity. Solid green polygon indicates the boundary of the plant and foundry, blue filled circles with labels indicate monitoring wells, known source areas are indicated, and Lake Michigan and Hickory Creek are identified.

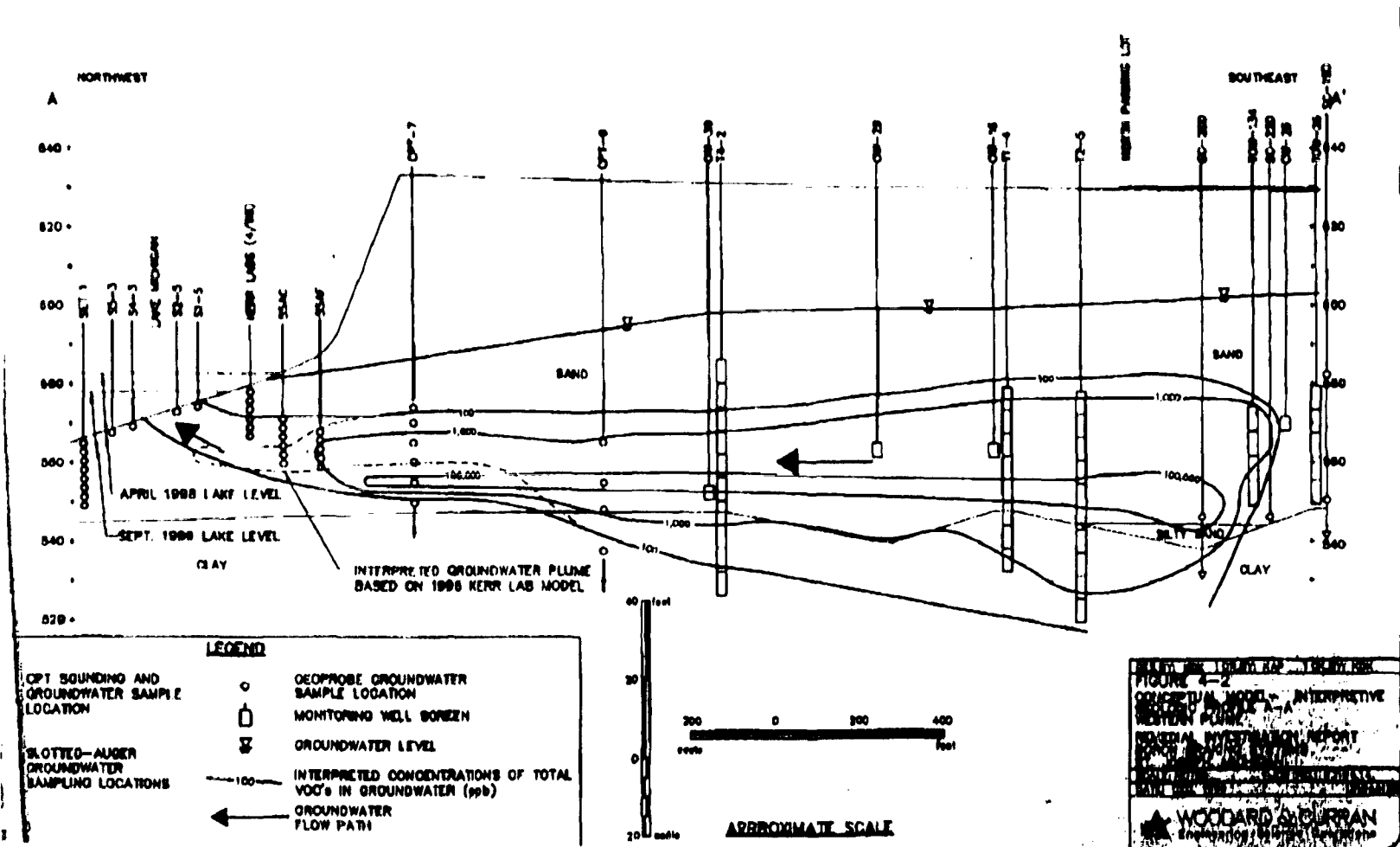


Figure 2: Cross-section through the western plume. Best available copy from Woodward and Curran [1999].

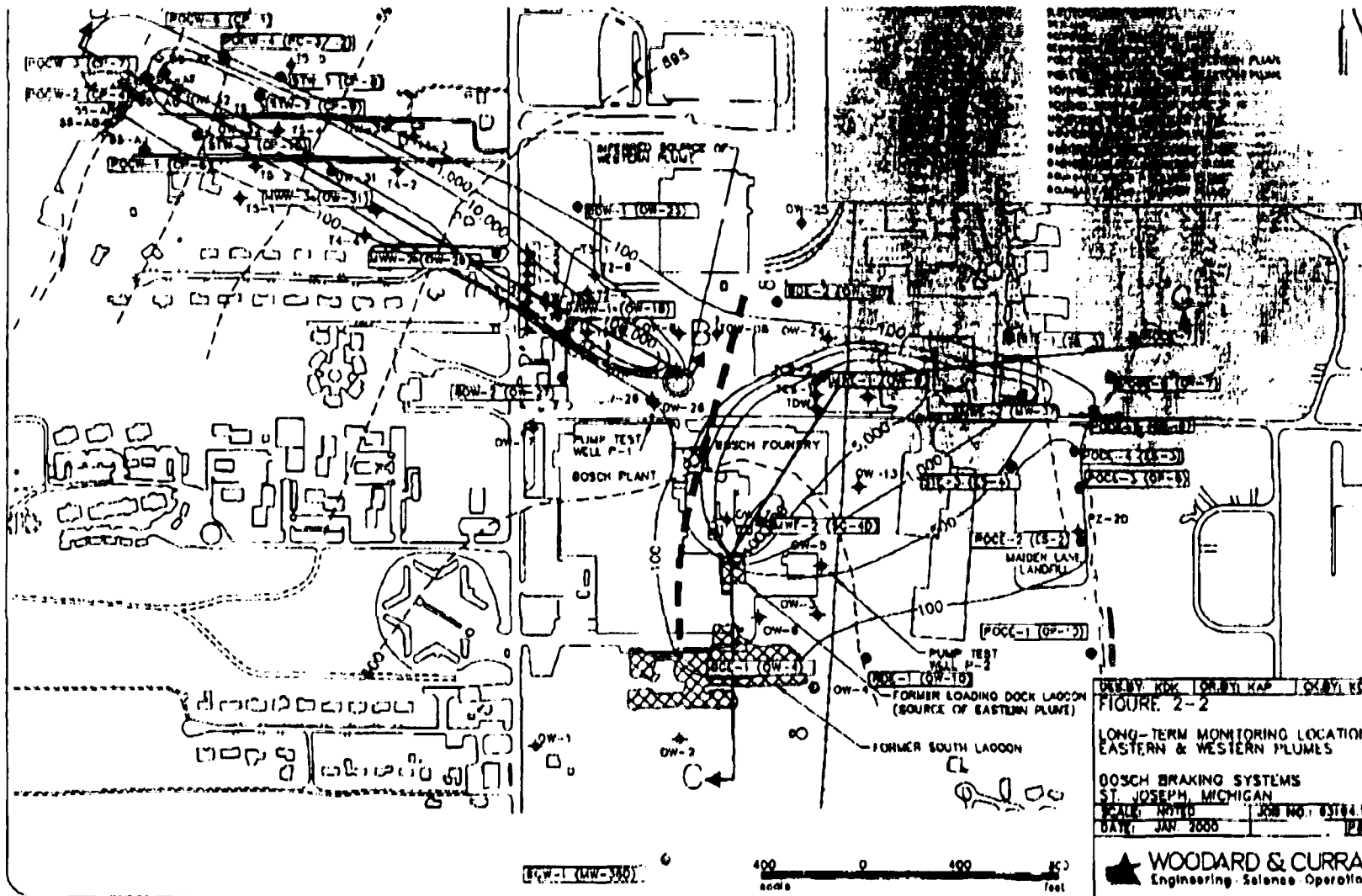


Figure 3. Map view of western and eastern plumes (north-south dashed line separates them). Best available copy from Woodward and Curran [2000].

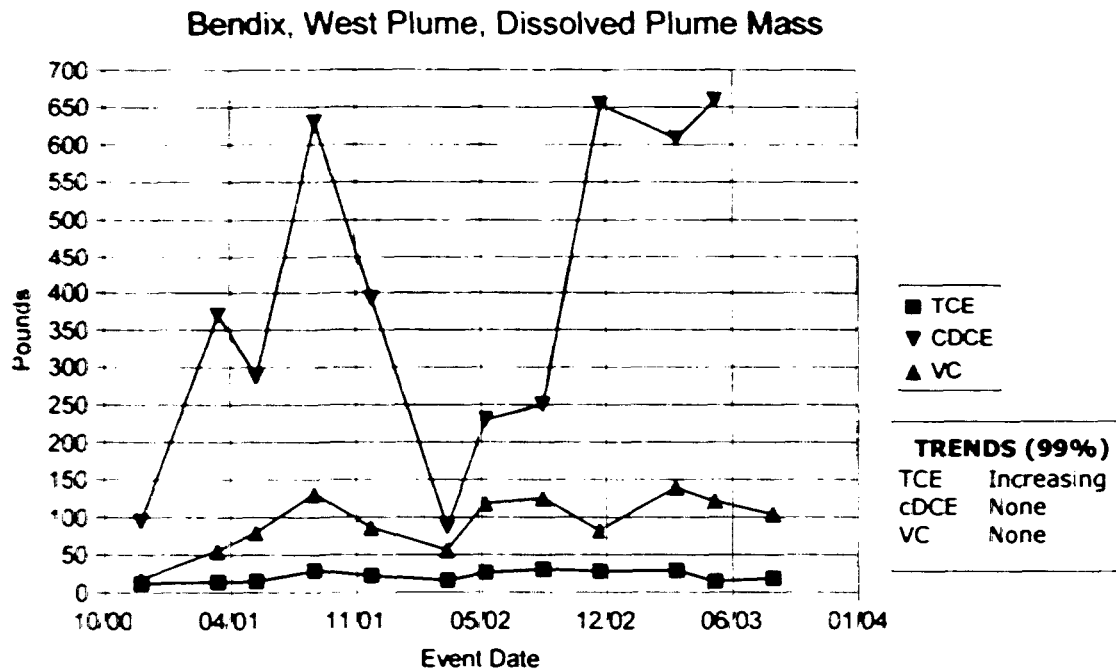
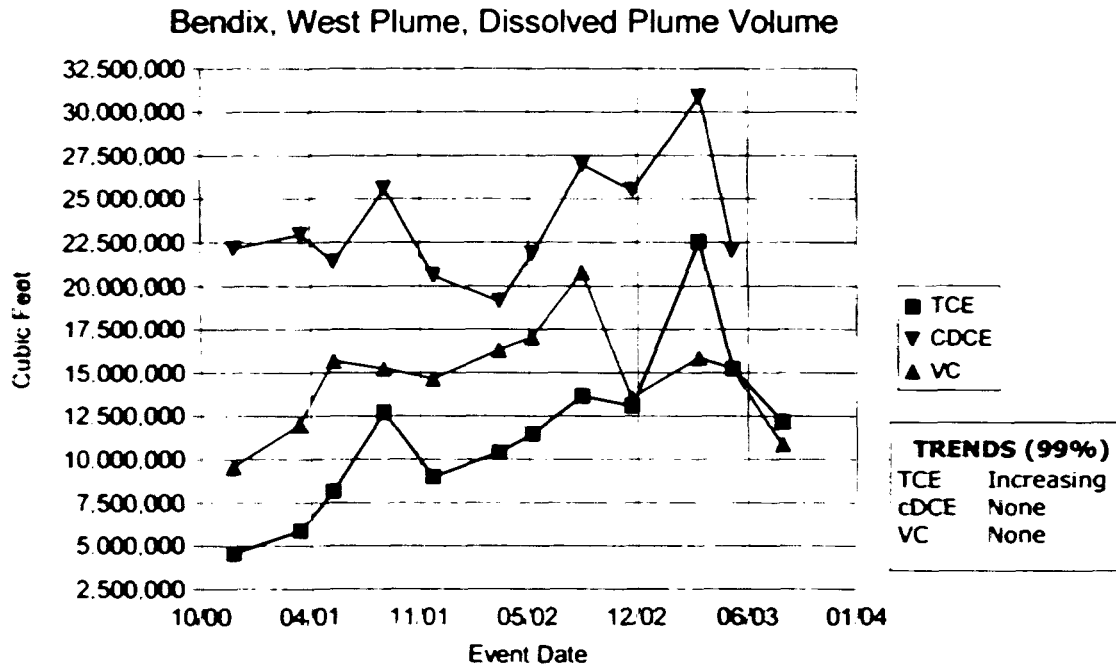


Figure 4 Western plume volume and mass versus time for TCE, cDCE, and VC.



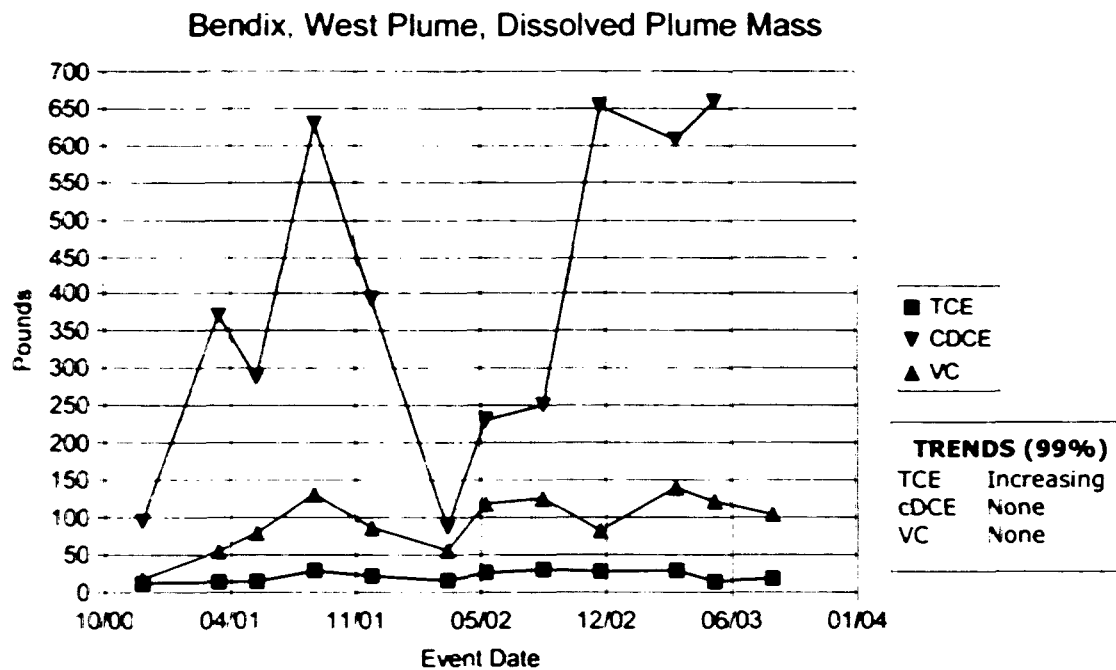
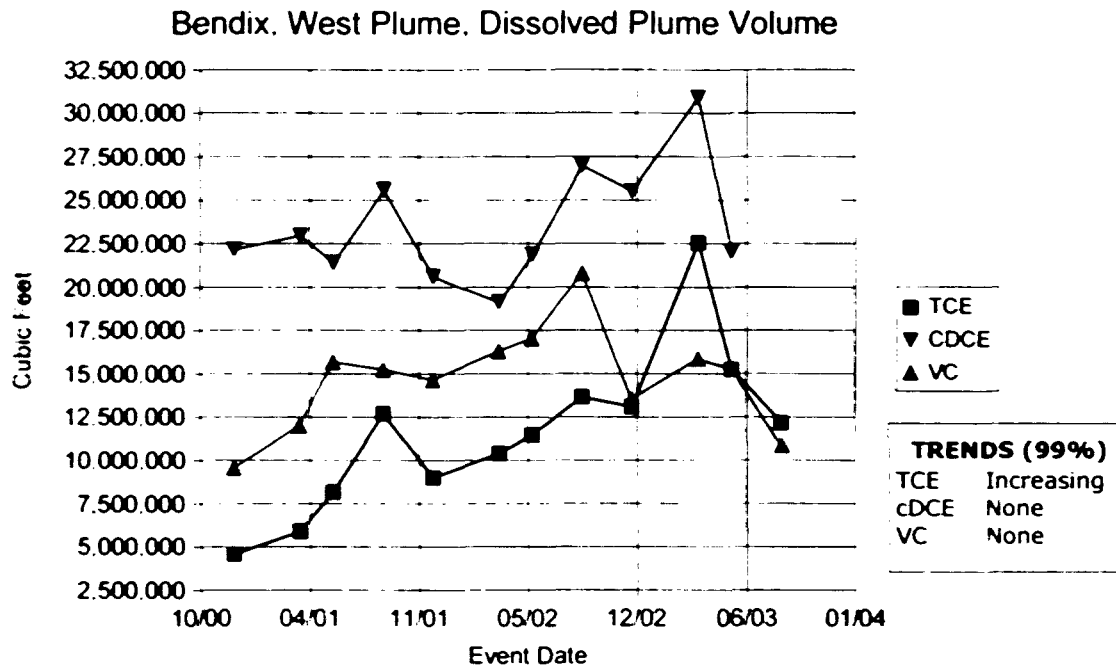
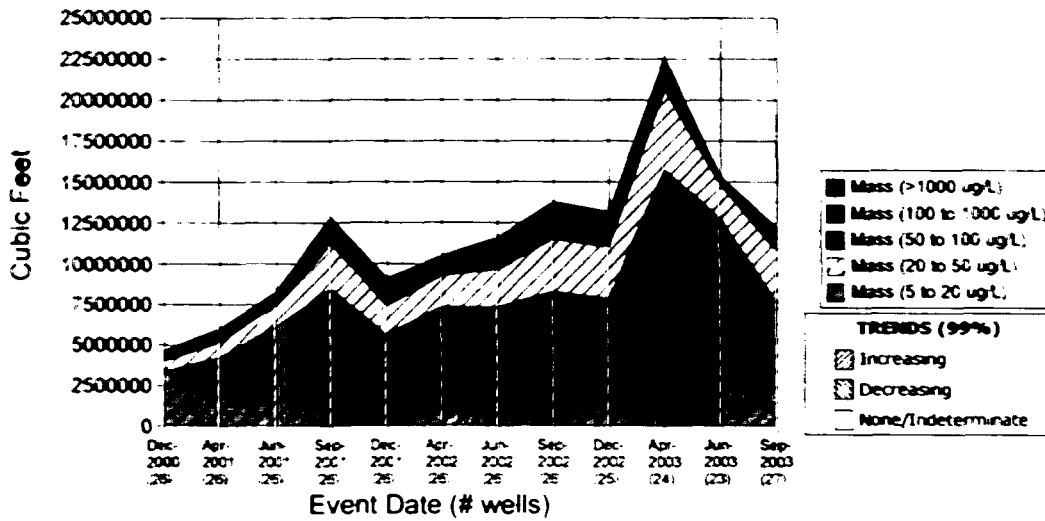


Figure 4. Western plume volume and mass versus time for TCE, cDCE, and VC.

### Bendix, West Plume, Dissolved TCE Plume Volume



### Bendix, West Plume, Dissolved TCE Mass

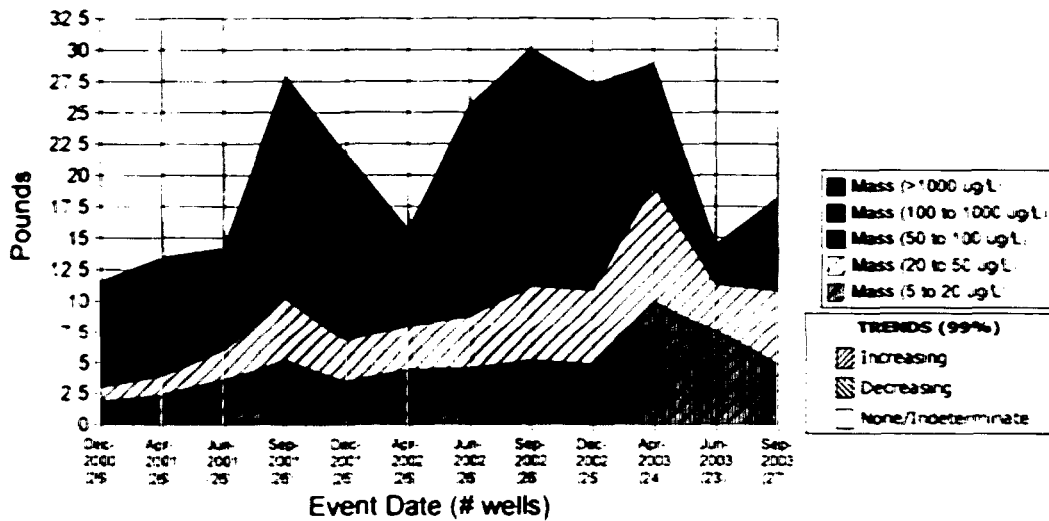
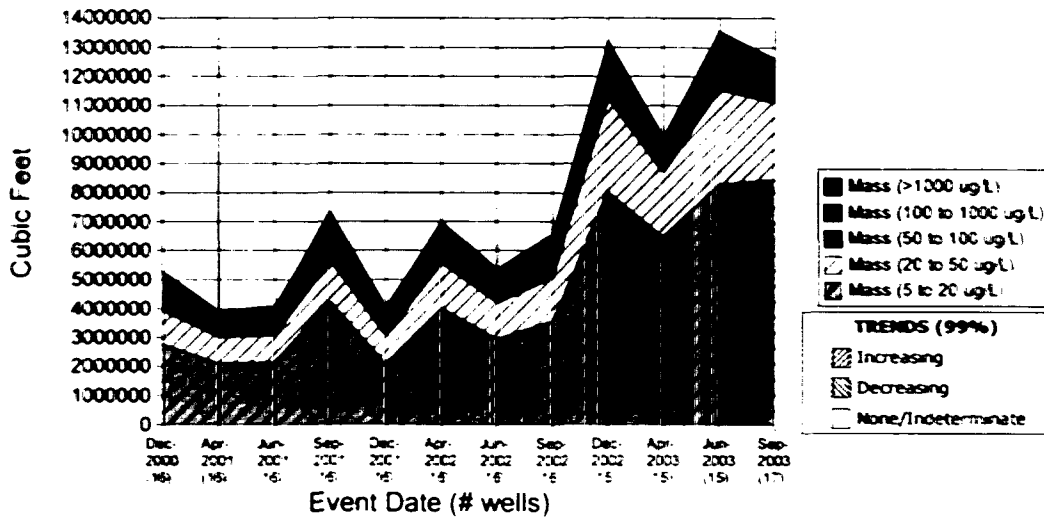


Figure 6. Plume volume (top) and mass (bottom) for TCE in the west plume, as determined by MVS and CARStat analyses. Only water volume and dissolved mass are considered. The overall behaviors, i.e., for all concentrations above 5 ug/L, are increasing volume and increasing mass.

### Bendix, East Plume, Dissolved TCE Plume Volume



### Bendix, East Plume, Dissolved TCE Mass

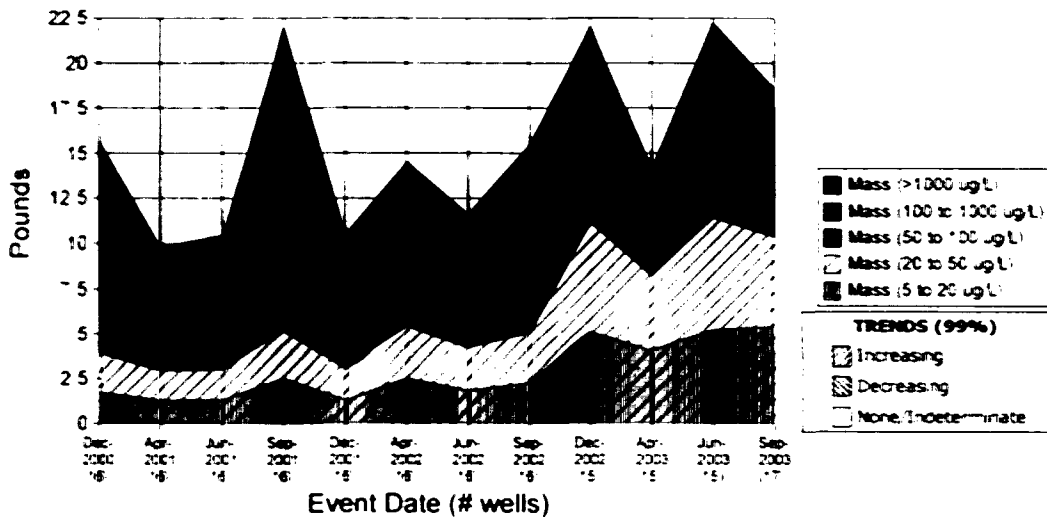
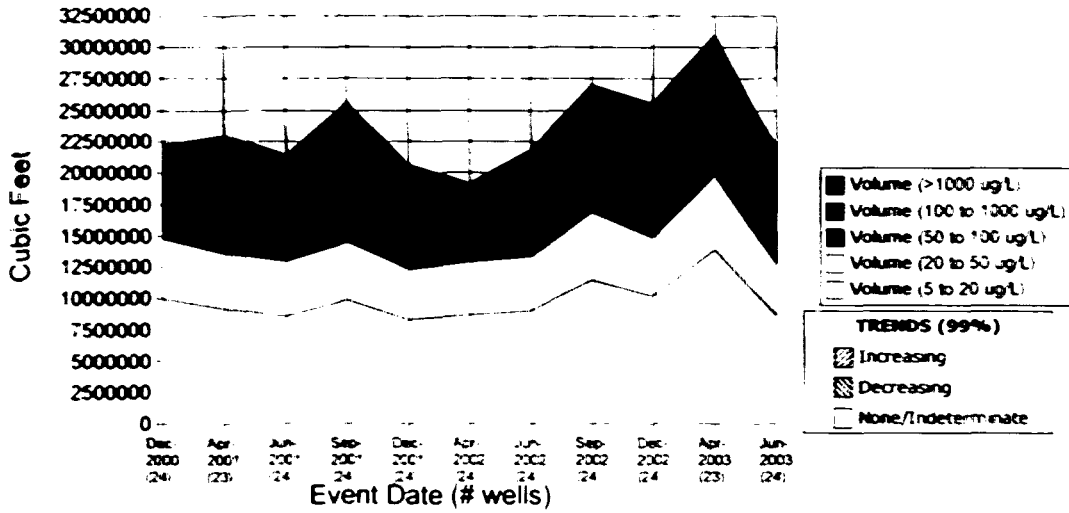


Figure 7. Plume volume (top) and mass (bottom) for TCE in the east plume, as determined by MVS and CARStat analyses. Only water volume and dissolved mass are considered. The overall behaviors, i.e., for all concentrations above 5 ug/L, are increasing volume and no trend for mass.

### Bendix, West Plume, Dissolved cis-1,2-DCE Volume



### Bendix, West Plume, Dissolved cis-1,2-DCE Mass

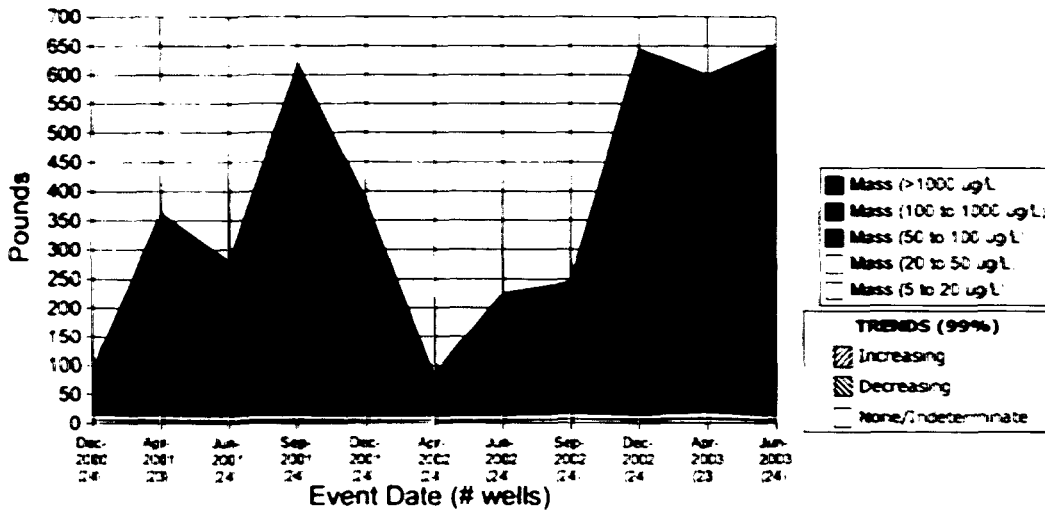
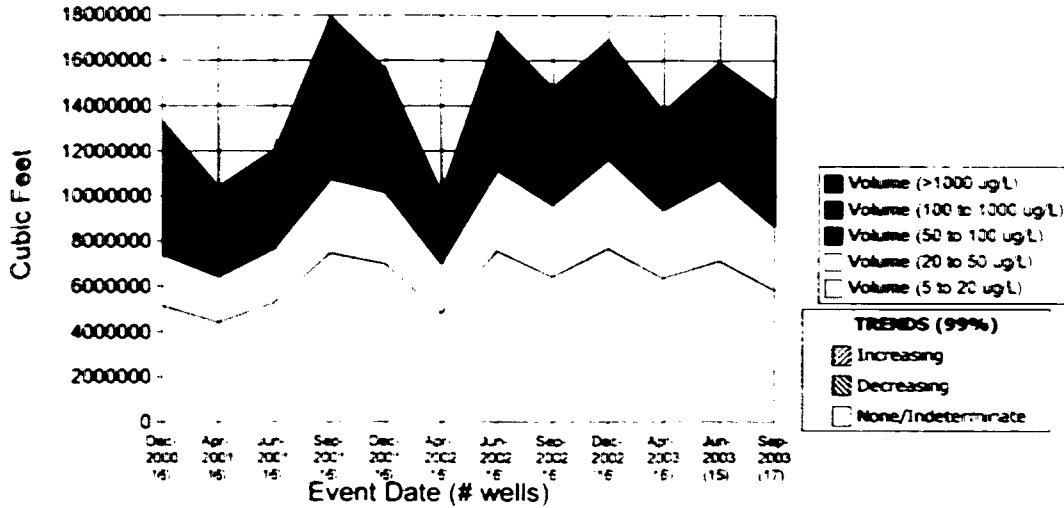


Figure 8. Plume volume (top) and mass (bottom) for cis-1,2-DCE in the west plume, as determined by MVS and trend analyses. Only water volume and dissolved mass are considered. The overall behaviors, i.e., for all concentrations above 5 µg/L, are no trend for volume and no trend for mass.

### Bendix, East Plume, Dissolved cis-1,2-DCE Volume



### Bendix, East Plume, Dissolved cis-1,2-DCE Mass

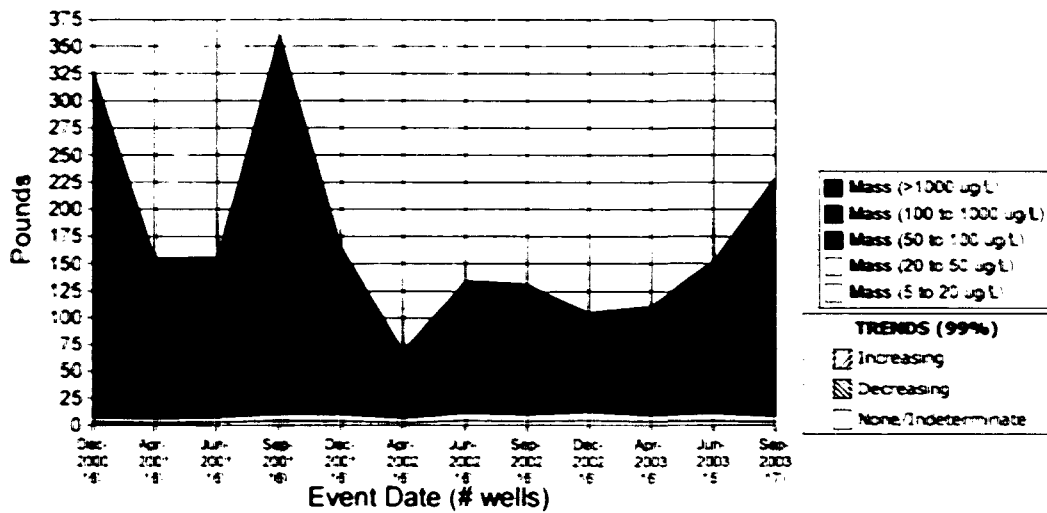
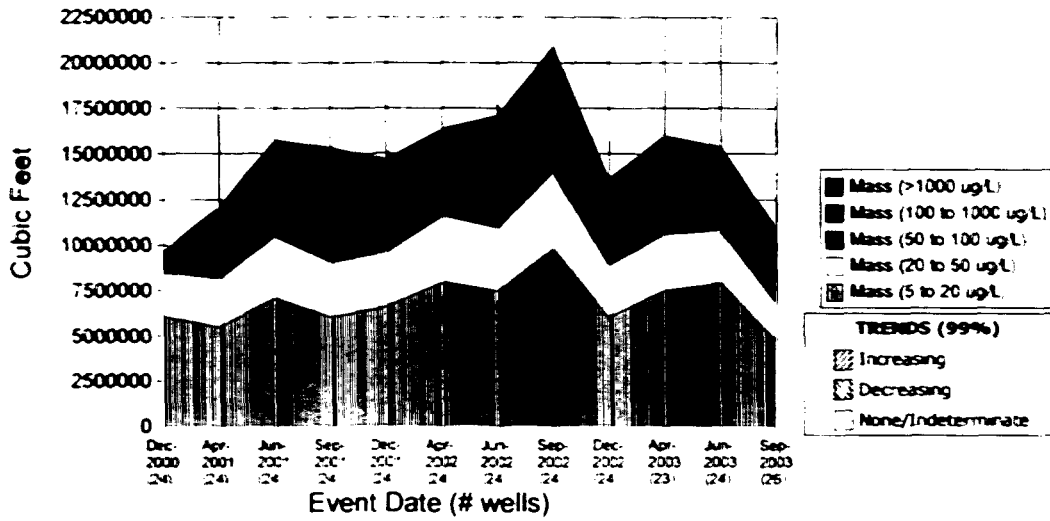


Figure 9. Plume volume (top) and mass (bottom) for cis-1,2-DCE in the east plume, as determined by MVS and trend analyses. Only water volume and dissolved mass are considered. The overall behaviors, i.e., for all concentrations above 5 µg/L, are no trend for volume and no trend for mass.

### Bendix, West Plume, Dissolved VC Plume Volume



### Bendix, West Plume, Dissolved VC Mass

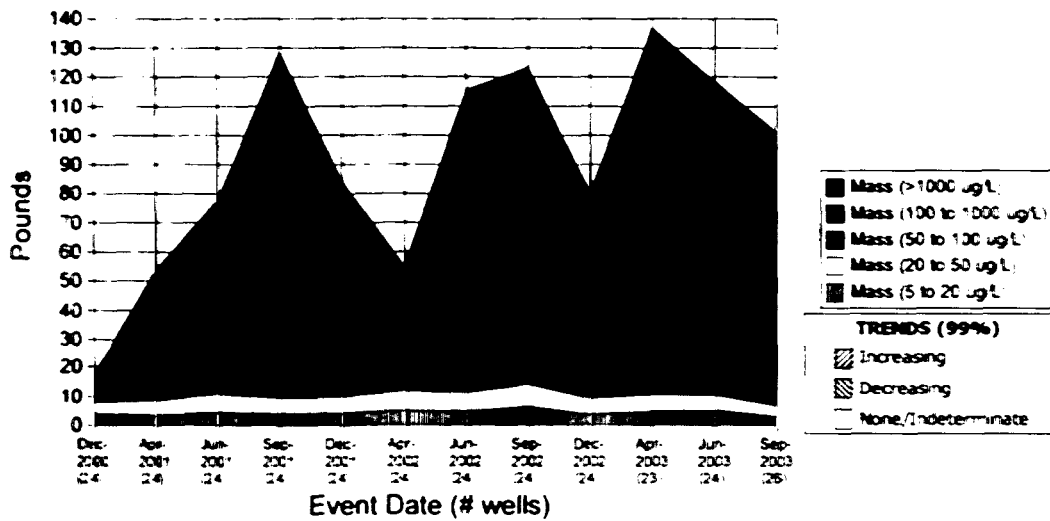
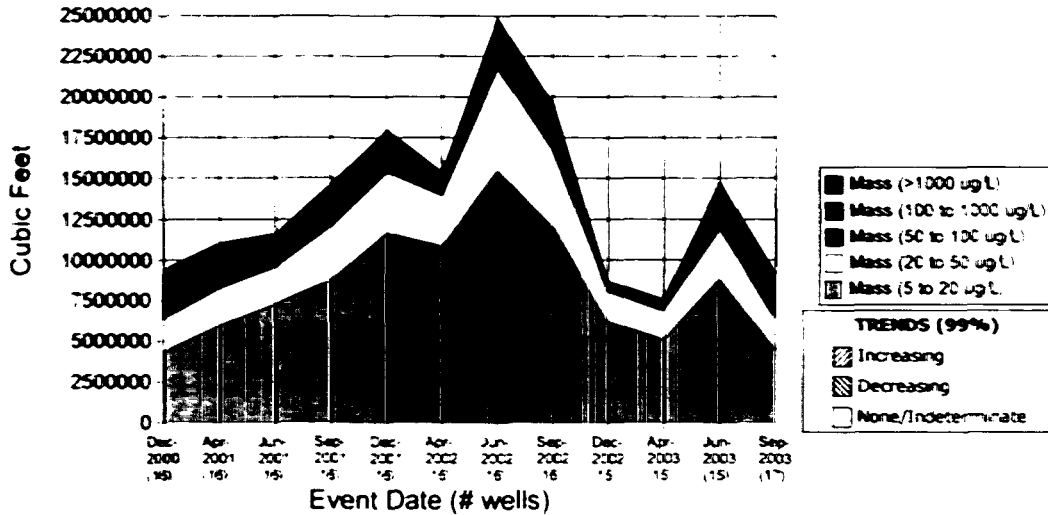


Figure 10. Plume volume (top) and mass (bottom) for VC in the west plume, as determined by MVS and CARStat analyses. Only water volume and dissolved mass are considered. The overall behaviors, i.e., for all concentrations above 5 ug/L, are no trend for volume and no trend for mass.

### Bendix, East Plume, Dissolved VC Plume Volume



### Bendix, East Plume, Dissolved VC Mass

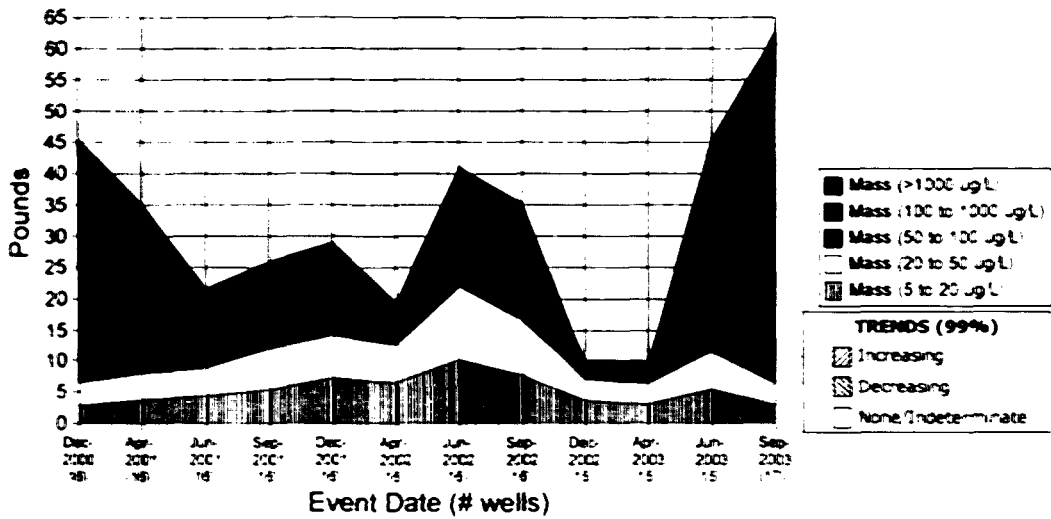


Figure 11. Plume volume (top) and mass (bottom) for VC in the east plume, as determined by MVS and CARStat analyses. Only water volume and dissolved mass are considered. The overall behaviors, i.e., for all concentrations above 5 ug/L, are no trend for volume and no trend for mass.

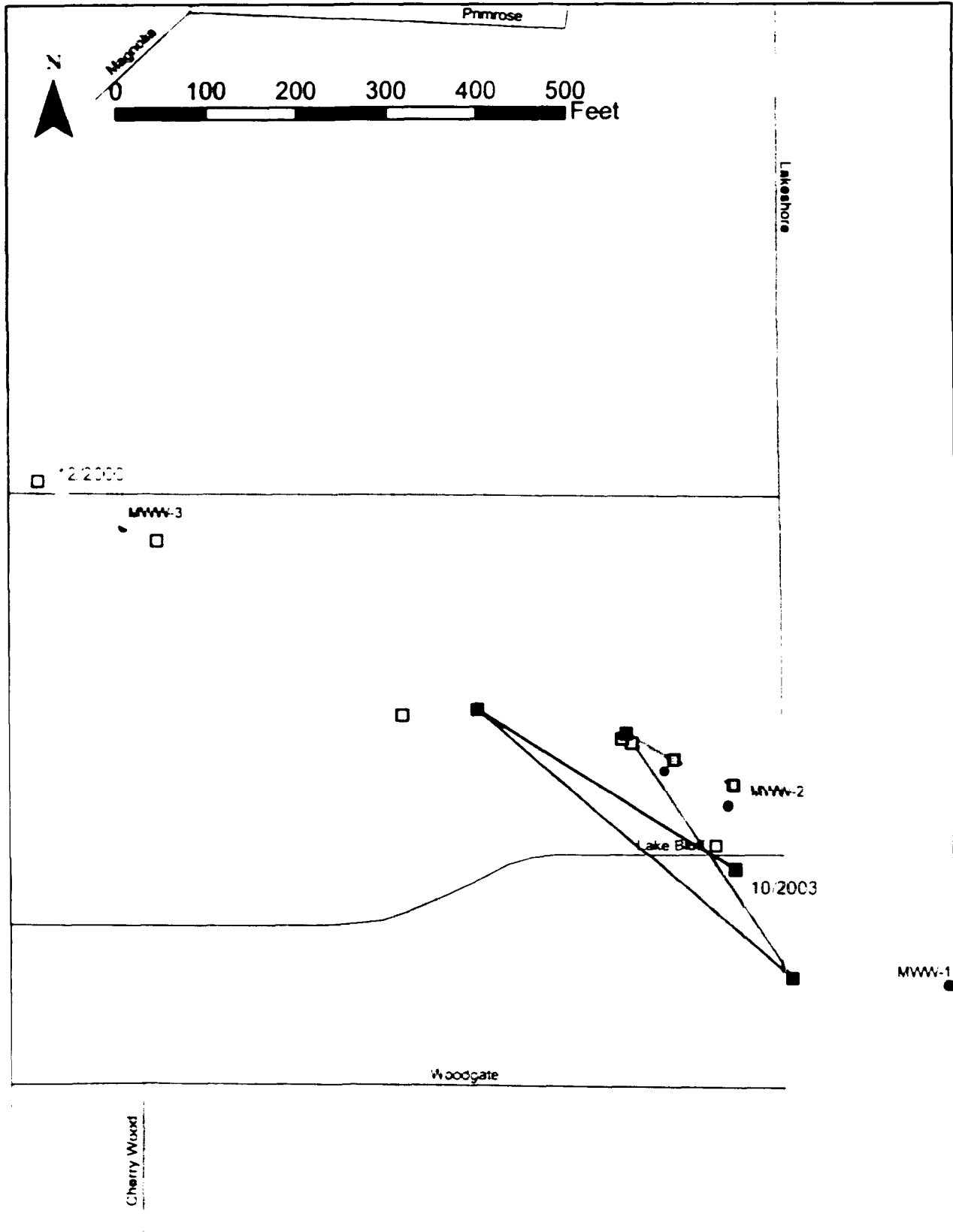


Figure 12. Migration of centers of TCE plume mass for 12 monitoring events from 12/2000 (lightest) to 10/2003 (darkest).  
Subterranean Research, Inc.



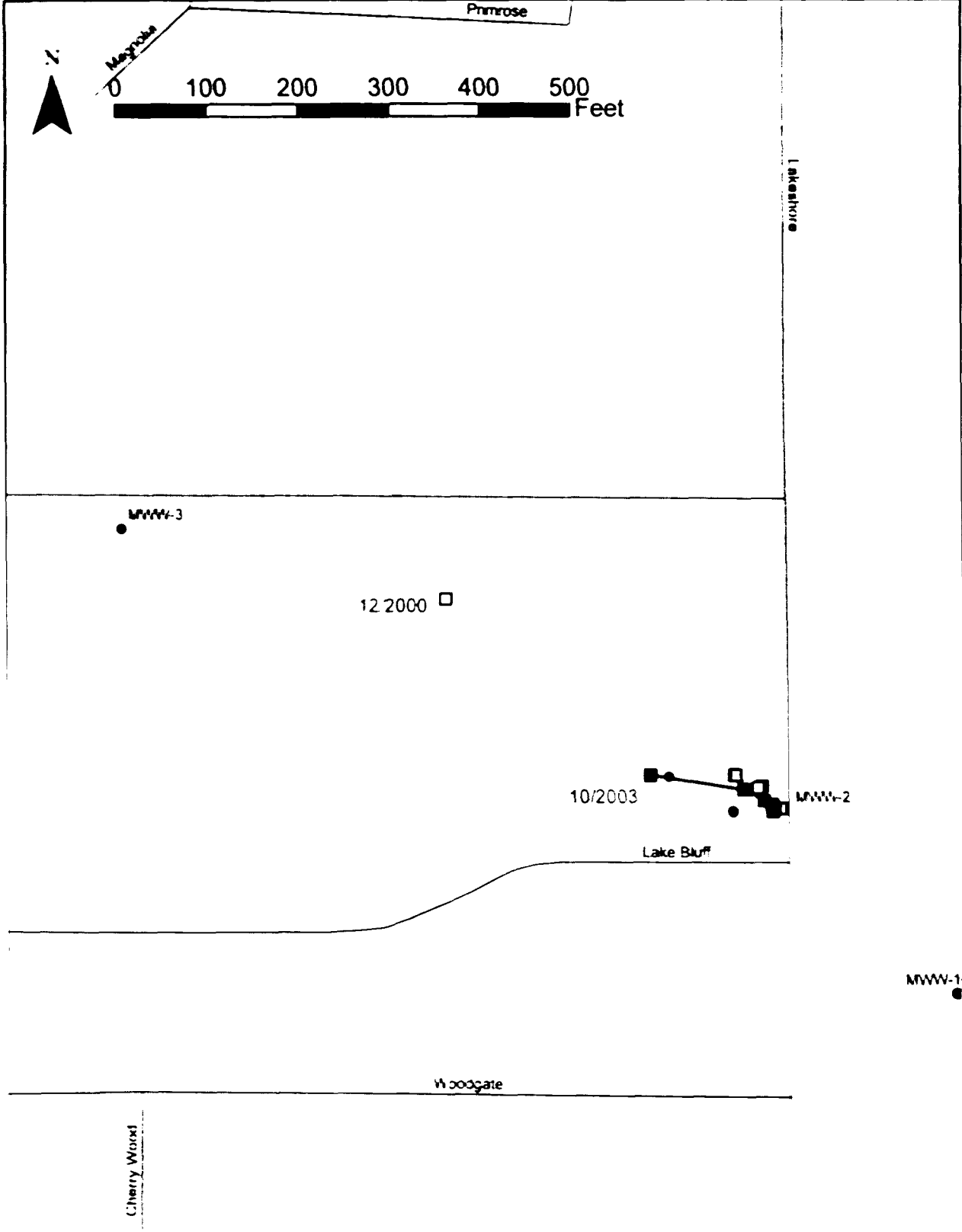


Figure 1. Migration of centers of CE plume mass for 12 monitoring events from 12/2000 (lightest) to 10/2003 (darkest).  
Subterranean Research, Inc. 48 of 60

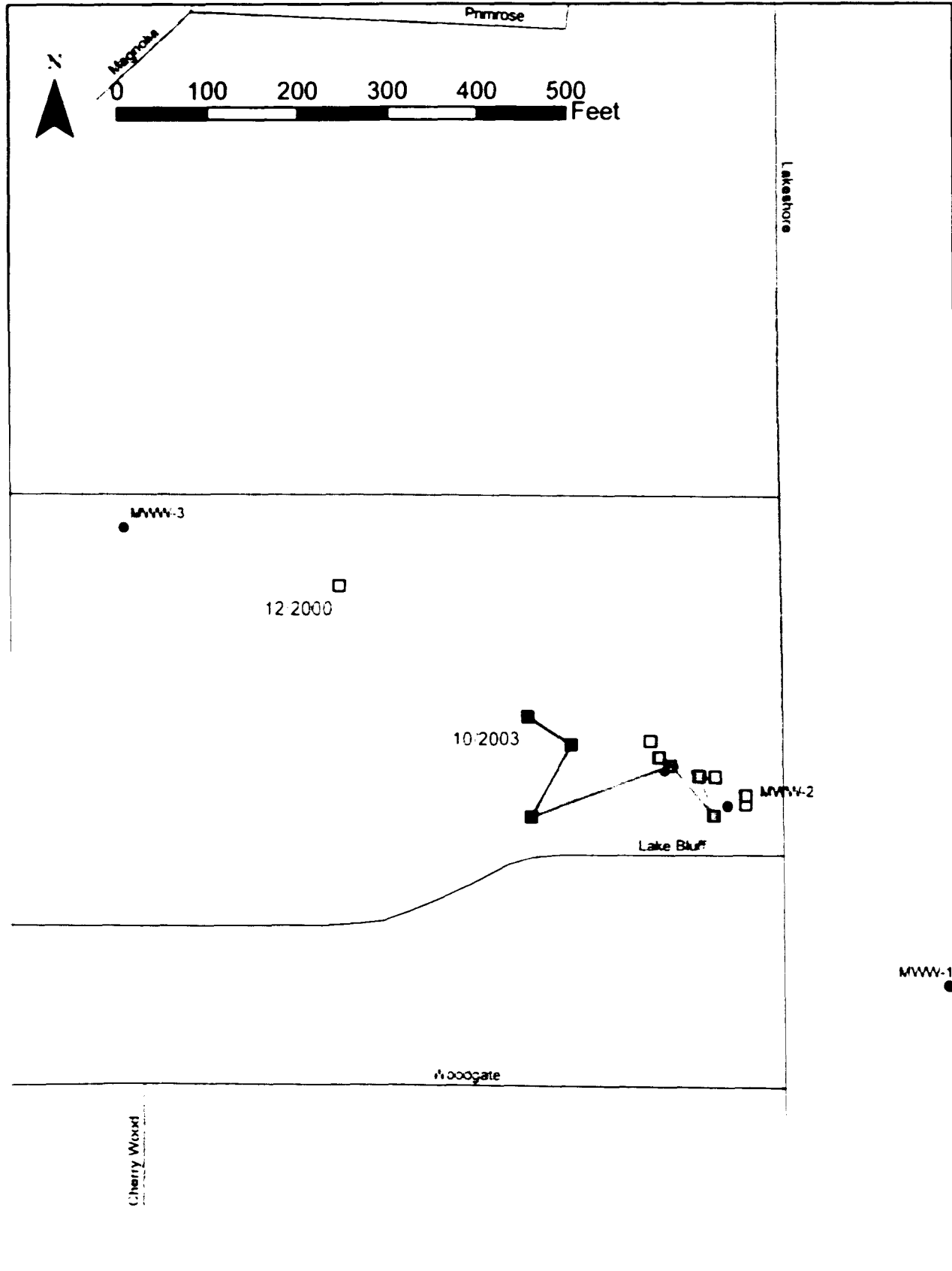


Figure 1. Migration of centers of C plume mass for 12 monitoring events from 12-2000 (lightest) to 12-2003 (darkest).  
Subterranean Research, Inc.

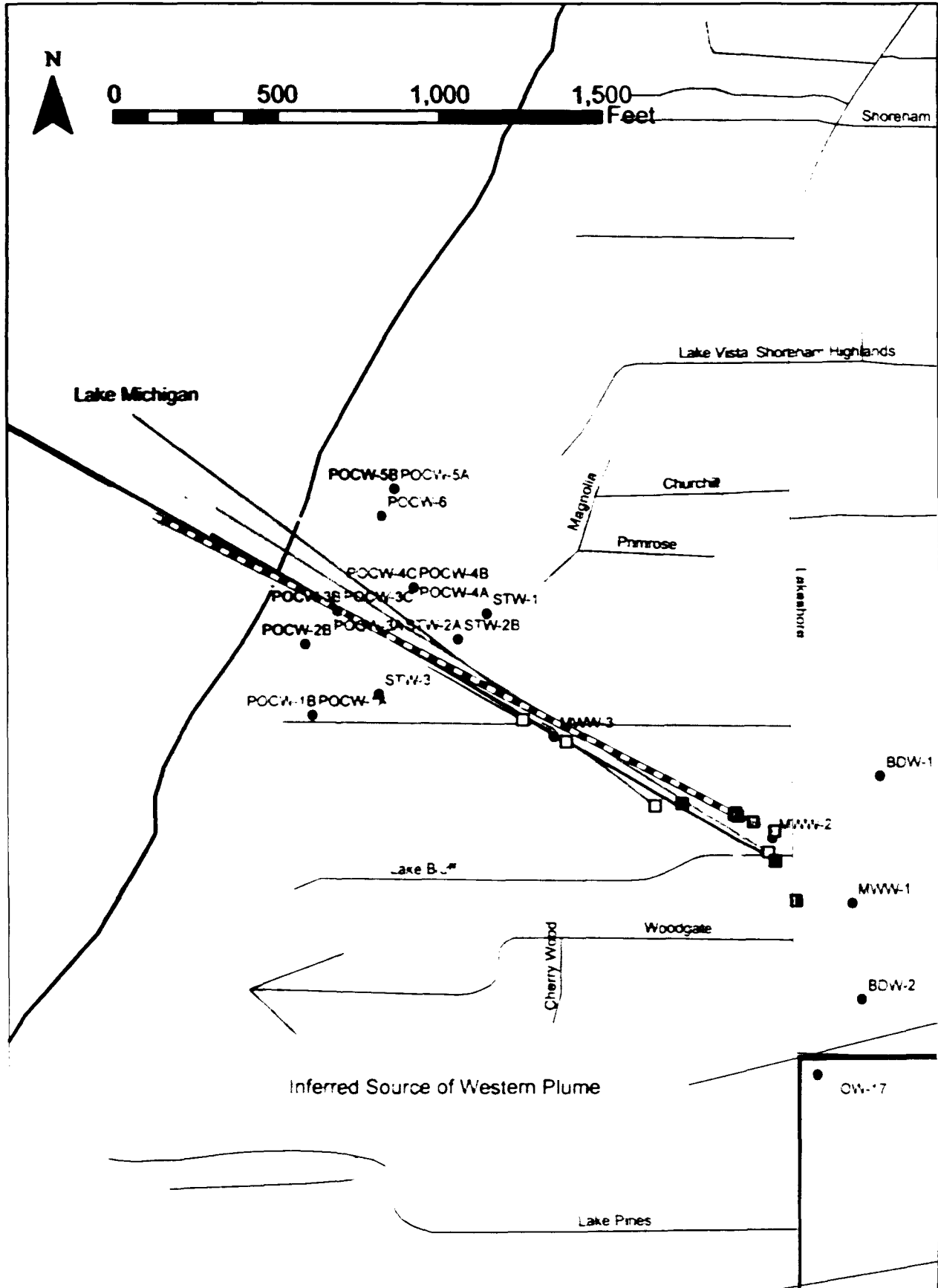


Figure 15 Rays showing west TCE plume alignments for 12 monitoring events (darker lines are more recent) and median (dashed).  
Subterranean Research, Inc. 50 of 60

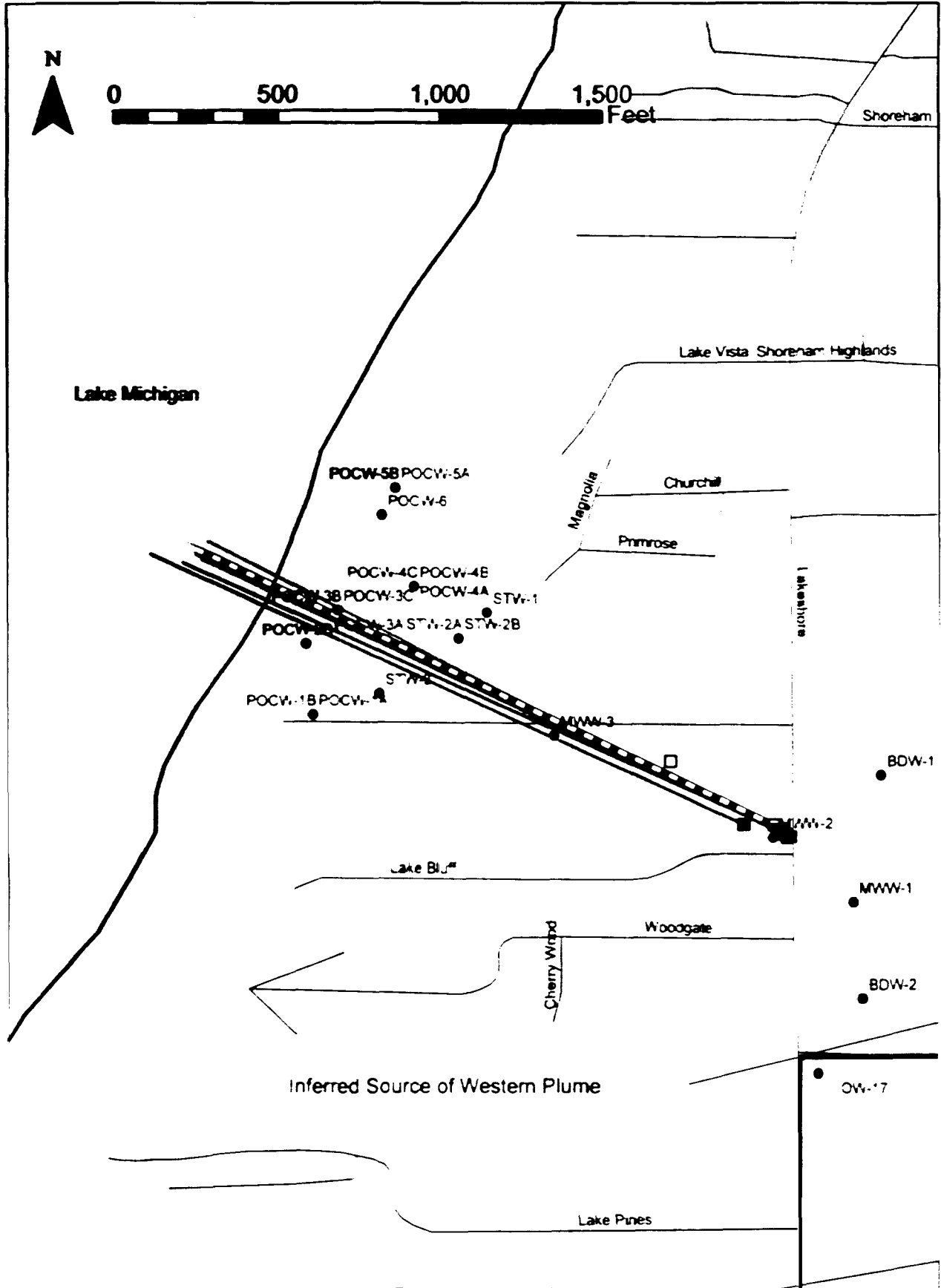


Figure 15 Rays showing west TCE plume alignments for 12 monitoring events (darker lines are more recent) and median (dashed).  
Subterranean Research, Inc. 51 of 60

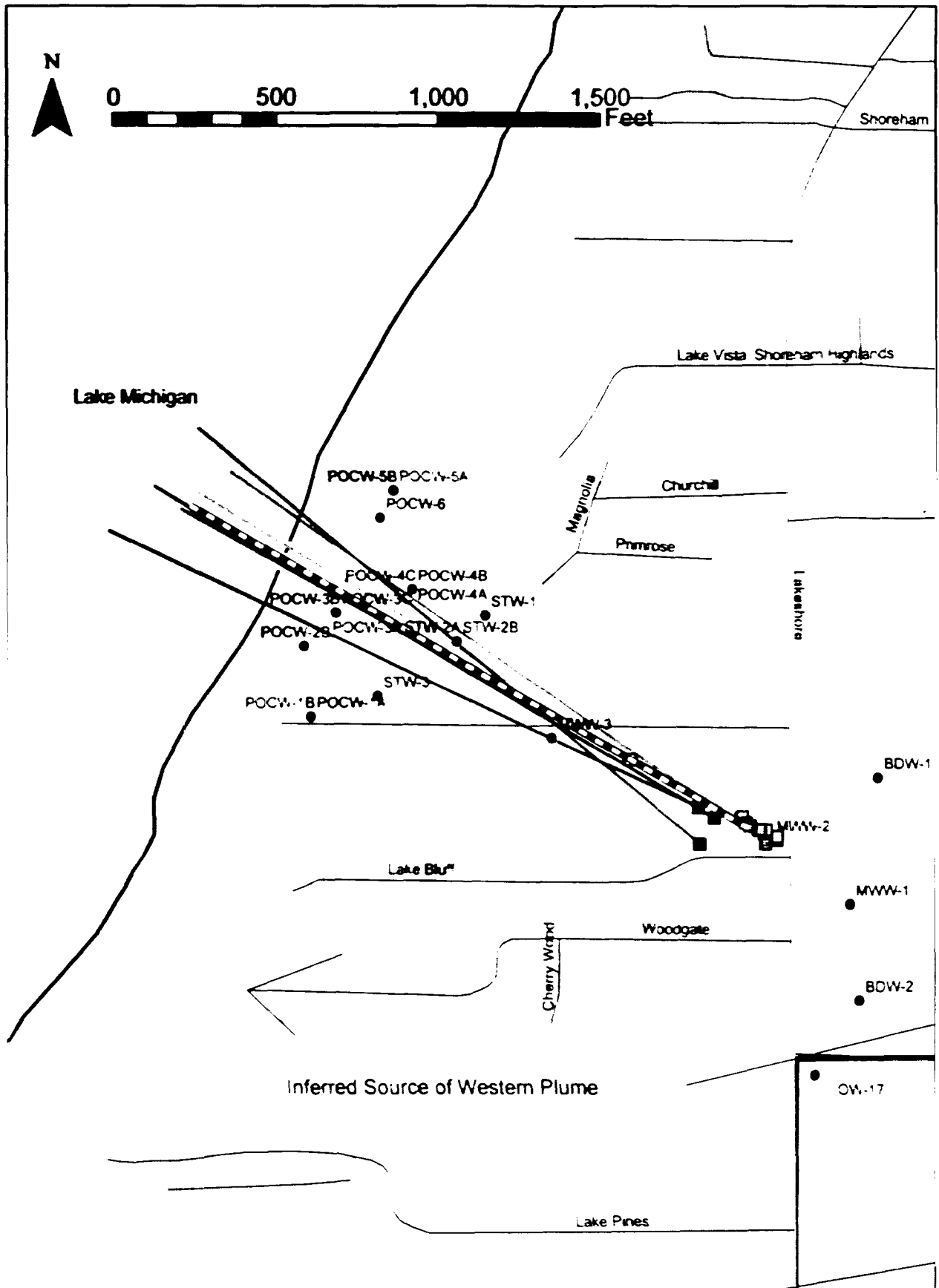


Figure 15 Rays showing west TCE plume alignments for 12 monitoring events (darker lines are more recent) and median (dashed).  
Subterranean Research, Inc. 52 of 60

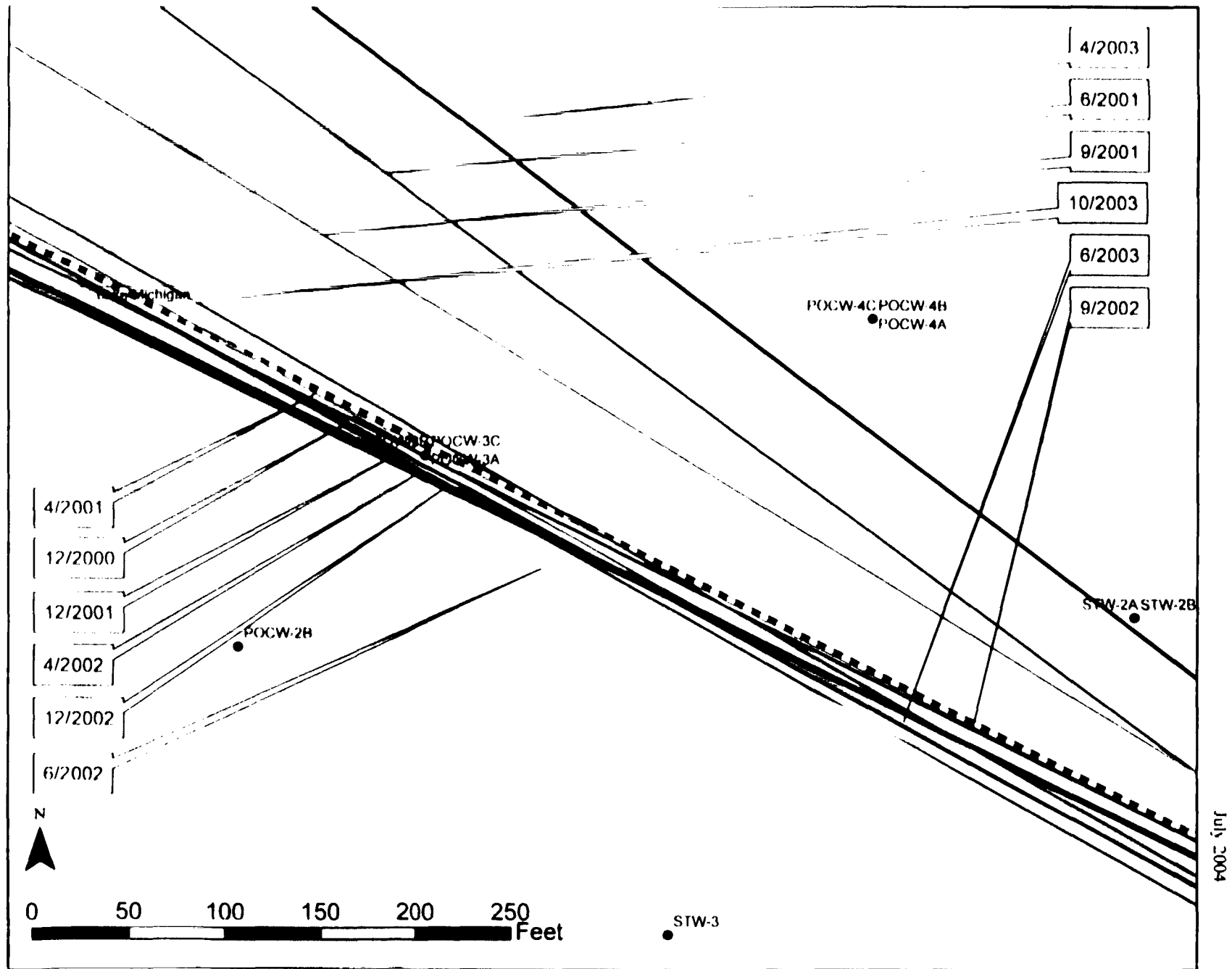


Figure 18. Zoomed version of Figure 15, TCE plume alignments for 12 monitoring events, focusing on region of POCW wells.

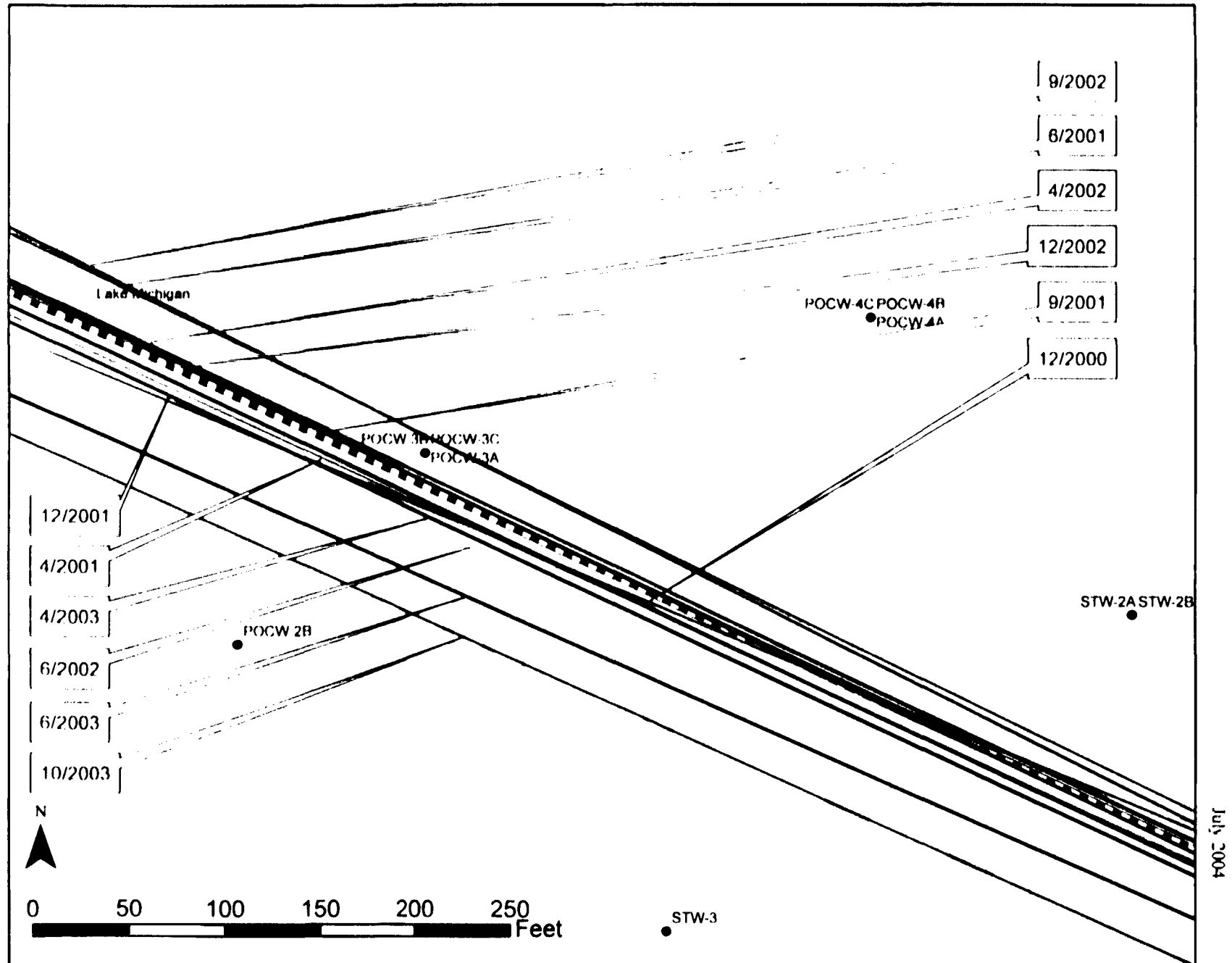


Figure 1 . Zoomed version of Figure 1 , c CE plume alignments for 12 monitoring events, focusing on region of POW wells.

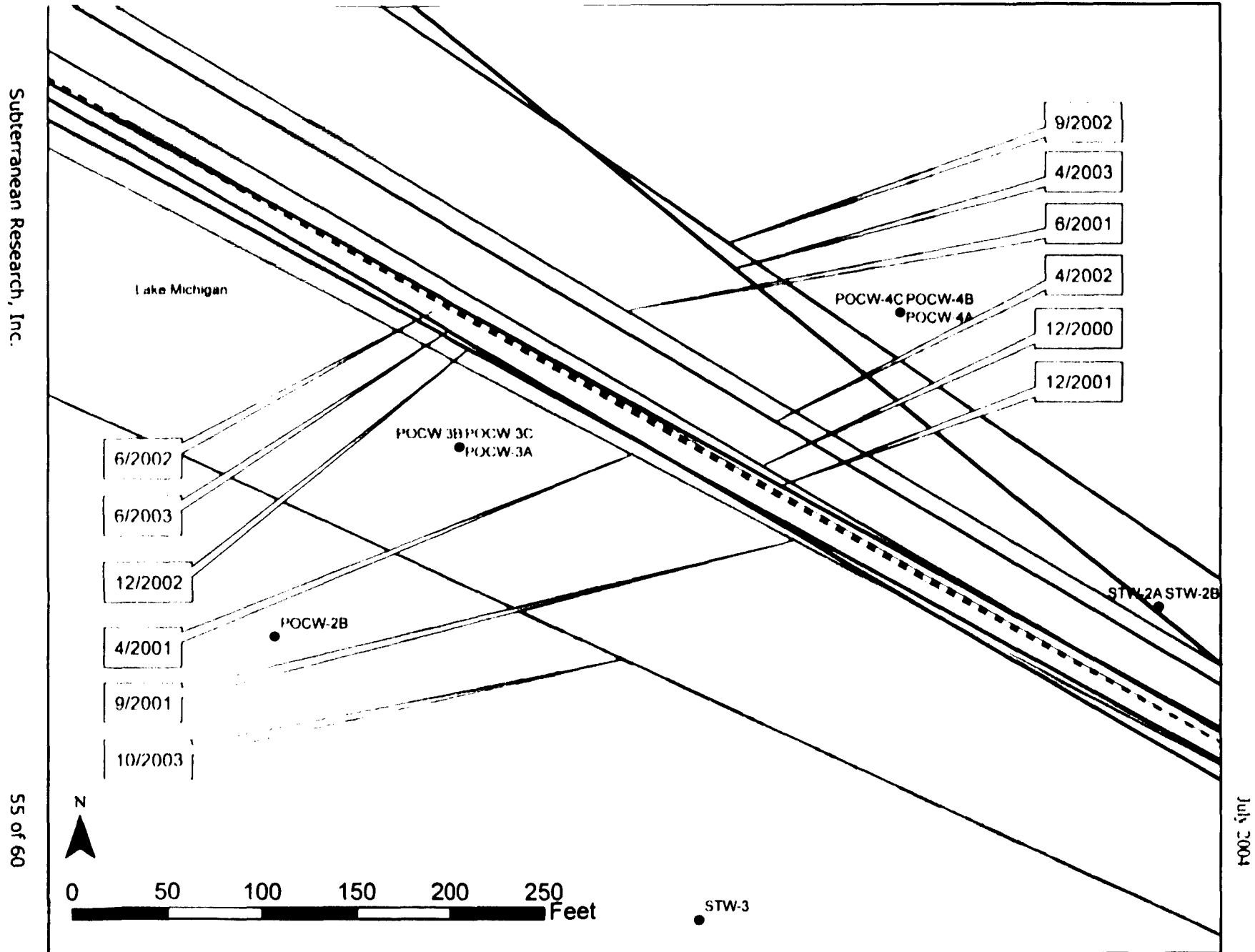


Figure 2 . Zoomed version of Figure 1 , C plume alignments for 12 monitoring events, focusing on region of POCW wells.

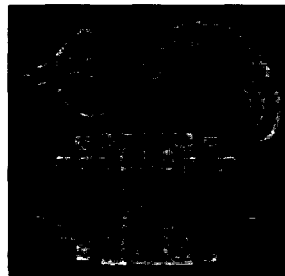


July 2004

**APPENDIX I:  
EXCERPTS FROM *PAM*™ DOCUMENTATION**

**Description of Software Package  
to Calculate  
Plume Assessment Metrics (*PAM*™)**

Version 0.1



David E. Dougherty  
Subterranean Research, Inc.  
June 2004

## 4. ANALYZING SPATIAL MOMENTS

The spatial moments of a plume are calculated from the spatial data in three steps, once the data and processing options have been imported (see Section 2). These three steps follow:

1. Develop a triangulation of the spatial locations at which the observation data were obtained.  
This triangulation is the process of constructing a finite element mesh that has nodes located exactly at observation locations and that is constructed with the best possible shape to keep estimation errors of concentrations between the observations, obtained using interpolation, as small as possible.
2. Develop calculation rules for determining the spatial moments of the plume using the observation data and the corresponding triangulation.
3. Perform the calculations.

### 4.1 Triangulation and Interpolation

Triangulation of the observation locations is performed using the Qhull algorithms [Barber *et al.*, 1993] as included in MATLAB<sup>®</sup>. Qhull constructs a Delaunay mesh from the set of observation locations  $x^o$  and  $y^o$ . The resulting mesh is first constructed as a mesh of triangles that uses the observation locations as vertices of the triangles and that covers the convex hull of the observation locations. The triangles are constructed so that no data points lie inside the so-called circumcircle of every other triangle. In effect, the triangles in the Delaunay mesh are as close to equiangular as the observation locations permit. Figure 4-1(a) shows a set of observation locations and Figure 4-1(b) shows the observations, the convex hull of the observation locations, and the corresponding Delaunay triangulation.

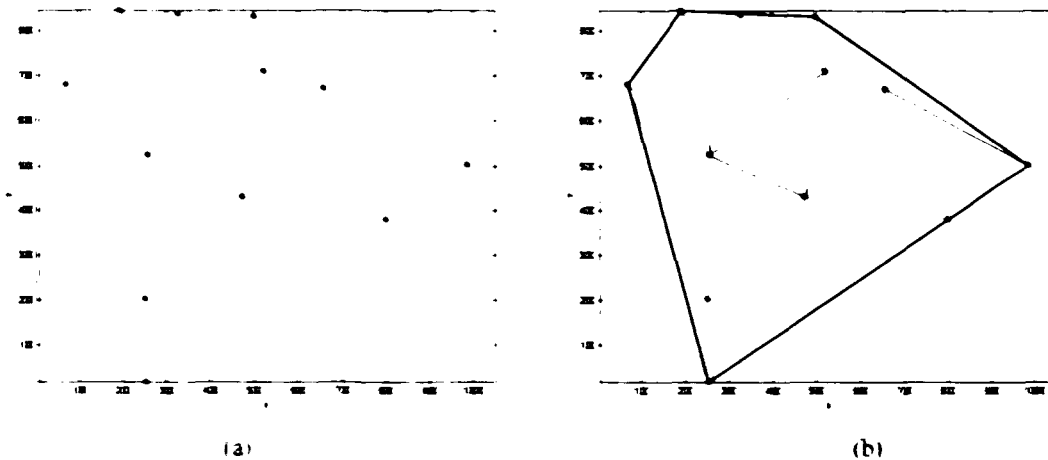


Figure 4-1. (a) Set of 12 observation points. (b) Same set of observation points, their convex hull (thick black line), and the triangular mesh that is determined by Delaunay triangulation.

The triangles are completely described by the  $x$  and  $y$  coordinates of the three distinct vertices (or nodes) of each triangle in a specific order (either clockwise or counterclockwise around the perimeter of the triangle).

The concentration of a dissolved contaminant at a location within a triangle is interpolated using a linear finite element method. In *PAM*<sup>™</sup>, the user can either interpolate using the nodal values themselves, or may specify that the logarithms of the nodal values are interpolated and that the antilogarithm is invoked whenever a value is needed. Future versions of *PAM*<sup>™</sup> may add other interpolation methods, such as inverse distance or natural neighbor.

Outside of the set of triangles (i.e., outside of the triangulation) the concentration is not specified and, if necessary, can be set to zero.

#### 4.2 Calculation Rules

The definitions of the spatial moments of interest in this version of *PAM*<sup>™</sup> are as follows. In these definitions,  $n$  is the porosity,  $c$  denotes the dissolved concentration,  $B$  is the saturated aquifer thickness,  $A_i$  indicates the area of the  $i$ -th triangle,  $N_T$  indicates the number of triangles in the triangulation  $T$ ,  $A$  is the union of nonoverlapping triangles  $A_i$ , and  $\gamma(c - \hat{c})$  is an indicator function that equals 0 or 1 depending on whether  $c$  is inferior or superior to  $\hat{c}$ .

- Volume of Plume (water phase only, excludes solids)

$$V_{c > \hat{c}} = \iint_A n B \gamma \, dx \, dy$$

- Dissolved Mass

$$M_{c > \hat{c}} = \iint_A c n B \gamma \, dx \, dy$$

- Center of Dissolved Mass

$$\bar{x}_{c > \hat{c}} = \frac{\iint_A x c n B \gamma \, dx \, dy}{M_{c > \hat{c}}}$$

$$\bar{y}_{c > \hat{c}} = \frac{\iint_A y c n B \gamma \, dx \, dy}{M_{c > \hat{c}}}$$

- Spreads of Dissolved Plume (data coordinate system)

$$S_{x^{2|c > \hat{c}}} = \left[ \frac{\iint_A (x - \bar{x})^2 c n B \gamma \, dx \, dy}{M_{c > \hat{c}}} \right]^{1/2}$$

$$S_{y^{2|c > \hat{c}}} = \left[ \frac{\iint_A (y - \bar{y})^2 c n B \gamma \, dx \, dy}{M_{c > \hat{c}}} \right]^{1/2}$$

$$S_{xy^{2|c > \hat{c}}} = \left[ \frac{\iint_A (x - \bar{x})(y - \bar{y}) c n B \gamma \, dx \, dy}{M_{c > \hat{c}}} \right]^{1/2}$$

- Spreads of Dissolved Plume (principal direction coordinate system)

$$S_{\text{min}(x,y) > z} = \frac{S_{\text{xx}(x,y) > z} + S_{\text{yy}(x,y) > z}}{2}$$

$$S_{\text{directional}(x,y) > z} = \left[ (S_{\text{xx}(x,y) > z} - S_{\text{min}(x,y) > z})^2 - S_{\text{yy}(x,y) > z}^2 \right]^{1/2}$$

$$S_{\text{MAX}(x,y) > z} = S_{\text{min}(x,y) > z} + S_{\text{directional}(x,y) > z}$$

$$S_{\text{MIN}(x,y) > z} = S_{\text{min}(x,y) > z} - S_{\text{directional}(x,y) > z}$$

- Orientation of Dissolved Plume Major Axis

$$\theta = .A + \frac{1}{2} \tan^{-1} \left( \frac{2S_{\text{xy}(x,y) > z}}{S_{\text{xx}(x,y) > z} - S_{\text{yy}(x,y) > z}} \right)$$

where the value of  $A$  depends on the signs and magnitudes of the indicated spreads.

These calculations depend on performing integrations over the convex hull of the observed data locations. This is accomplished in two steps. The first is to recognize that the area  $A$  is the union of the areas  $A_i$ , which means that the integral over  $A$  is the sum of the integrals of  $A_i$ . The second is to replace the integral over each  $A_i$  by a quadrature (an approximate integral). The approximate integral is calculated as a sum over some number of quadrature points of the products of a weight coefficient times the integrand evaluated at the localized coordinates associated each quadrature point. That is, if the integrand is denoted by  $f(x, y)$  and the location of the  $q$ -th quadrature point is  $(x_q, y_q)$ , then

$$\iint_A f(x, y) dx dy = \sum_{i=1}^{N_i} \left[ \iint_{A_i} f(x, y) dx dy \right] \approx \sum_{i=1}^{N_i} \left[ \sum_{q=1}^{N_q} W_q f(x_q, y_q) \right]$$

The final step in this development is to select the number of quadrature points, the locations of the quadrature points, and the quadrature weights assigned to each quadrature point. The selection of these parameters depends on the integrand  $f$  and the accuracy with which the integral should be approximated. If we assume that  $c$ ,  $n$ , and  $B$  can vary linearly with the coordinates within each triangle, then the integrands of the second moments may be quintic (that is, fifth degree). Because thickness and porosity always appear as a product and because the product can never be less than zero, we express their product as a single variable that can vary linearly across each triangle. In this way the integrand of the second moments may be fourth degree.

Cowper [1973] published several quadrature rules for triangles, including one for quintic polynomials that uses seven integration points that uses all seven points *within* the triangle, illustrated in Figure 4-2, that never uses any of the vertices. This ensures that any nodal value of zero does not have an undue influence on the calculated moments. The coordinates and the weights of each quadrature point are given by Cowper.

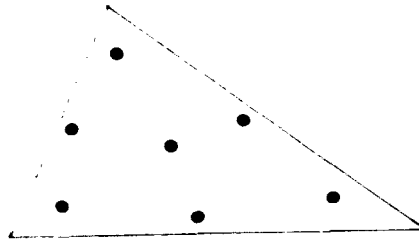


Figure 4-2. Schematic of 7-point numerical integration on a triangle. Each black dot is a quadrature point.

If more than one sample result exists at a single monitoring point at a given monitoring event (i.e., duplicate samples), then the user may elect to use the maximum (the default), median, or average of these. Different choices will lead to different magnitudes of mass and volume.

If there are multiple samples from the same monitoring event and the same map (areal) location, but from different elevations (such as a monitoring well nest), then it is necessary to select a representative value from these overlapping samples. The median of overlapping samples is used by default, but a user may elect to use the maximum or average. Different selections lead to different results.

### 4.3 Calculations

The spatial moment calculations in *P.A.M.*<sup>™</sup> are performed using MATLAB<sup>®</sup>.



# **Bendix Corporation Statistical Analysis Report**

**Sampling Period: 12/2000 to 10/2003**

**Prepared By:**



Volpe National Transportation Systems Center  
U.S. Department of Transportation  
On behalf of EPA Region 5  
July 2004

## **INTRODUCTION**

On behalf of EPA Region 5, the Volpe National Transportation Systems Center (Volpe Center) performed a statistical analysis on the groundwater monitoring data collected from the Bendix Corporation Superfund site. For this analysis, the Volpe Center utilized the environmental statistic software application CARStat 2.1.8 (Compliance, Assessment, Remediation Statistics) from Discerning Systems Inc. The analysis compared the contaminant concentrations obtained from on-site groundwater sampling to the EPA mandated clean-up standards. A baseline comparison test was also performed to compare the most current contaminant concentrations to a baseline period. Finally, the analysis identified increasing or decreasing trends in the contaminant concentrations over time. The purpose of the analysis is to provide statistical support for assessing the progress and effectiveness of the site's groundwater remediation.

## **SITE BACKGROUND**

The Bendix Corporation Allied Automotive (Bendix) superfund site, located in St. Joseph, Michigan, is a 36-acre lot at which manufacturing has been conducted. The current owner of the site is Bosch Inc. The site is approximately one half mile from Lake Michigan and 500 yards from Hickory Creek. A groundwater divide occurs at the site. Groundwater on the west side of the site flows to Lake Michigan, while groundwater on the east side flows to Hickory Creek.

From 1965 to 1975, unlined lagoons formerly located in the southeast corner of the site were used for the disposal of wastewater generated by the manufacturing facility. The lagoons were drained and filled with soil in 1978. During their operation, the lagoons received wastewater containing tetrachloroethene and trichloroethene, among other contaminants. A secondary source area to which contaminants migrated from elsewhere has been identified as the parking lot across Maiden Lane north of the main building on the site. Groundwater at the site and down-gradient of the site is contaminated with various volatile organic compounds (VOCs). Two contaminated groundwater plumes have been noted as originating at the site: an eastern plume, which discharges to Hickory Creek, and a western plume, which discharges to Lake Michigan. Published reports and scholarly papers indicate that natural attenuation is occurring in both plumes.

A Record of Decision (ROD) for the site was signed on September 30, 1997. That ROD called for monitored natural attenuation of both the East and West plumes. This monitoring began in 2000. In addition, the ROD called for a soil vapor extraction (SVE) system for the eastern plume. The SVE system began operation in the summer of 1999. Other activities relating to the site include (1) sampling since 2000 to establish alternative concentration limits (ACLs) for point of compliance wells, which were installed for both the eastern and western plumes and (2) institutional controls to limit the risk to people from drinking contaminated groundwater or from other direct contact with contaminated groundwater (groundwater, it should be noted, is not presently a source of potable water).

## STATISTICAL TESTS

Three different statistical tests were run on the site data. A brief description of the statistical tests is provided. A detailed description of the tests, including the relevant equations of each test, is provided in the "CARStat 2.1.8 Statistical Guide" and "CARStat 2.1.8 Users Manual".

- **Comparison to Standard**

The comparison to standard test takes onsite, down-gradient data and computes a statistical upper confidence limit (UCL), which is compared to the clean-up standard. If the UCL is above the standard, an exceedance is declared. The UCL is based on the distribution of the data and is determined by CARStat using the Shapiro-Wilks test. The distribution of each data set is presented as "Normal Limit", "Lognormal Limit" or "Nonparametric Limit" in the header of the resulting CARStat graphs. This test is important in determining if a sampling location has achieved its clean-up goals because looking at a single measurement indicates very little about the true concentration at a sampling location.

- **Comparison to Baseline**

The comparison to baseline test takes a user defined baseline period, generally the first two-years of sampling, and calculates an upper prediction limit (UPL) and a lower prediction limit (LPL) of the contaminant concentrations for that period. All subsequent samples are compared to the baseline period. If a sample pops above the UPL then the sampling location is declared significantly worse, while if a sample drops below the LPL it is declared significantly better. The UPL and LPL are based on the distribution of the data and is determined by CARStat using the Shapiro-Wilks test. The distribution of each data set is presented as "Normal Limit", "Lognormal Limit" or "Nonparametric Limit" in the header of the resulting CARStat graphs.

- **Trend Analysis**

Trend analysis was performed using Sen's non-parametric test for trend. This test is well suited for environmental data that typically have irregular spaced measurement periods and non-detect data. The Sen's test is used to identify both increasing and decreasing trends. During the Comparison to Baseline test, trend analysis is performed only on the data falling within the baseline period. CARStat identifies the period used in each analysis by highlighting the dates along the horizontal axis in each of the resulting CARStat graphs.

In order to compute the prediction and confidence limits identified above, choices must be made with regard to a number of statistical options. Table 1 shows the options used for this analysis for each of the statistical tests. The trend analysis is automatically performed by CARStat during each of the other two tests and does not require separate statistical options.



**Table 1: Statistical Options**

<b>Statistical Test</b>	<b>Statistical Option</b>	<b>Option Choice</b>
All	Confidence Level	95%
	Data Distribution Fit	Normal or non-parametric (as appropriate)
Comparison to Standard	Percentile Compared	50th (translates to the mean for normally distributed data)
	Time Period	Most recent four samples
Comparison to Baseline	Baseline Time Period	September 1999 to October 2002 (includes the first 8 samples for most locations)

### **ANALYSIS METHODOLOGY**

Statistical tests were performed for each contaminant at each individual monitoring well. The following methodology was used to perform the statistical analysis for the individual wells.

1. The upper confidence limit (UCL) for the contaminant concentration of the most recent 4 samples in each well was compared to the clean-up standard using the comparison to standard test.
2. Comparison to baseline tests were run at each well location to identify those locations where intrawell contamination was improving or getting worse.
3. Trend analysis was performed during each of the statistical tests.

### **DATA DETAILS**

The statistical analysis used twelve rounds of data collected between September 1, 1999, and December 31, 2003. The collection of data was not identical for each monitoring well and contaminant, however. The number of samples collected from individual monitoring wells ranged from one to twelve. At least 4 samples (i.e., data points) from a well are required to run the statistical tests; therefore, wells with less than 4 samples could not be included in the statistical analysis. Data was analyzed from the samples collected from the 40 monitoring wells (including nested wells) identified in Table 2

**Table 2: Monitoring Wells**

<b>Monitoring Well</b>	<b>Location on Site</b>
BDE-1	East Plume boundary
BDE-2	East Plume boundary
BGE-1	East Plume background
MWE-1	Center line of East Plume
MWE-2	Center line of East Plume
POCE-1	Upgradient of discharge point of East Plume
POCE-2	Upgradient of discharge point of East Plume
POCE-3	Upgradient of discharge point of East Plume
POCE-4	Upgradient of discharge point of East Plume
POCE-5	Upgradient of discharge point of East Plume
POCE-6	Upgradient of discharge point of East Plume
POCE-7	Upgradient of discharge point of East Plume
STE-1	Upgradient of East Plume POC wells
STE-2	Upgradient of East Plume POC wells
STE-3	Upgradient of East Plume POC wells
OW-17	
OW-25	
BDW-1	West Plume boundary
BDW-2	West Plume boundary
BGW-1	West Plume background
MWW-1	Center line of West Plume
MWW-2	Center line of West Plume
MWW-3	Center line of West Plume
POCW-1A	Upgradient of discharge point of West Plume
POCW-1B	Upgradient of discharge point of West Plume
POCW-2A	Upgradient of discharge point of West Plume
POCW-2B	Upgradient of discharge point of West Plume
POCW-3A	Upgradient of discharge point of West Plume
POCW-3B	Upgradient of discharge point of West Plume
POCW-3C	Upgradient of discharge point of West Plume
POCW-4A	Upgradient of discharge point of West Plume
POCW-4B	Upgradient of discharge point of West Plume
POCW-4C	Upgradient of discharge point of West Plume
POCW-5A	Upgradient of discharge point of West Plume
POCW-5B	Upgradient of discharge point of West Plume
POCW-6	Upgradient of discharge point of West Plume
STW-1	Upgradient of West Plume POC wells
STW-2A	Upgradient of West Plume POC wells
STW-2B	Upgradient of West Plume POC wells
STW-3	Upgradient of West Plume POC Wells

This analysis focused on the contaminants of concern identified by the site's RPM. The contaminants and associated clean-up concentrations are presented in Table 3.

**Table 3: Contaminants of Concern**

<b>Contaminate</b>	<b>Standard<sup>a</sup> ng/L</b>
1,1,1-Trichloroethane	200
1,1-Dichloroethane	---
1,1-Dichloroethene	7
Cis-1,2-Dichloroethylene	70
Trans-1,2-Dichloroethene	100
Trichloroethylene (TCE)	5
Vinyl Chloride	2

<sup>a</sup>Part 201 Generic Cleanup Criteria and Screening Levels, Groundwater, Residential & Commercial Drinking Water Criteria, Attachment A, MDEQ

## RESULTS

This section summarizes the results of the statistical analysis based on the methodology outlined in the previous section. Detailed results of the analysis including graphs, tables and equations from all the statistical tests are provided in the appendix.

Tables 4 summarize the results of the statistical tests performed on the contaminants of concern. Only the wells with at least one statistically significant result are listed in the tables. A statistical significant result includes contamination exceeding the cleanup standard, contamination becoming significantly worse or better, or contamination showing an increasing or decreasing trend. The following is a description of the statistical significant results in presented in tables 4.

- **Exceeded Standard (Comparison to Standard Test)**

“Yes” means the UCL for the contaminant concentration of the most recent 4 samples exceeded the clean-up standard. These well locations are considered contaminated.

- **Significantly Worse or Better (Comparison to Baseline Test)**

“Significantly Worse” means the contaminant concentration of the most recent sample exceed the baseline UPL for that well location. This signifies the concentration of the most recent sample statistically exceeds previous sample concentrations within the well and is evidence that the contamination is becoming worse at the well location.

“Significantly Better” means the contamination concentration of the most recent sample was below the baseline LPL for that well location. This signifies the concentration of the most recent sample was statistically below previous concentrations of the well and is evidence that the contamination is significantly better at the well location.

- **Increasing or Decreasing Trend (Sen’s Test)**

“Increasing” signifies the contaminant concentration within a well is increasing over time. Attention should be given to wells with increasing trends since this could signify migration of the contaminant, non-containment of the contamination source, or other possible problems with the remediation process. “Decreasing” signifies the contamination within a well is decreasing over time. A decreasing trend signifies that the contamination at the particular well location is degrading.

Table 5 provides a summary of the results in a cross-tab format by well location and contaminant.

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria) 200 ug/l.	Exceed Standard	Worse or Better?	Trend
<b>1,1,1-Trichloroethane</b> <b>1,1-Dichloroethane</b>			---			
MWE-1	Center line of East Plume				Worse	
POCF-3	Upgradient of discharge point of East Plume				Worse	
BDW-1	West Plume boundary				Worse	Increasing
BDW-2	West Plume boundary				Worse	
MWW-1	Center line of West Plume					Decreasing
POCW-1A	Upgradient of discharge point of West Plume				Worse	
POCW-3B	Upgradient of discharge point of West Plume				Worse	
<b>1,1-Dichloroethene</b>			7 ug/l.			
MWE-1	Center line of East Plume	27.367		Yes		
STE-2	Upgradient of East Plume POC wells	10.000		Yes		
MWW-2	Center line of West Plume	287.196		Yes		

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria)	Exceed Standard	Worse or Better?	Trend
MWW-3	Center line of West Plume	19.419		Yes	Worse	
POCW-1A	Upgradient of discharge point of West Plume				Better	
POCW-3A	Upgradient of discharge point of West Plume	9.464		Yes		
POCW-3B	Upgradient of discharge point of West Plume	24.874		Yes		
POCW-3C	Upgradient of discharge point of West Plume	13.001		Yes		
STW-2A	Upgradient of West Plume POC wells	9.881		Yes		
STW-2B	Upgradient of West Plume POC wells	10.169		Yes		
<b>Cis-1,2-Dichloroethylene</b>			70 ug/l.			
MWE-1	Center line of East Plume	10853.538		Yes		
POCE-3	Upgradient of discharge point of East Plume	145.107		Yes		

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria)	Exceed Standard	Worse or Better?	Trend
POCE-6	Upgradient of discharge point of East Plume	234.603		Yes		
STE-2	Upgradient of East Plume POC wells	2186.152		Yes		
STE-3	Upgradient of East Plume POC wells	120.396		Yes		Decreasing
BDW-1	West Plume boundary	246.635		Yes		
MWW-2	Center line of West Plume	67122.781		Yes		
MWW-3	Center line of West Plume	7134.139		Yes	Worse	
POCW-1A	Upgradient of discharge point of West Plume				Worse	
POCW-2A	Upgradient of discharge point of West Plume	89.707		Yes		Decreasing
POCW-3A	Upgradient of discharge point of West Plume	787.005		Yes		Decreasing
POCW-3B	Upgradient of discharge point of West Plume	1432.831		Yes		

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UC1	Standard (MDEQ Residential Criteria)	Exceed Standard	Worse or Better?	Trend
Trans-1,2-Dichloroethene	POCW-3C	Upgradient of discharge point of West Plume	1082.431	Yes		
	STW-1	Upgradient of West Plume POC wells			Worse	
	STW-2A	Upgradient of West Plume POC wells	813.287	Yes		
	STW-2B	Upgradient of West Plume POC wells	1010.644	Yes		
	MWE-1	Center line of East Plume	111.862	Yes	Worse	
	STE-3	Upgradient of East Plume POC wells				Decreasing
	MWW-2	Center line of West Plume	827.558	Yes		
	MWW-3	Center line of West Plume			Worse	
	POCW-1A	Upgradient of discharge point of West Plume			Worse	
	POCW-3A	Upgradient of discharge point of West Plume				Decreasing



**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria) 5 ug/L	Exceed Standard	Worse or Better?	Trend	
Trichloroethylene (TCE)	BDE-1						
	BDE-2						
	MWE-1	221.854		Yes		Decreasing	
	MWE-2	5.014		Yes			
	STE-1						
	STE-2	24.856		Yes			
	STE-3	65.347		Yes	Worse	Increasing	
	BDW-1	48.119		Yes	Worse	Increasing	
	MWW-1	188.133		Yes			
	MWW-2	679.770		Yes			
	POCW-1A	Upgradient of discharge point of West Plume	16.529		Yes		

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria)	Exceed Standard	Worse or Better?	Trend
POCW-2A	Upgradient of discharge point of West Plume	7.977		Yes		Decreasing
POCW-3B	Upgradient of discharge point of West Plume	1568.621		Yes		
POCW-3C	Upgradient of discharge point of West Plume	2671.479		Yes		Decreasing
POCW-4C	Upgradient of discharge point of West Plume	18.367		Yes		
STW-2B	Upgradient of West Plume POC wells	932.906		Yes		
STW-3	Upgradient of West Plume POC Wells	53.192		Yes		
<b>Vinyl Chloride</b>			2 ug/L			
BDE-1	East Plume boundary				Better	
BDE-2	East Plume boundary	610.379		Yes		Increasing
MWE-1	Center line of East Plume	3851.852		Yes	Worse	
POCE-2	Upgradient of discharge point of East Plume	38.720		Yes		

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria)	Exceed Standard	Worse or Better?	Trend
POCF-3	Upgradient of discharge point of East Plume	882.787		Yes		
POCF-6	Upgradient of discharge point of East Plume	2.838		Yes		
STE-2	Upgradient of East Plume POC wells	80.305		Yes		
STE-3	Upgradient of East Plume POC wells	24.393		Yes		Decreasing
BDW-1	West Plume boundary	23.129		Yes		
BDW-2	West Plume boundary	17.216		Yes		
MWW-1	Center line of West Plume	137.053		Yes		
MWW-2	Center line of West Plume	3129.307		Yes		
MWW-3	Center line of West Plume	4717.711		Yes	Worse	
POCW-2A	Upgradient of discharge point of West Plume	209.121		Yes	Worse	
POCW-3A	Upgradient of discharge point of West Plume	764.065		Yes		Decreasing

**Table 4: Results for Significant Monitoring Wells by Contaminant and Location**

Contaminants and Wells	Well Location	UCL	Standard (MDEQ Residential Criteria)	Exceed Standard	Worse or Better?	Trend
POCW-3B	Upgradient of discharge point of West Plume	854.079		Yes		
POCW-3C	Upgradient of discharge point of West Plume	393.375		Yes		
POCW-4A	Upgradient of discharge point of West Plume	4.676		Yes		
POCW-4B	Upgradient of discharge point of West Plume	3.960		Yes		
POCW-6	Upgradient of discharge point of West Plume					Decreasing
STW-2A	Upgradient of West Plume POC wells	963.897		Yes		
STW-2B	Upgradient of West Plume POC wells	73.298		Yes		
STW-3	Upgradient of West Plume POC Wells	3.179		Yes		

**Table 5: Summary of Results**

Well	1,1,1-Trichloroethane	1,1-Dichloroethane	1,1-Dichloroethene	Cis-1,2-Dichloroethylene	Trans-1,2-Dichloroethene	Trichloroethylene (TCE)	Vinyl Chloride
BDE-1							B
BDE-2							✓ ↑
BGE-1							
MWF-1		W	✓	✓	✓ W	✓ ↓	✓ W
MWF-2						✓	
POCE-1							
POCE-2							✓
POCE-3		W		✓			✓
POCE-4							
POCE-5							
POCE-6				✓			✓
POCE-7							
STE-1							
STE-2			✓	✓		✓	✓
STE-3				✓ ↓	↓	✓ W ↓	✓ ↓
OW-17							
OW-25							
BDW-1		W ↑		✓		✓ W ↑	✓
BDW-2		W					✓
BGW-1							
MWW-1						✓	✓
MWW-2			✓	✓	✓	✓	✓

**Table 5: Summary of Results**

MWW-1			✓	W	✓	W	W		✓	W	
POC'W-1A		W		B		W	W	✓			
POC'W-1B											
POC'W-2A					✓	↓		✓	↓	✓	W
POC'W-2B											
POC'W-3A			✓		✓	↓	↓			✓	↓
POC'W-3B		W	✓		✓			✓		✓	
POC'W-3C			✓		✓			✓	↓	✓	
POC'W-4A										✓	
POC'W-4B										✓	
POC'W-4C								✓			
POC'W-5A											
POC'W-5B											
POC'W-6											↓
STW-1						W					
STW-2A			✓		✓					✓	
STW-2B			✓		✓			✓		✓	
STW-3								✓		✓	

- ✓ UCL Exceeded the clean up standard.    ↓ Decreasing trend (Sen's test)    ↑ Increasing trend (Sen's test)  
 W Worse - the most recent sample exceeded the baseline UPL for that well location (Comparison to Baseline test)  
 B Better - the most recent sample was below the baseline LPL for that well location (Comparison to Baseline test)

## CONCLUSIONS

Three different types of statistical tests were applied to concentration data from chemical analyses of groundwater monitoring well samples from the Bendix site during the period of 12 2000 through 10 2003. The chemicals of concern, which provided the focus for this study, are 1,1-dichloroethene, cis-1,2-dichloroethene, trans-1,2-dichloroethene, trichloroethene, and vinyl chloride. The three statistical tests are used to determine (1) whether the concentration record indicates exceedance of pertinent standards, (2) whether the most recent datum in a monitoring well represents an improvement over earlier conditions, and (3) whether there is a trend over time of the concentration of any COC in each monitoring well. No exceedances, no changes in condition, and no trends were found for 1,1,1-trichloroethane in any monitoring well. The tests for all other COCs produced at least one exceedance, change, or trend, as discussed below.

Based on the Comparison to Standard test, the UCLs of the following five contaminants exceeded their clean-up standards as of 10 2003 in at least one well location:

- 1,1-dichloroethene
- cis-1,2-dichloroethylene
- trans-1,2-dichloroethene
- trichloroethylene (TCE)
- vinyl chloride

Exceedences for all of the five contaminants occurred at wells in both the western and eastern plumes. In many cases, the contamination was several orders of magnitude greater than the clean-up standards. The most significant exceedence of a standard is with trans-1,2-dichloroethene at well MMW-2.

Established clean-up standards do not exist for one contaminant of concern, 1,1-dichloroethane, it should be noted.

Based on the Comparison to Baseline test, the following six constituents had contamination that was worse as of 10 2003 in at least one well location:

- 1,1-dichloroethane
- 1,1-dichloroethene
- cis-1,2-dichloroethylene
- trans-1,2-dichloroethene
- trichloroethylene (TCE)
- vinyl chloride

In only two well locations was contamination better for a constituent. The locations and constituents for which contamination was better were

- BDE-1 for vinyl chloride
- POCW-1A for 1,1-dichloroethene.

Based on trend analysis the following five constituents had contamination that was decreasing as of 10/2003 in at least one well:

- 1,1-dichloroethane
- cis-1,2-dichloroethylene
- trans-1,2-dichloroethene
- trichloroethylene (TCE)
- vinyl chloride

In addition, the following three constituents had contamination that was increasing in at least one well:

- 1,1-dichloroethane
- trichloroethylene (TCE)
- vinyl chloride

Overall, the results of the statistical analysis for the individual wells suggest that, while there is some improvement, significant contamination exists at the site, and contamination is getting worse in some cases.



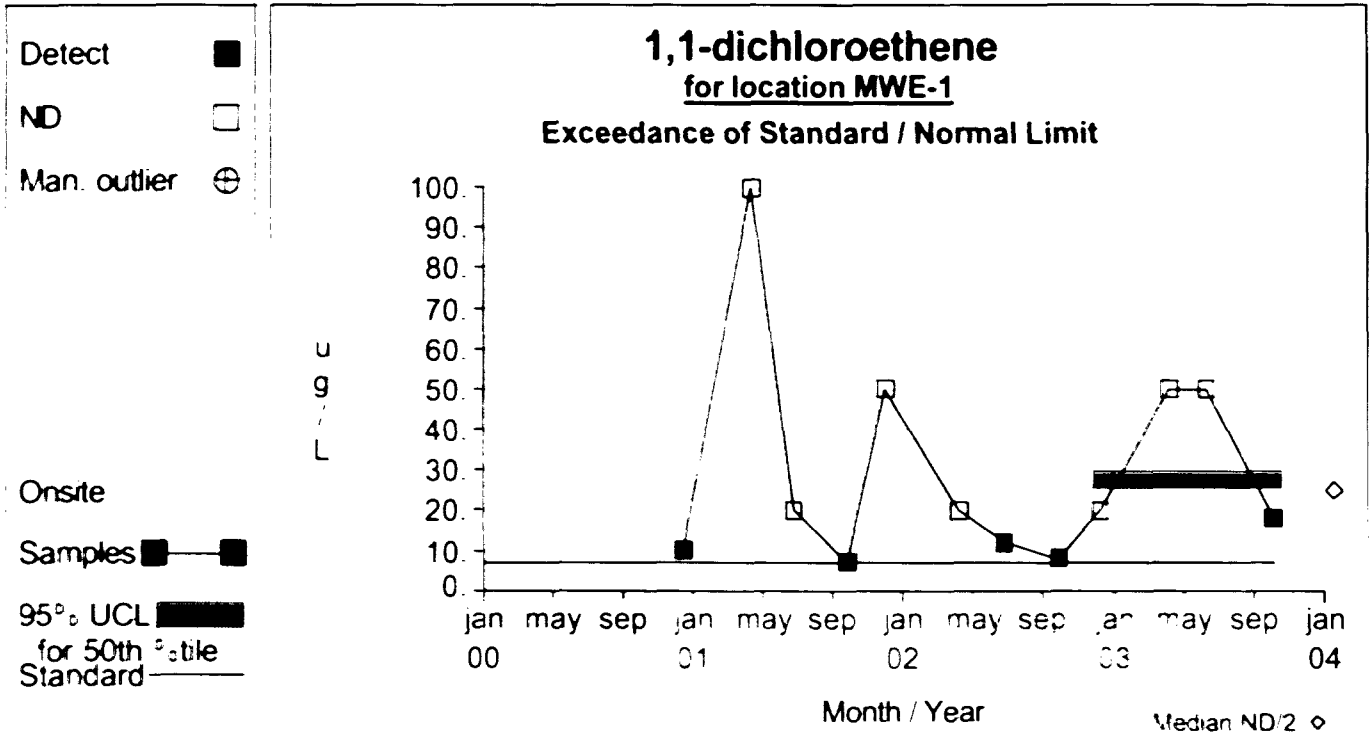
# **GRAPHS:**

**Comparison to Standards**

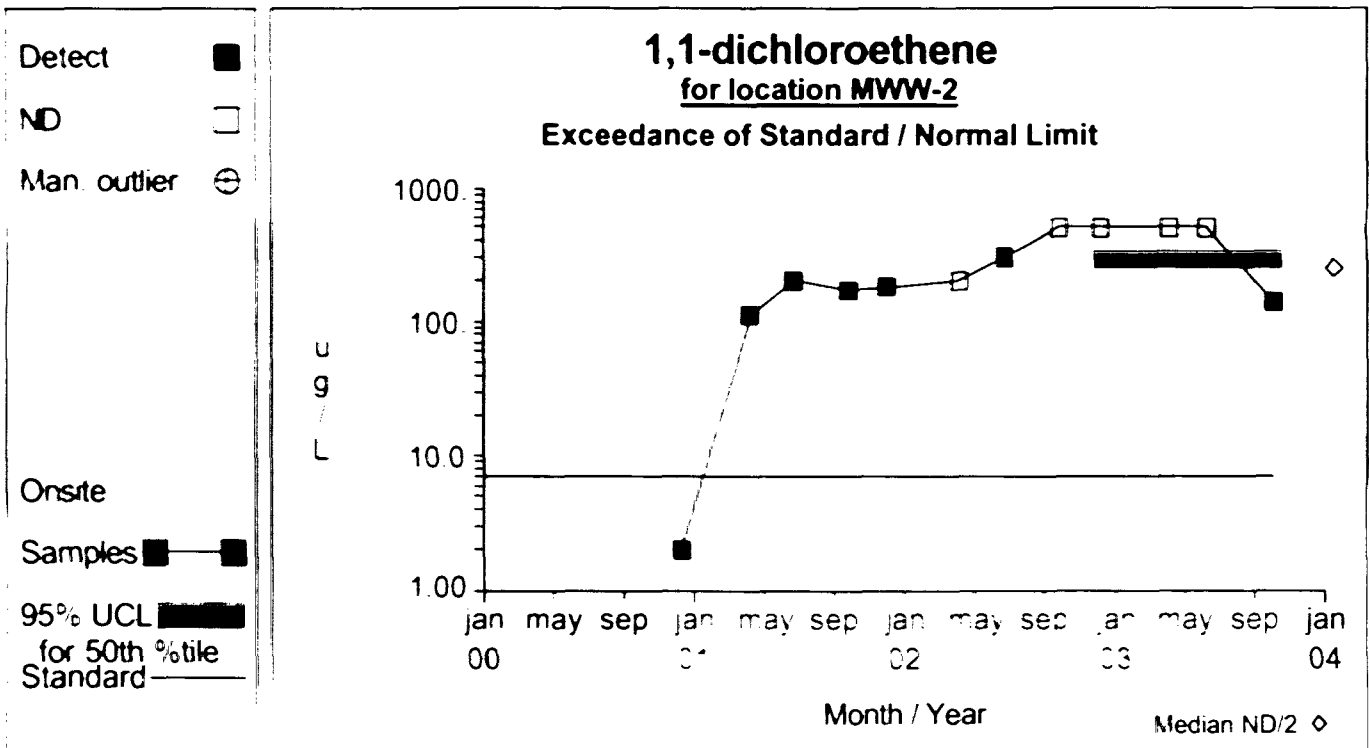
**Time Series**

**Comparison to Baseline**

### Comparison to Standard

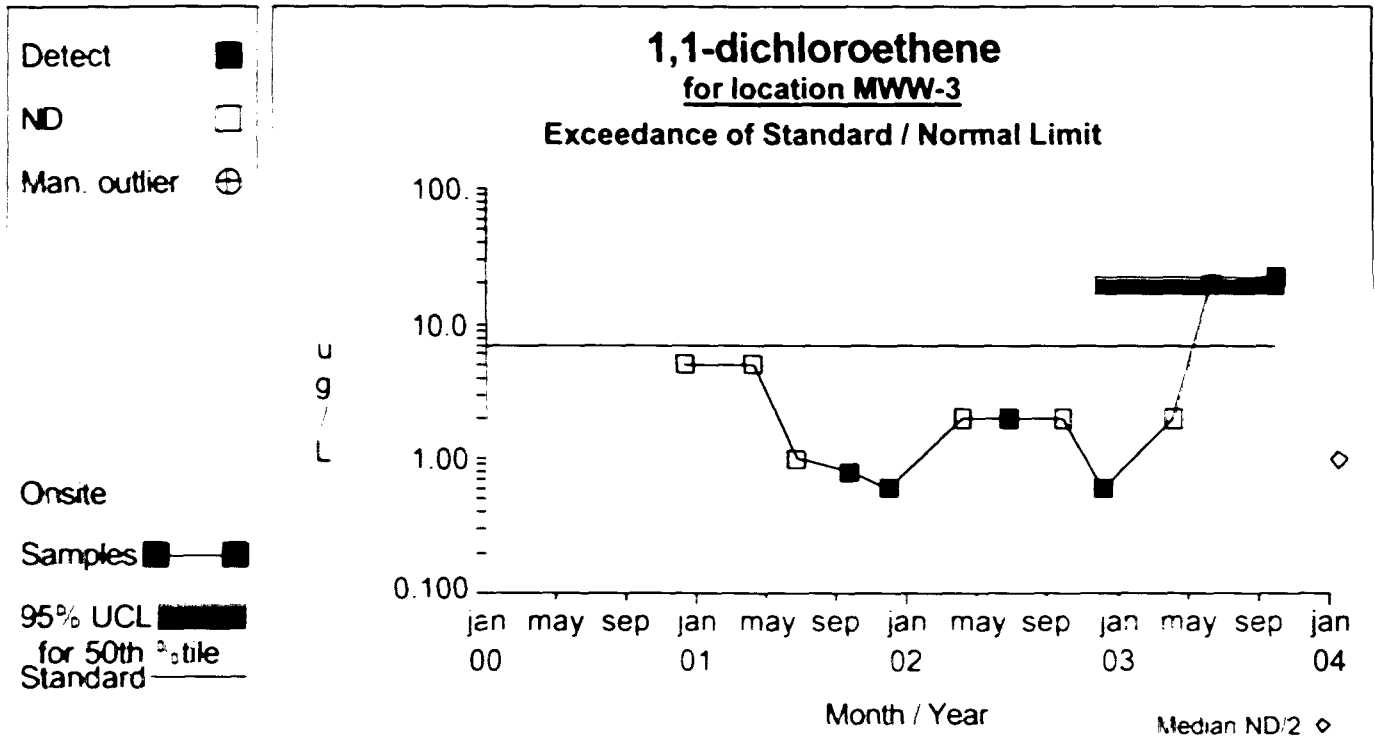


**Graph 47**

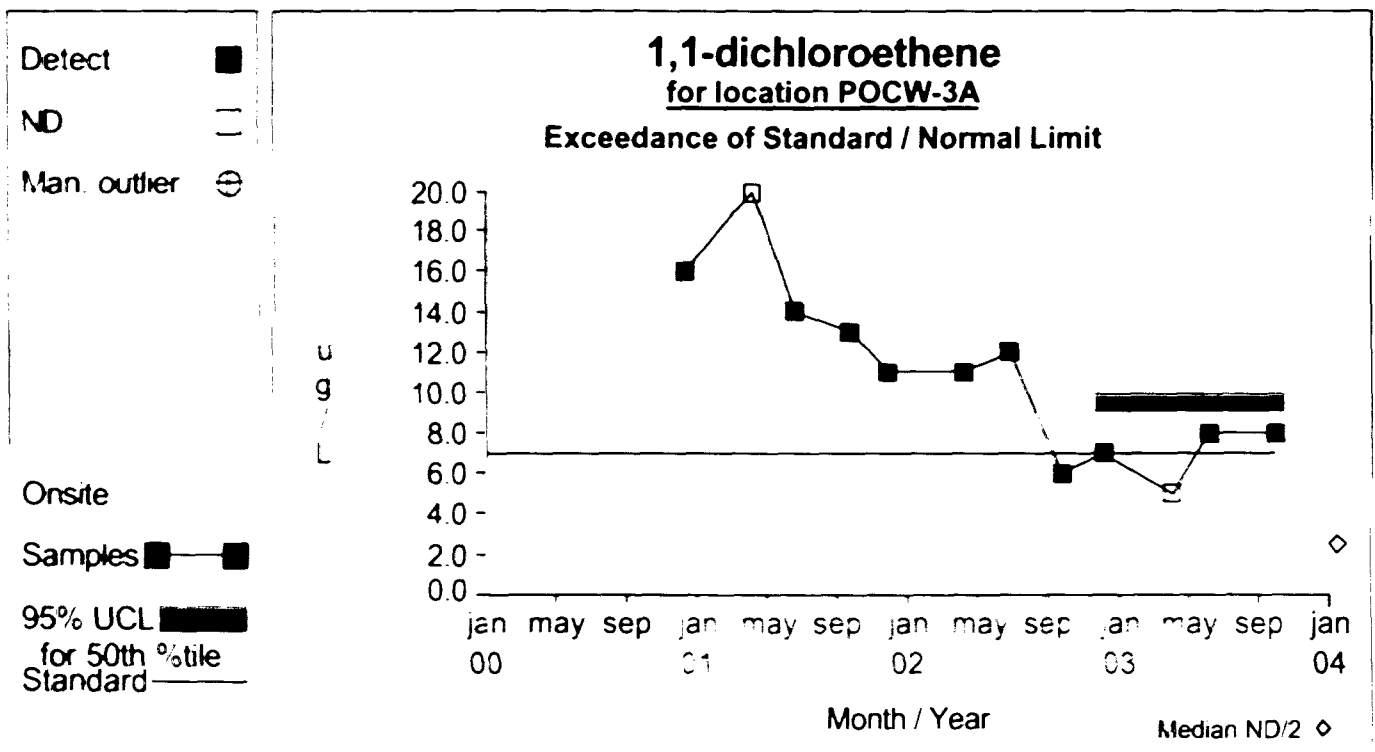


**Graph 50**

### Comparison to Standard

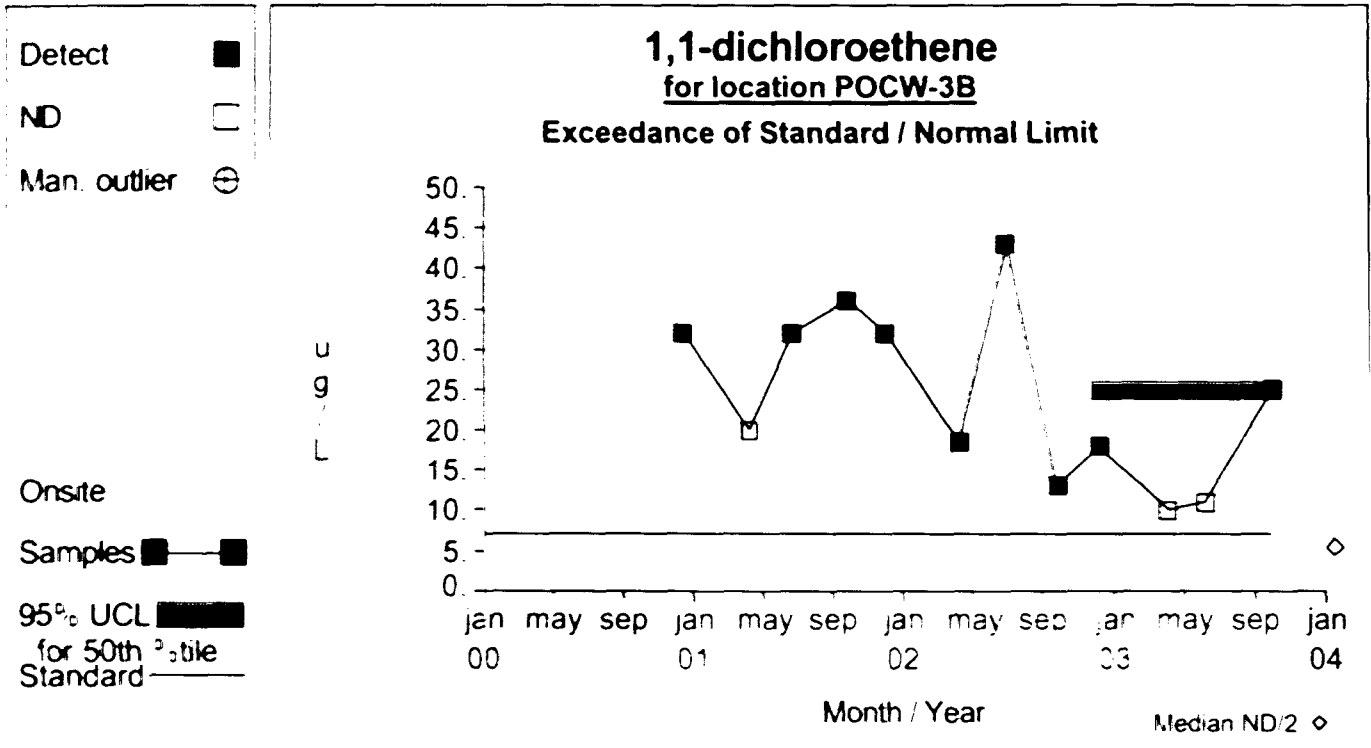


**Graph 51**

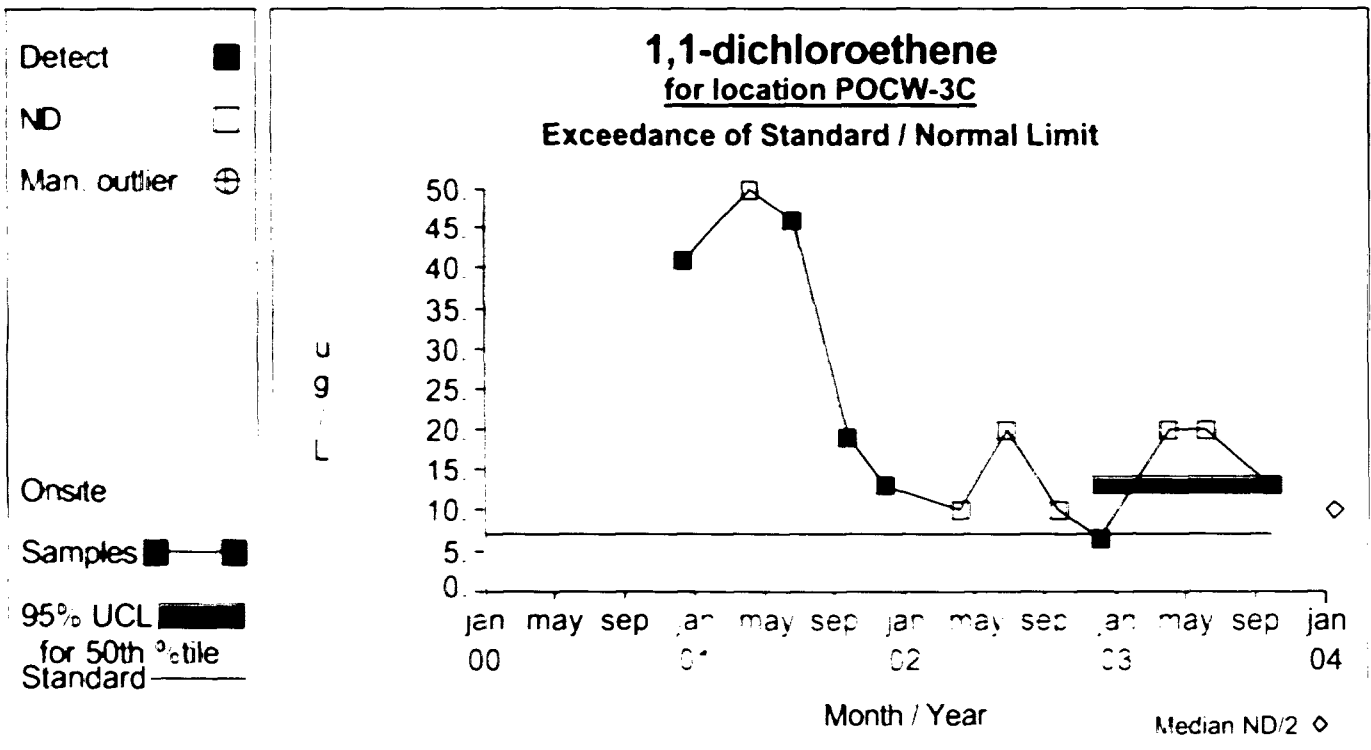


**Graph 65**

**Comparison to Standard**

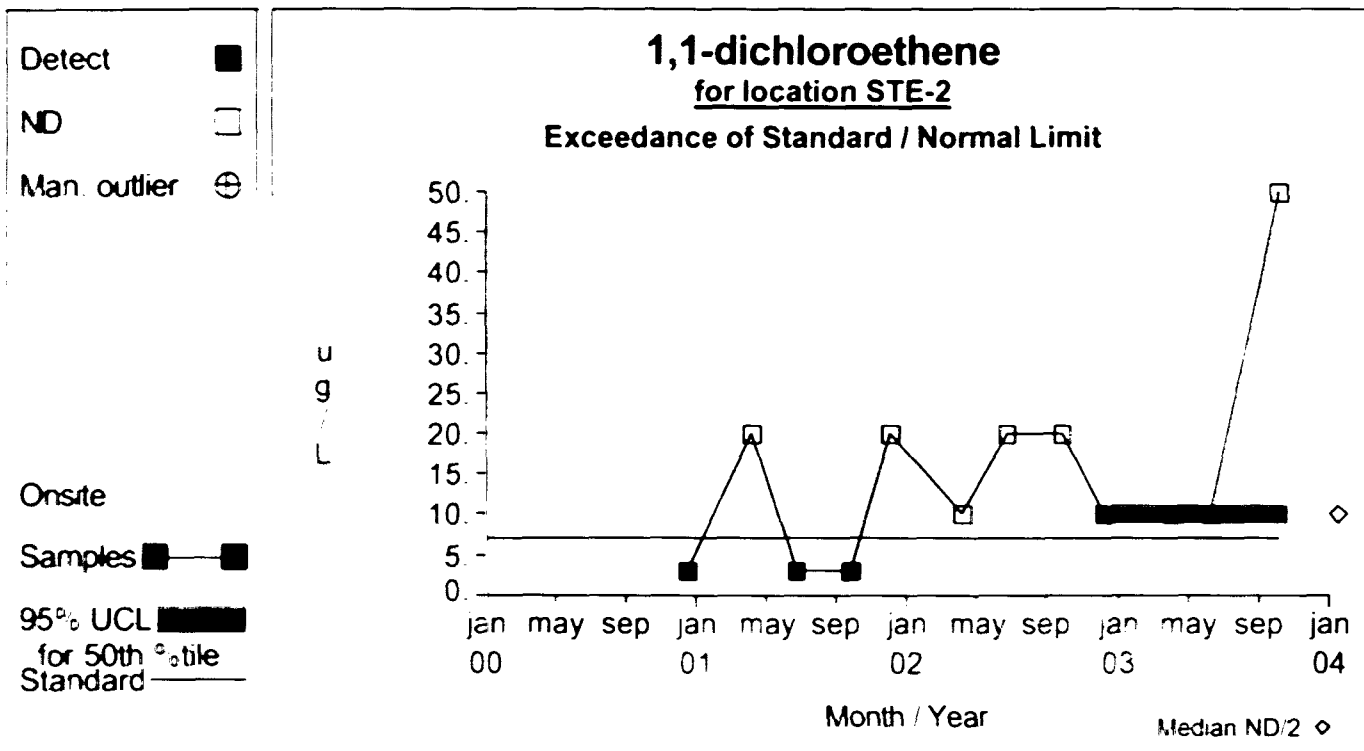


**Graph 66**

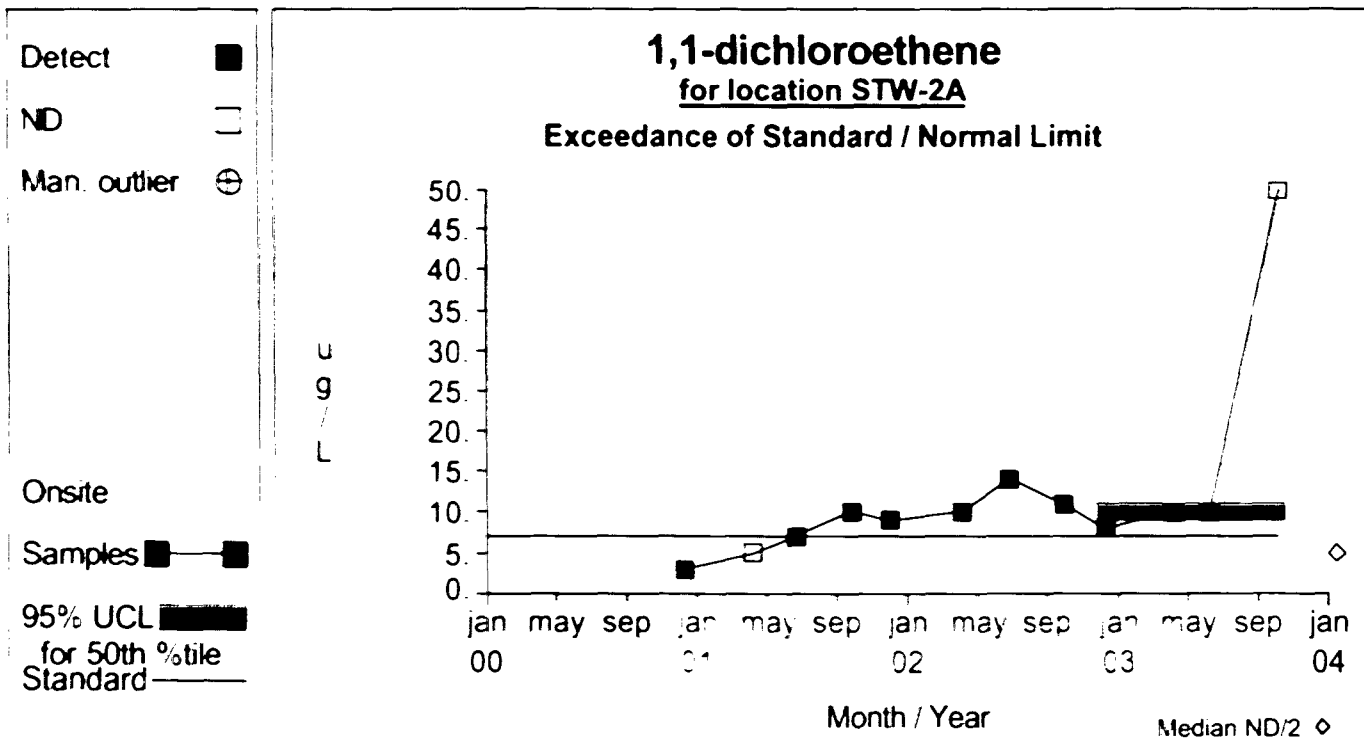


**Graph 67**

**Comparison to Standard**

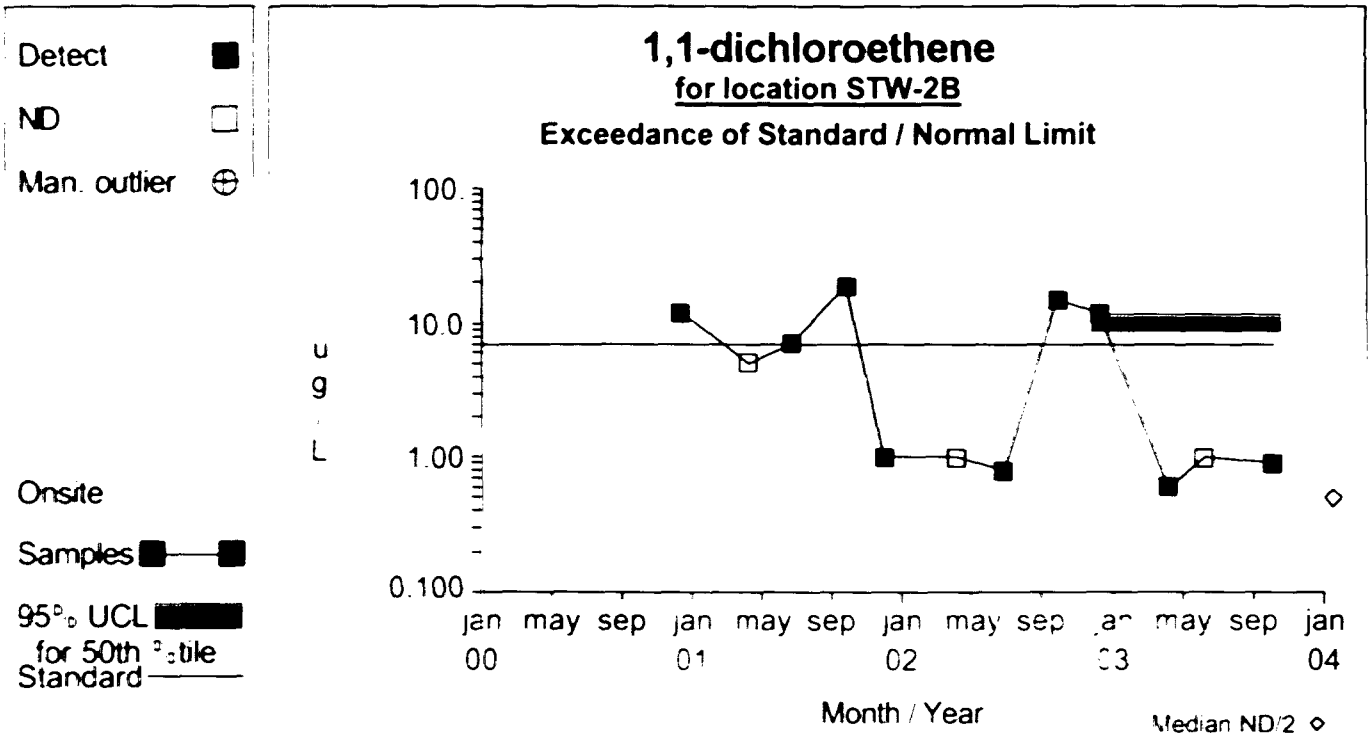


**Graph 75**

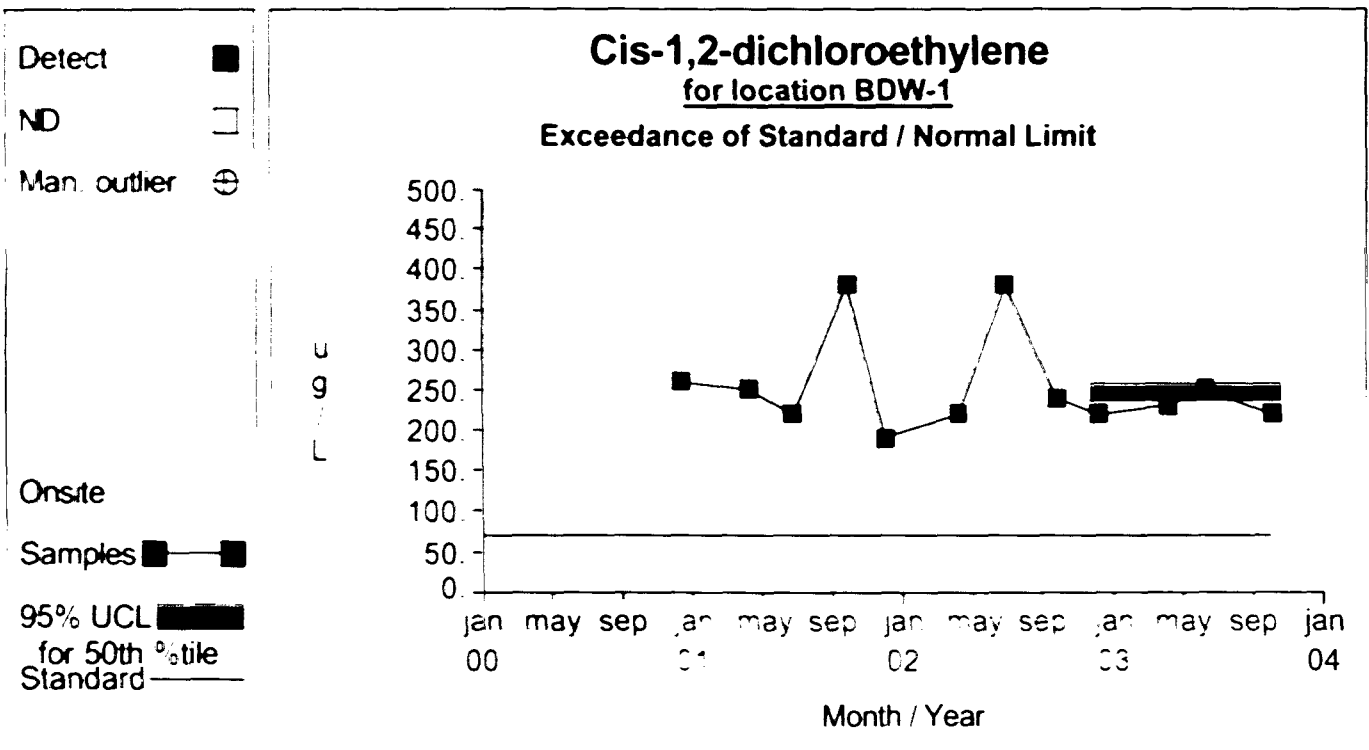


**Graph 78**

**Comparison to Standard**

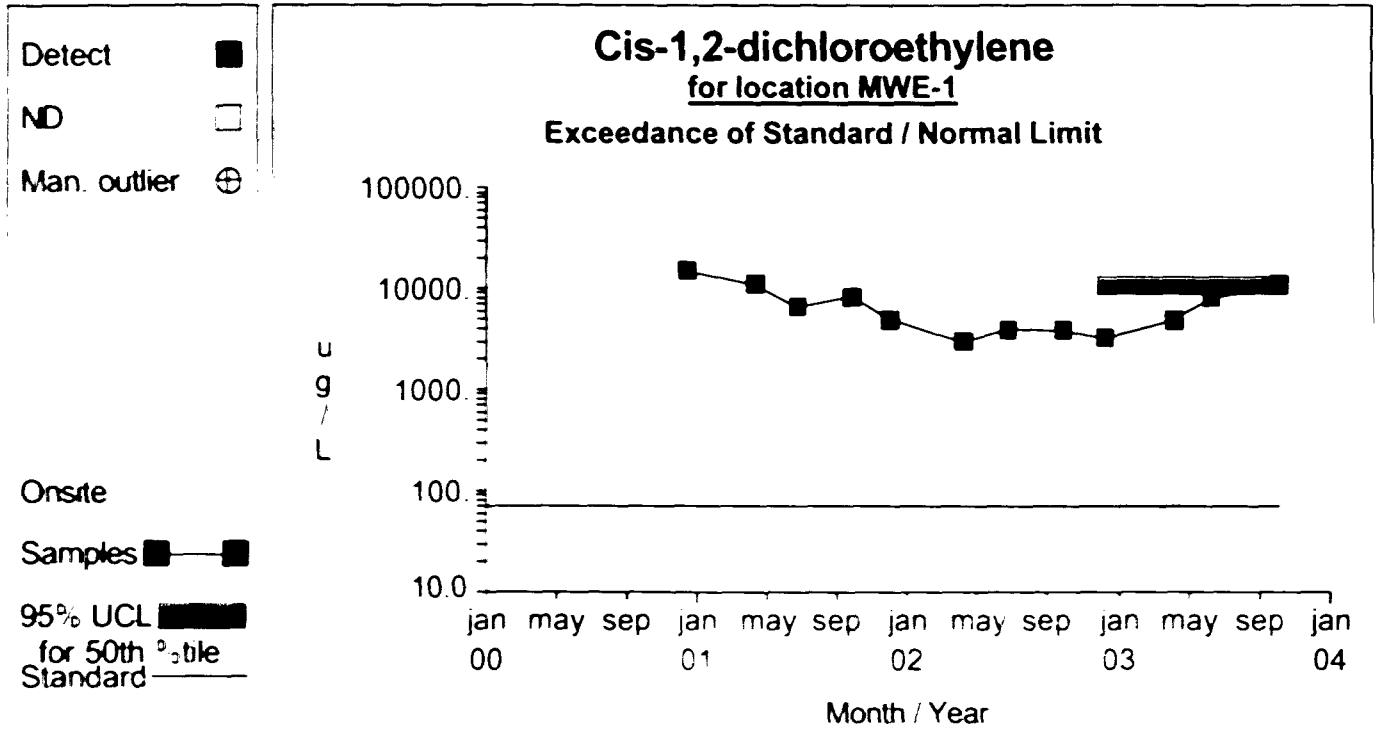


**Graph 79**

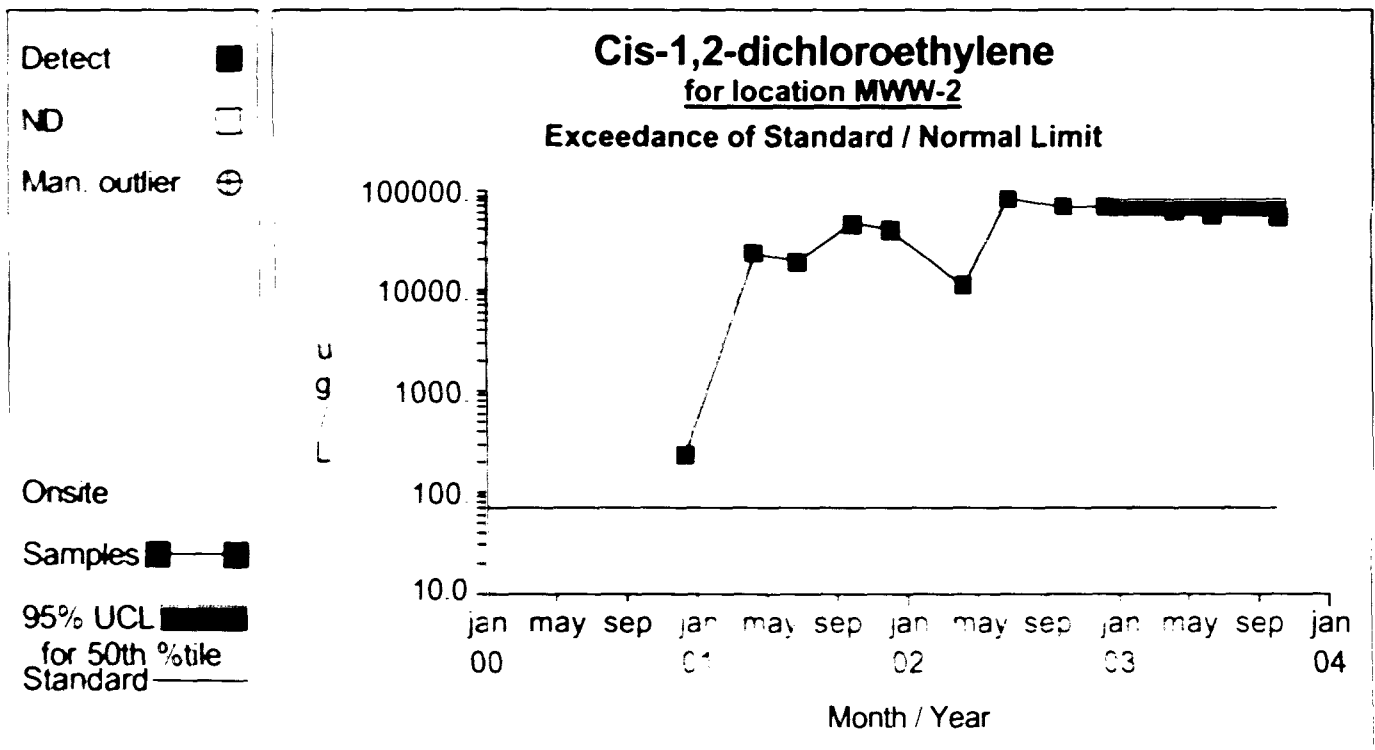


**Graph 83**

**Comparison to Standard**

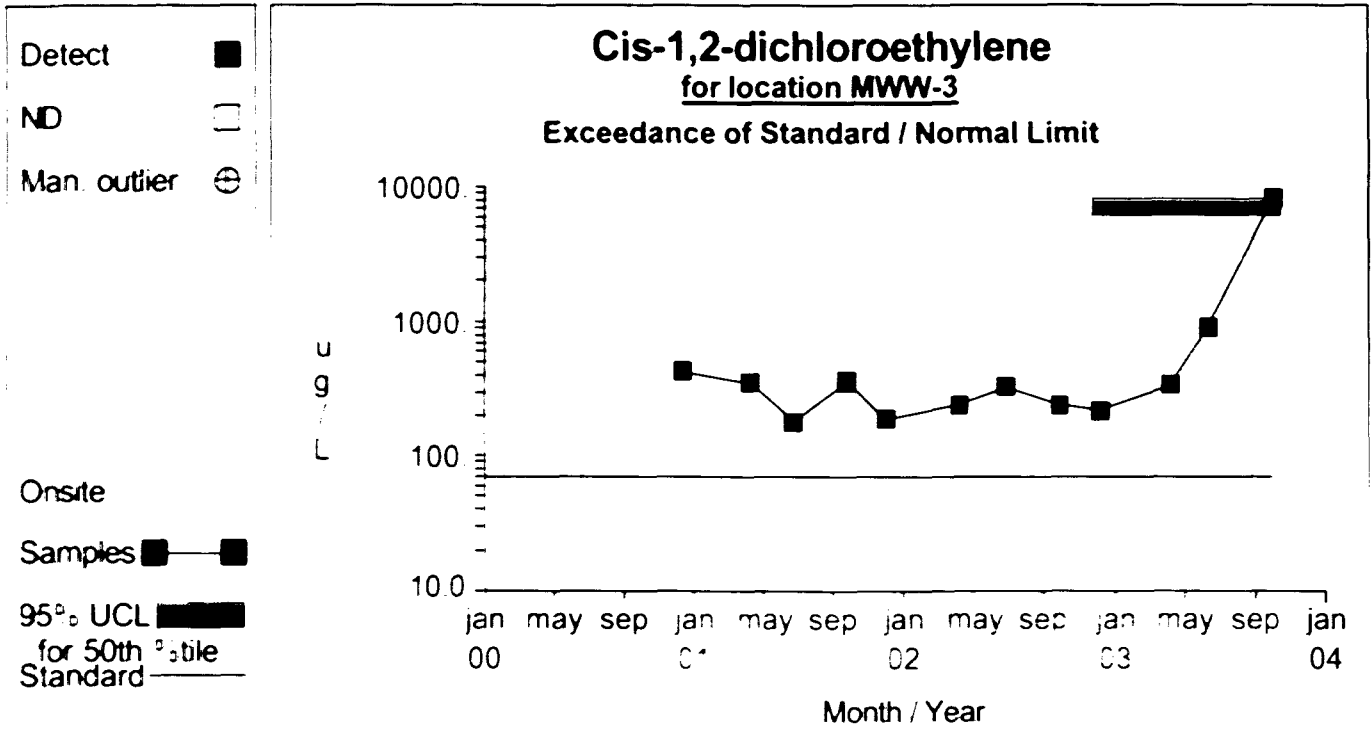


**Graph 87**

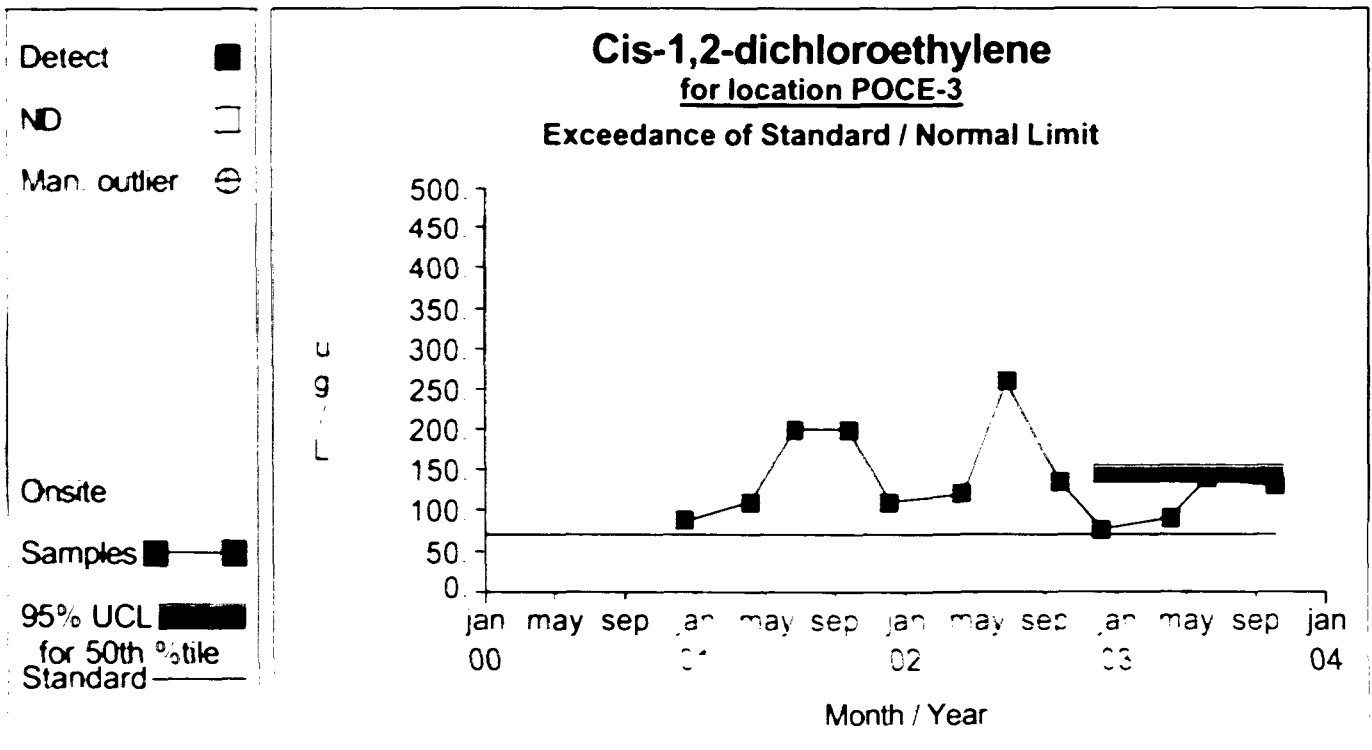


**Graph 90**

**Comparison to Standard**



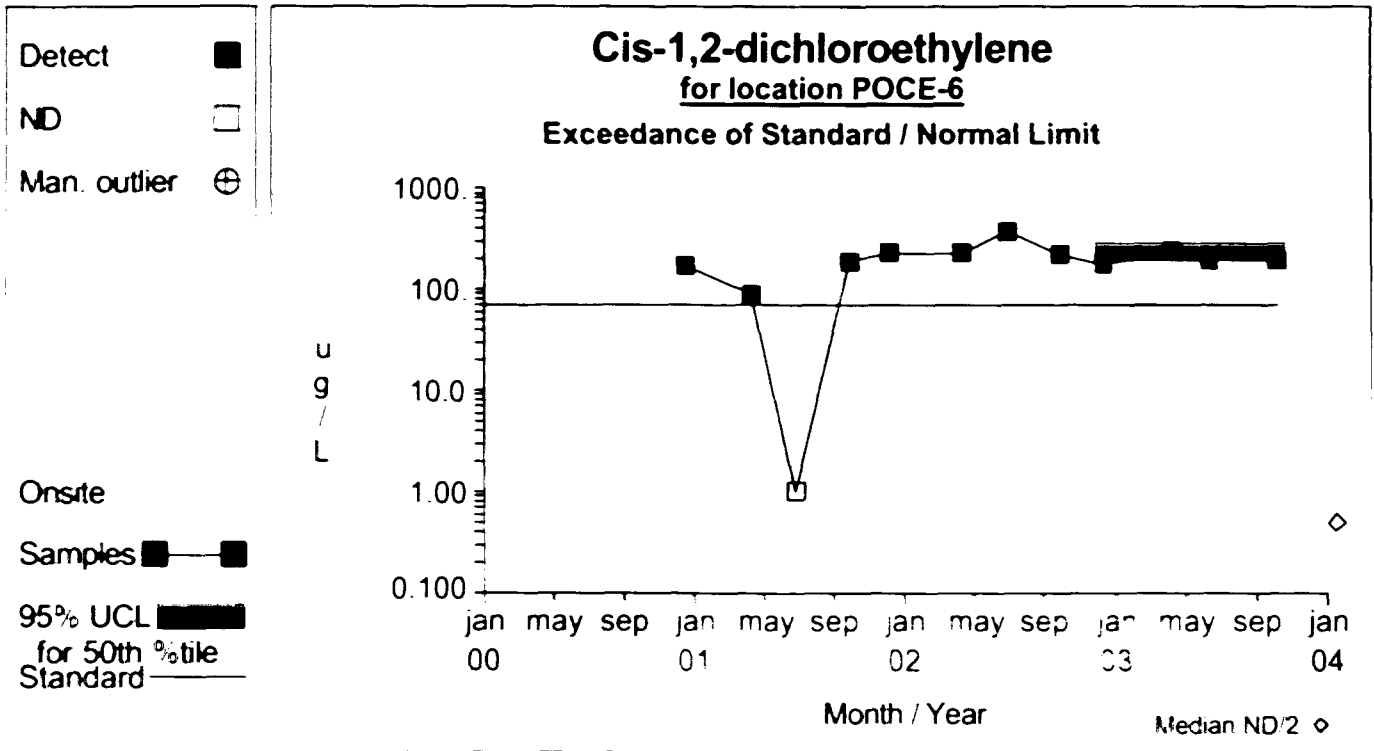
**Graph 91**



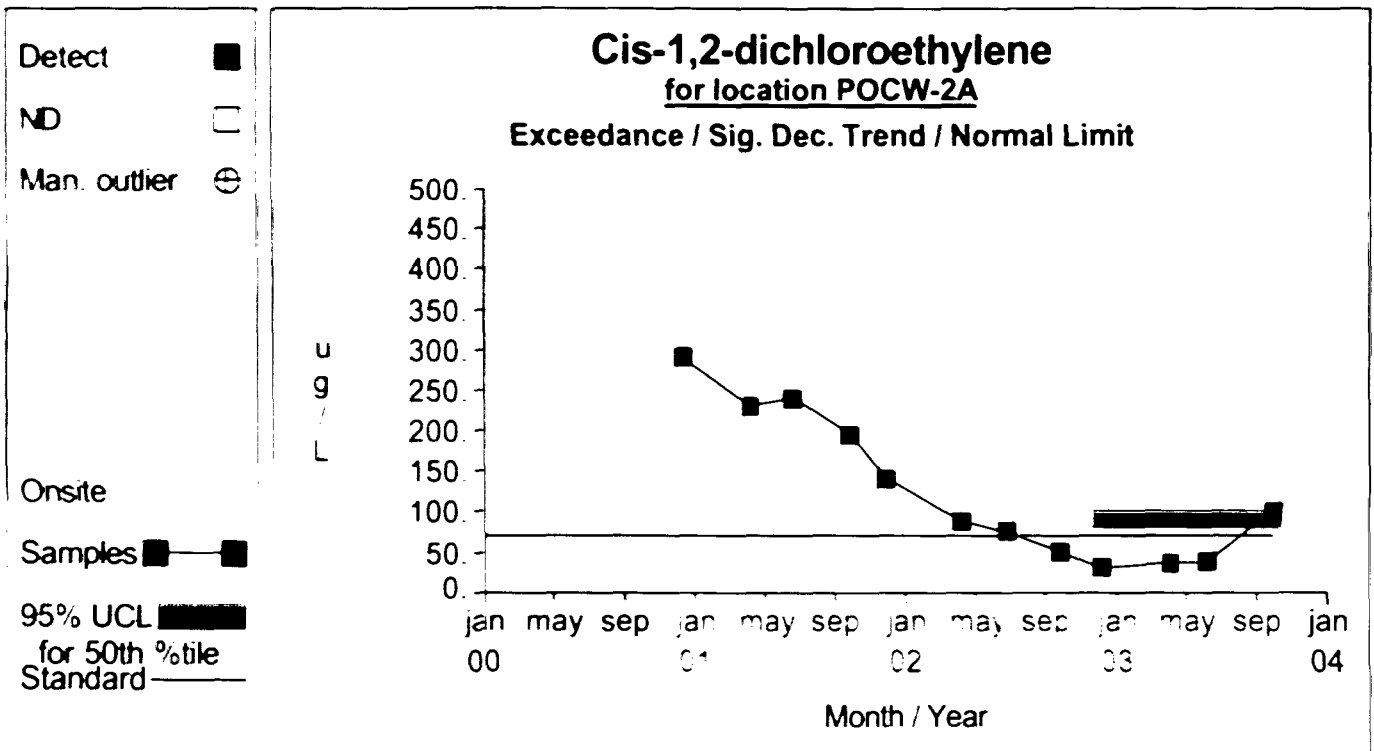
**Graph 96**



**Comparison to Standard**

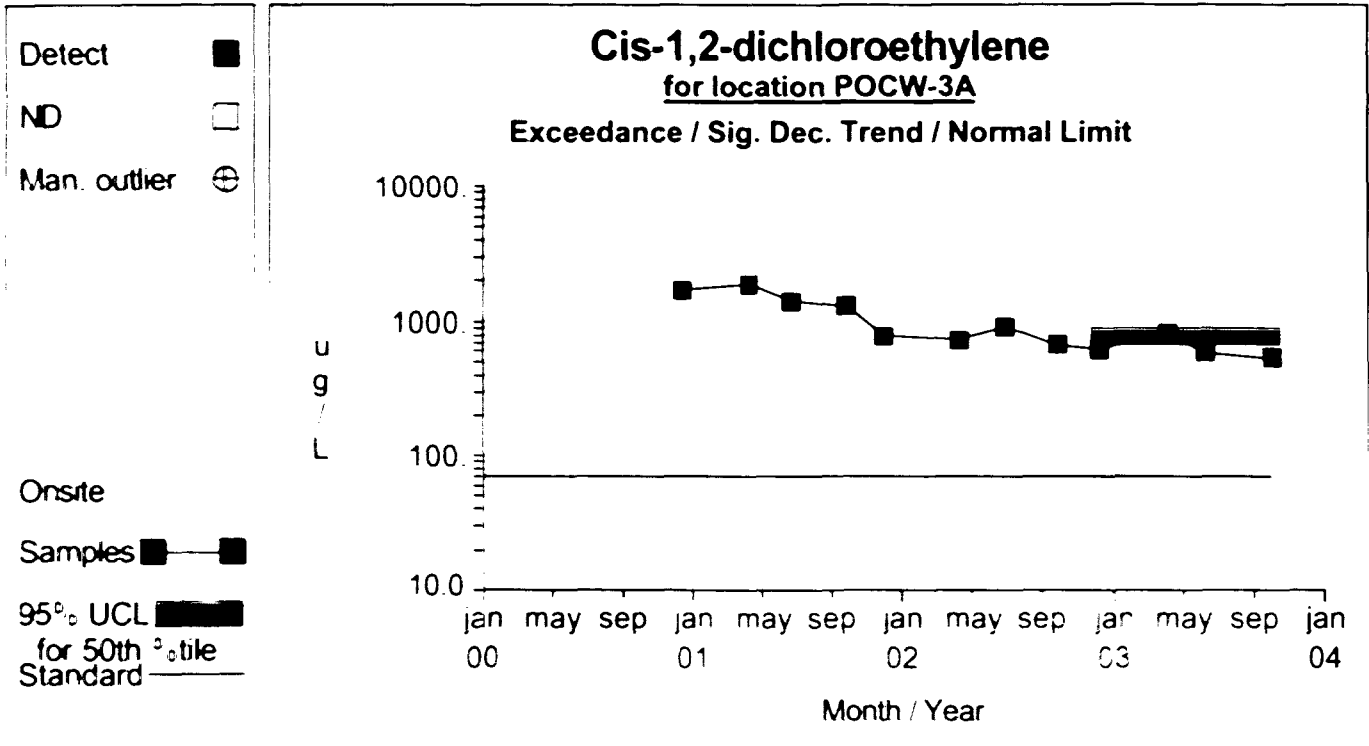


**Graph 99**

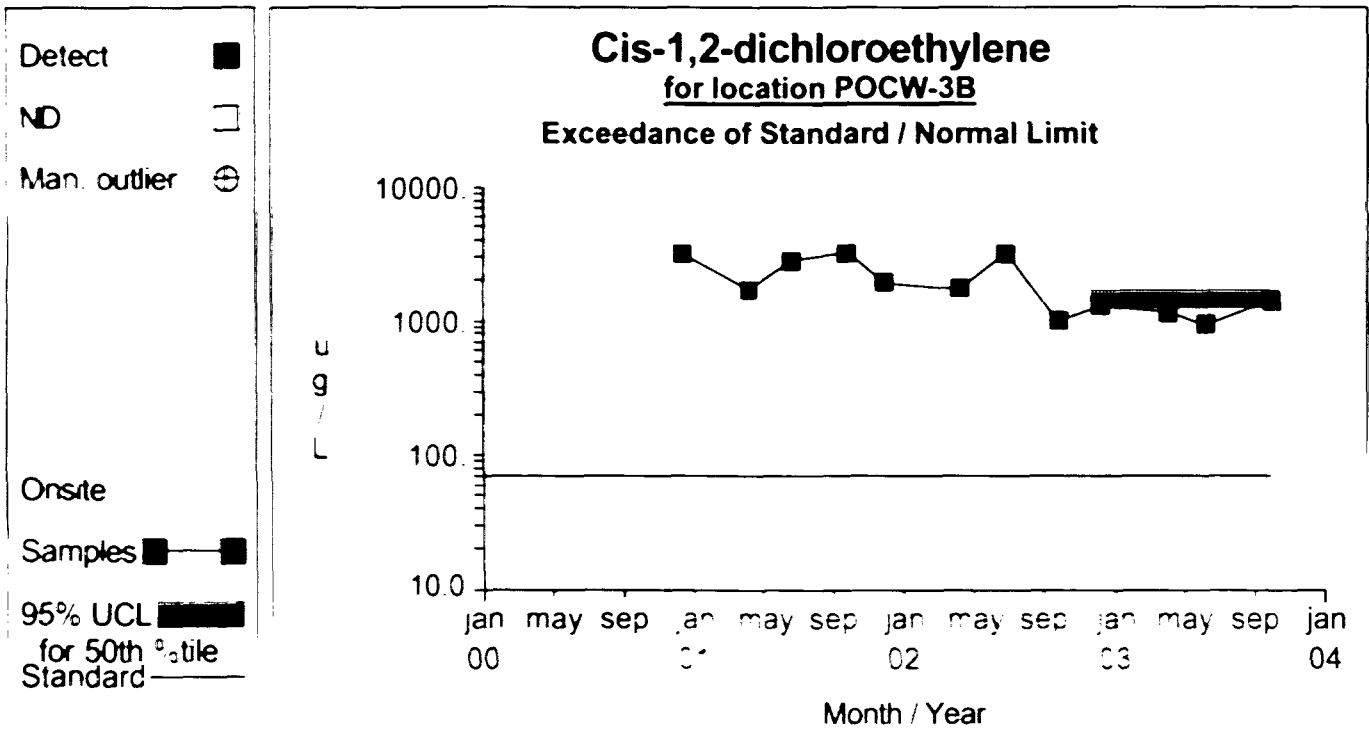


**Graph 103**

**Comparison to Standard**

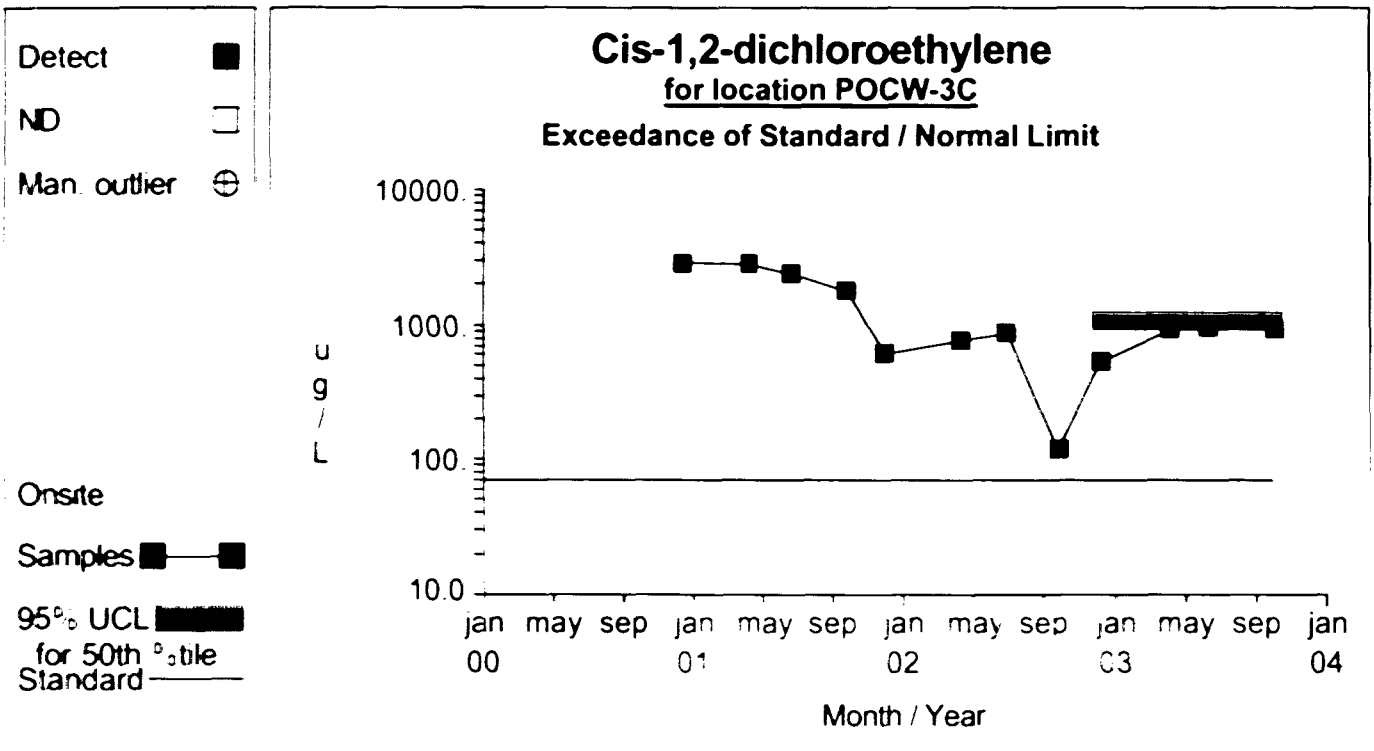


**Graph 105**

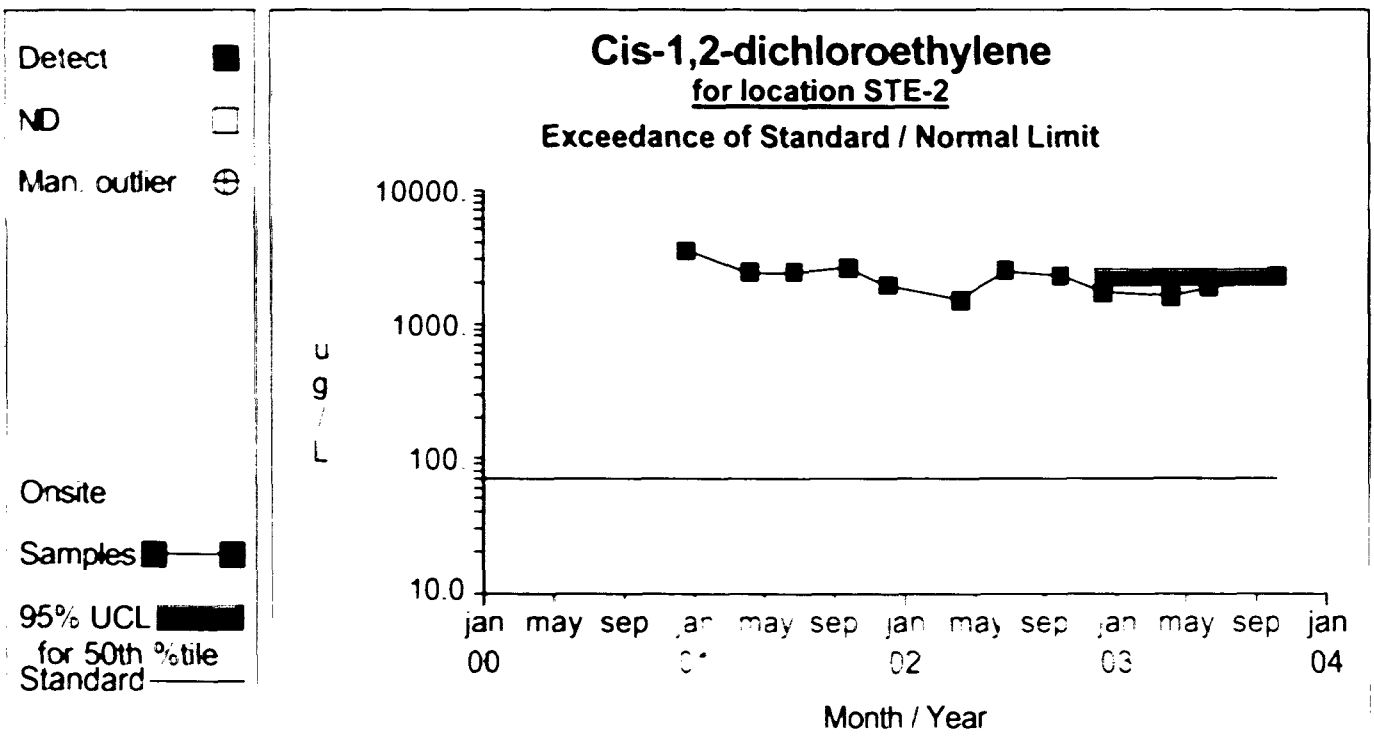


**Graph 106**

**Comparison to Standard**

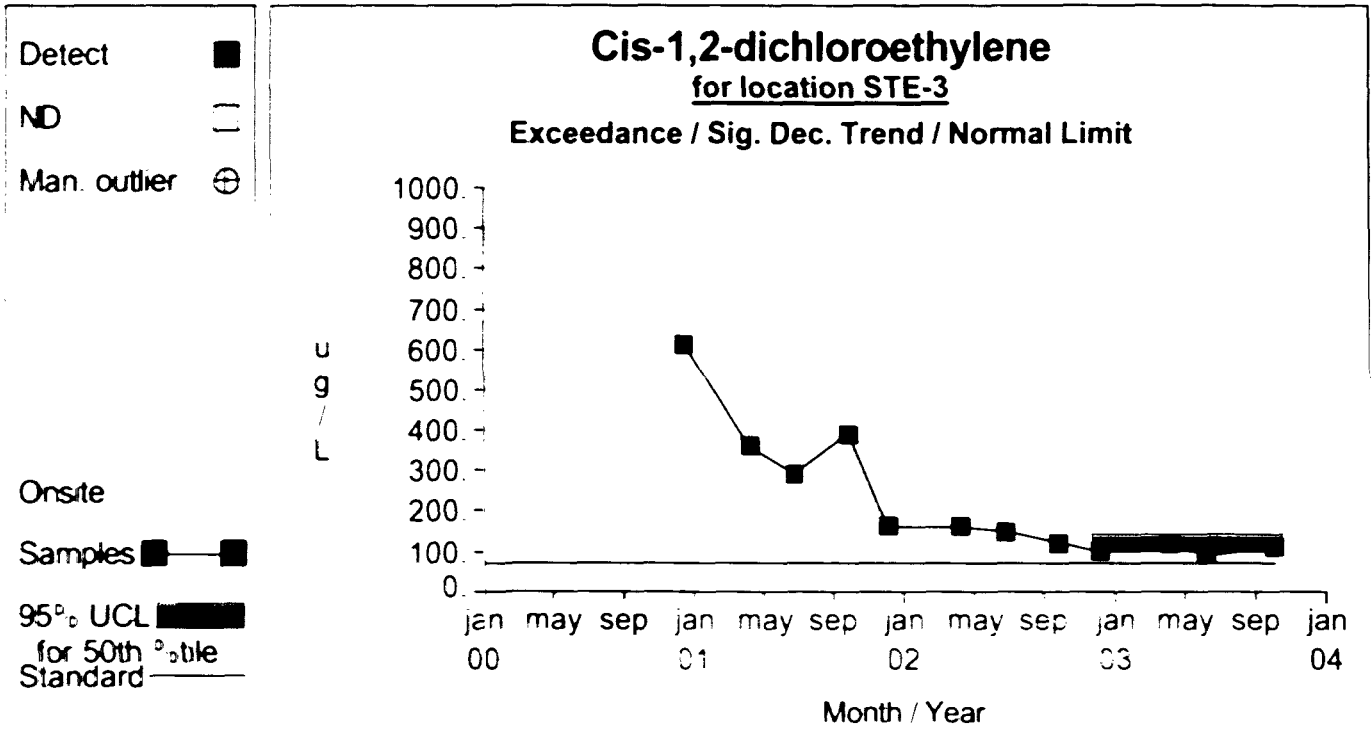


**Graph 107**

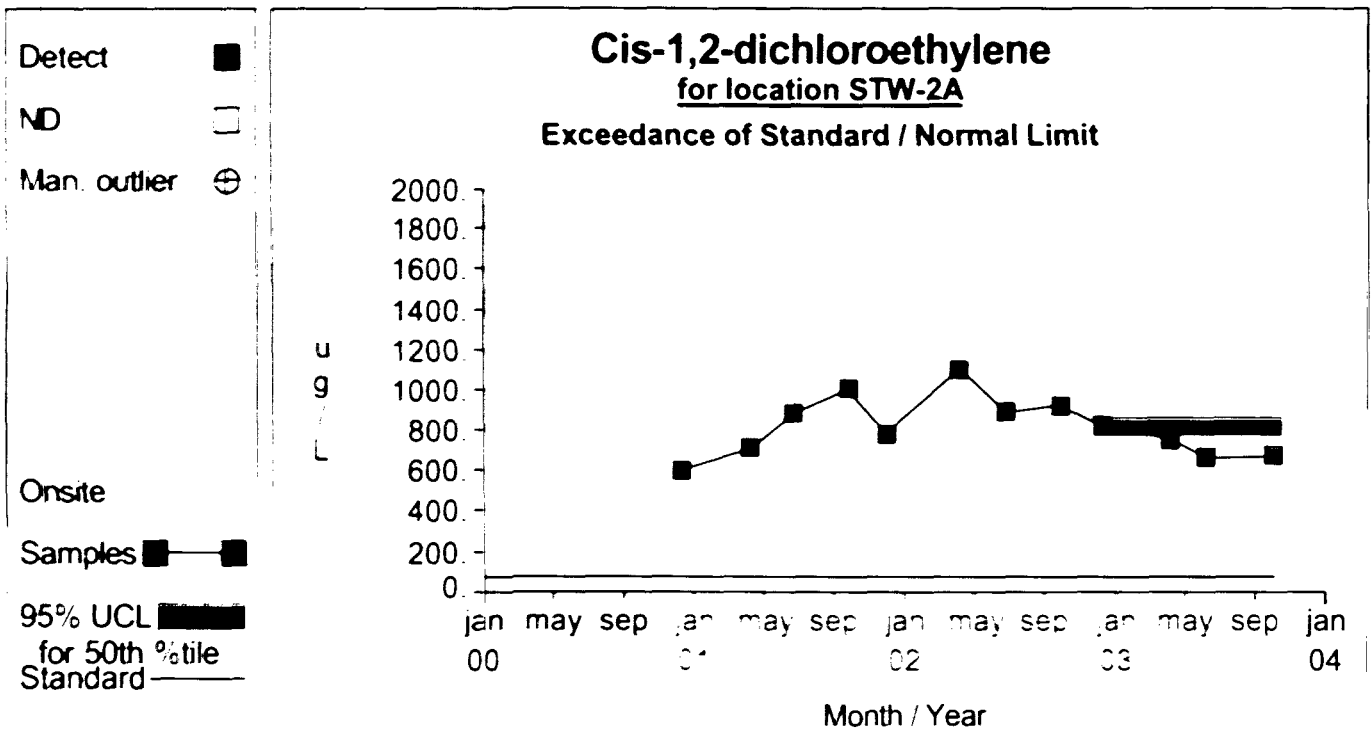


**Graph 115**

**Comparison to Standard**

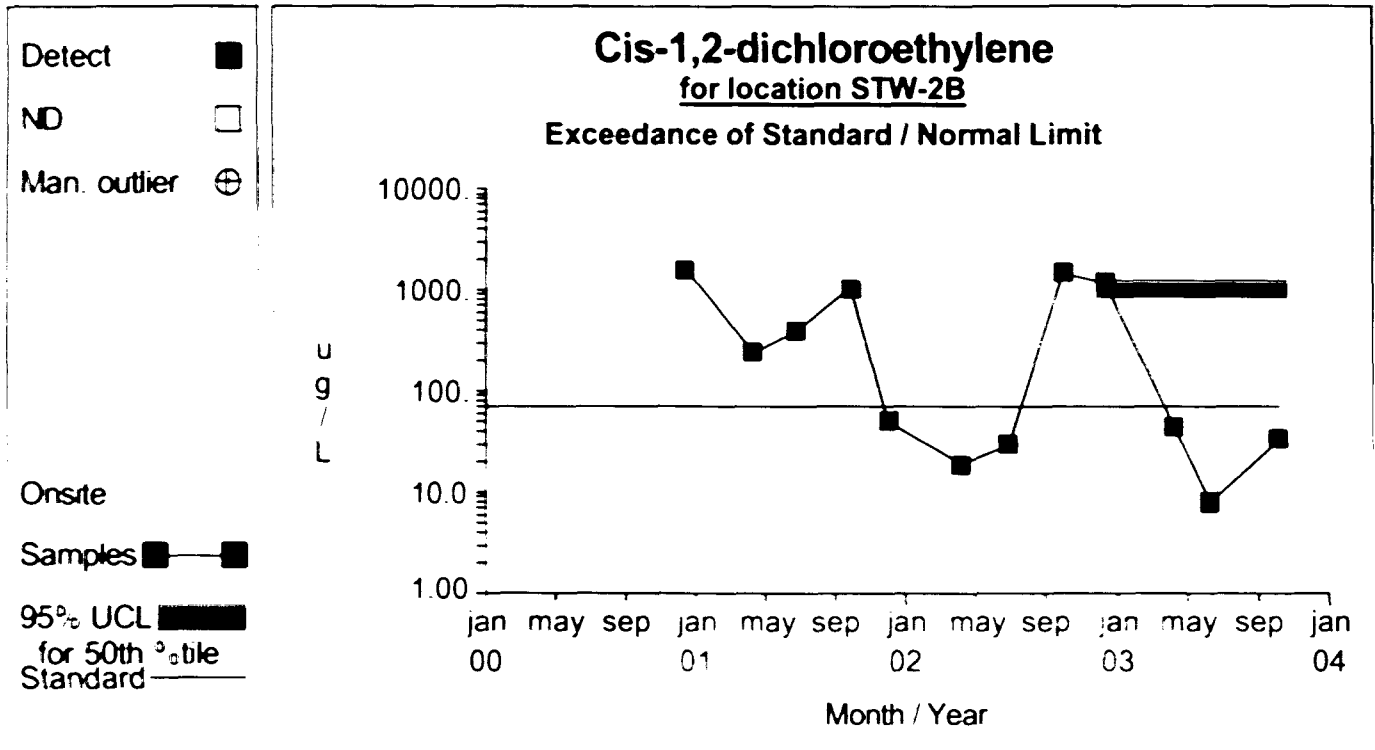


**Graph 116**

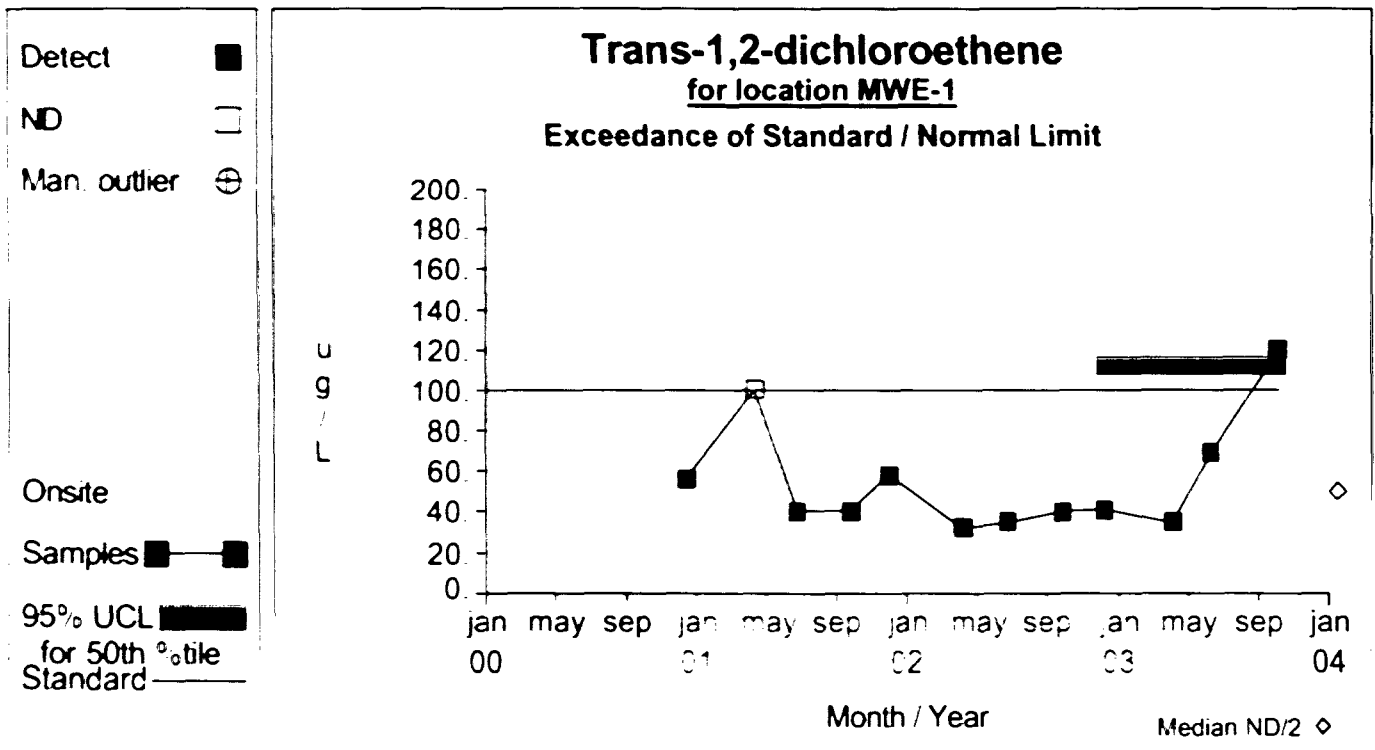


**Graph 118**

**Comparison to Standard**

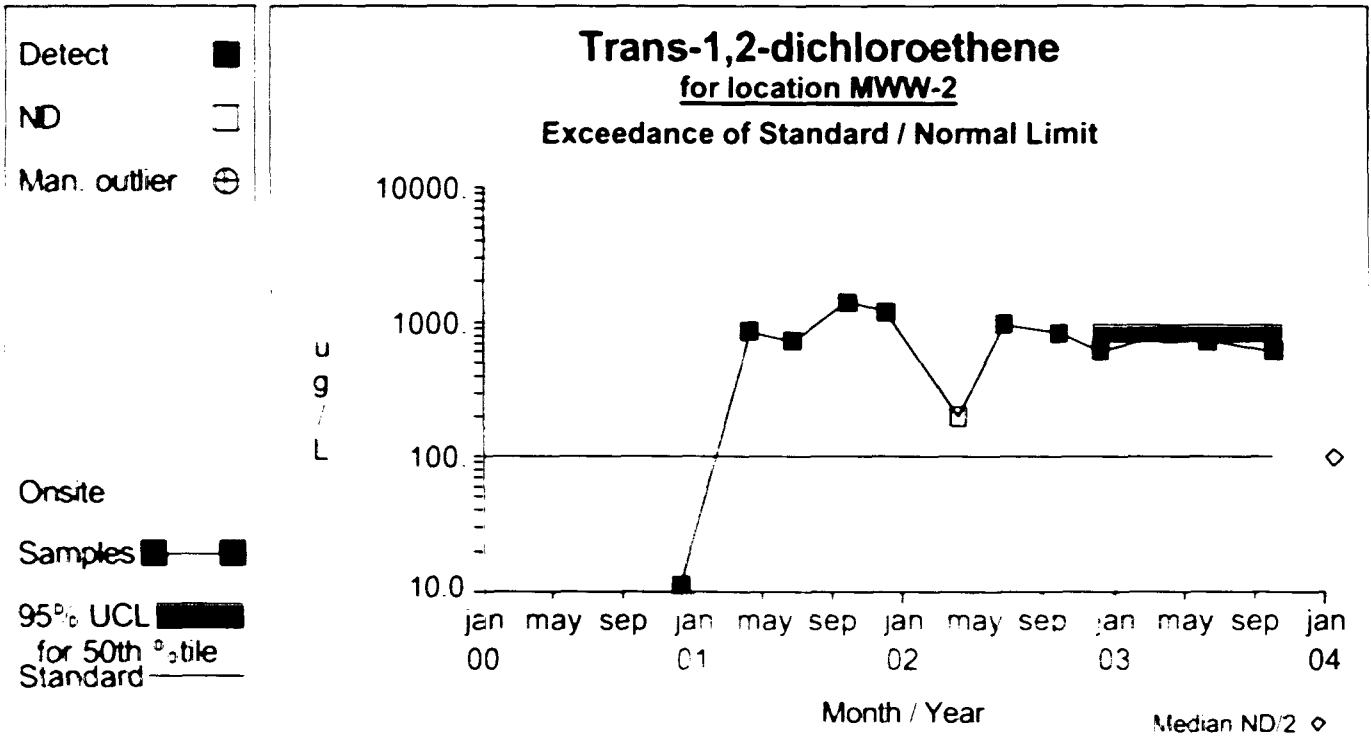


**Graph 119**

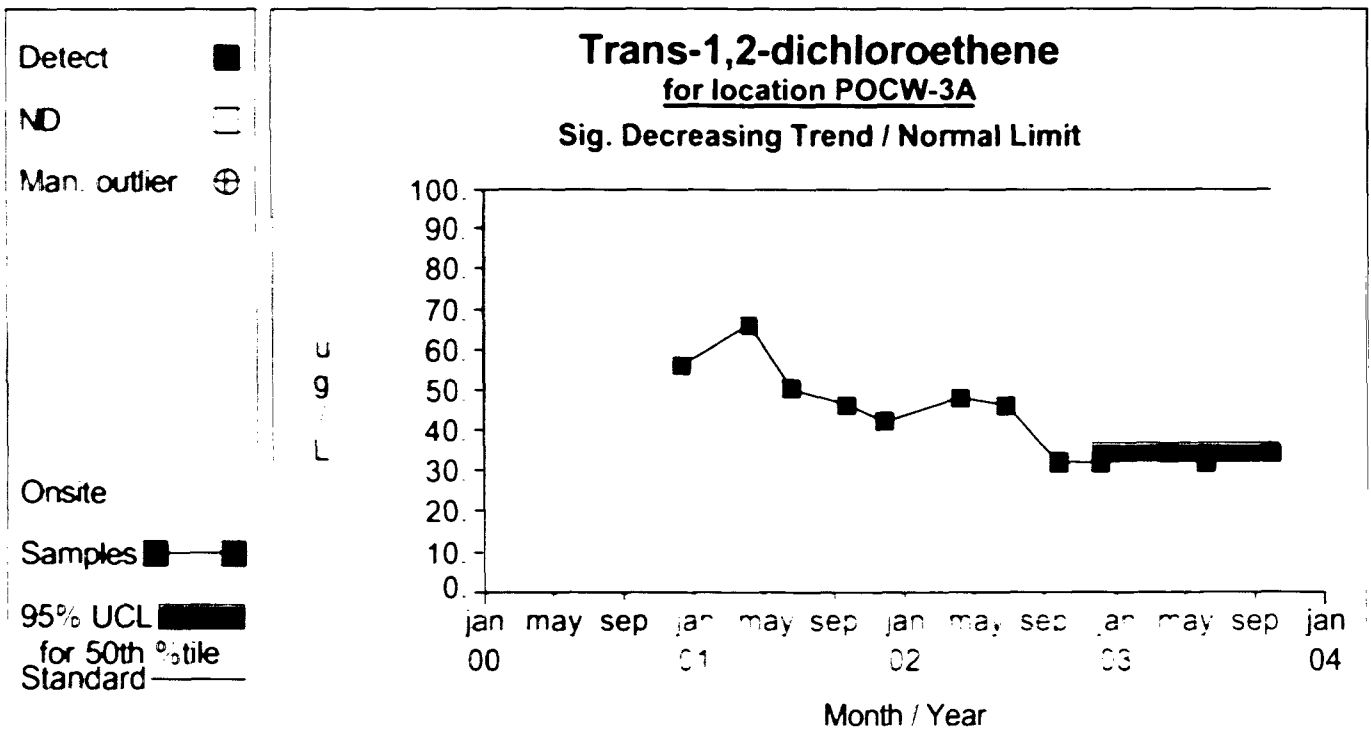


**Graph 127**

**Comparison to Standard**

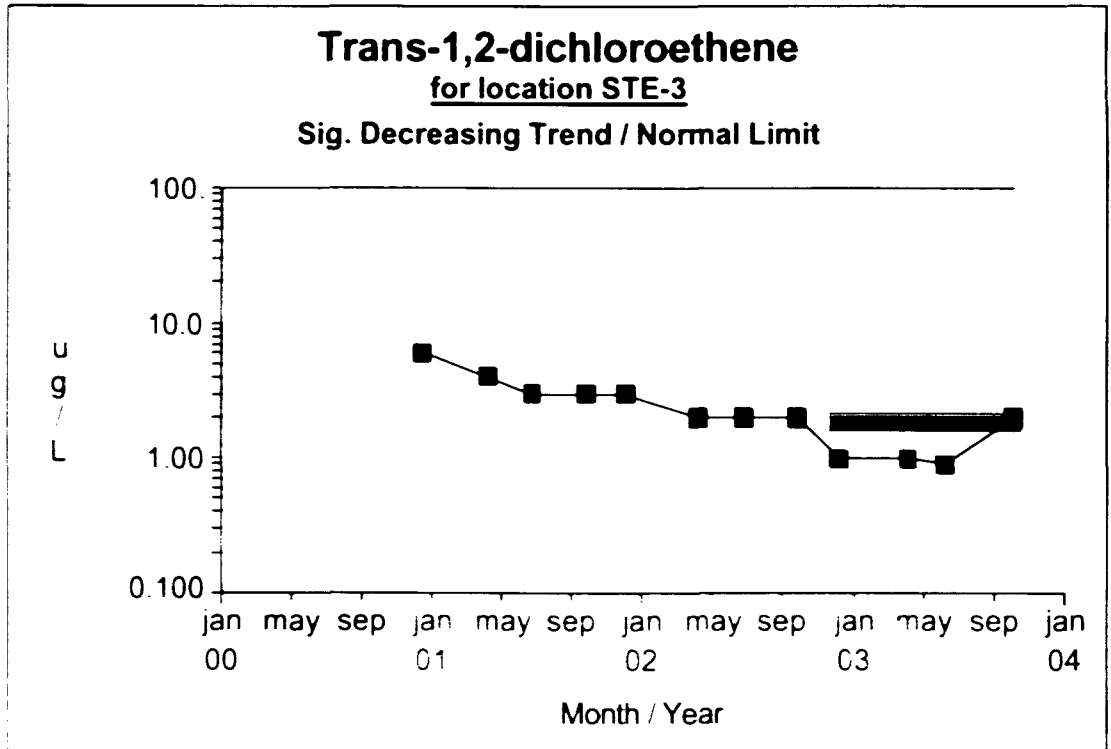
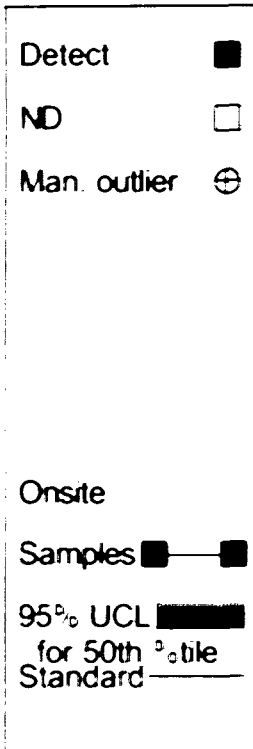


**Graph 130**

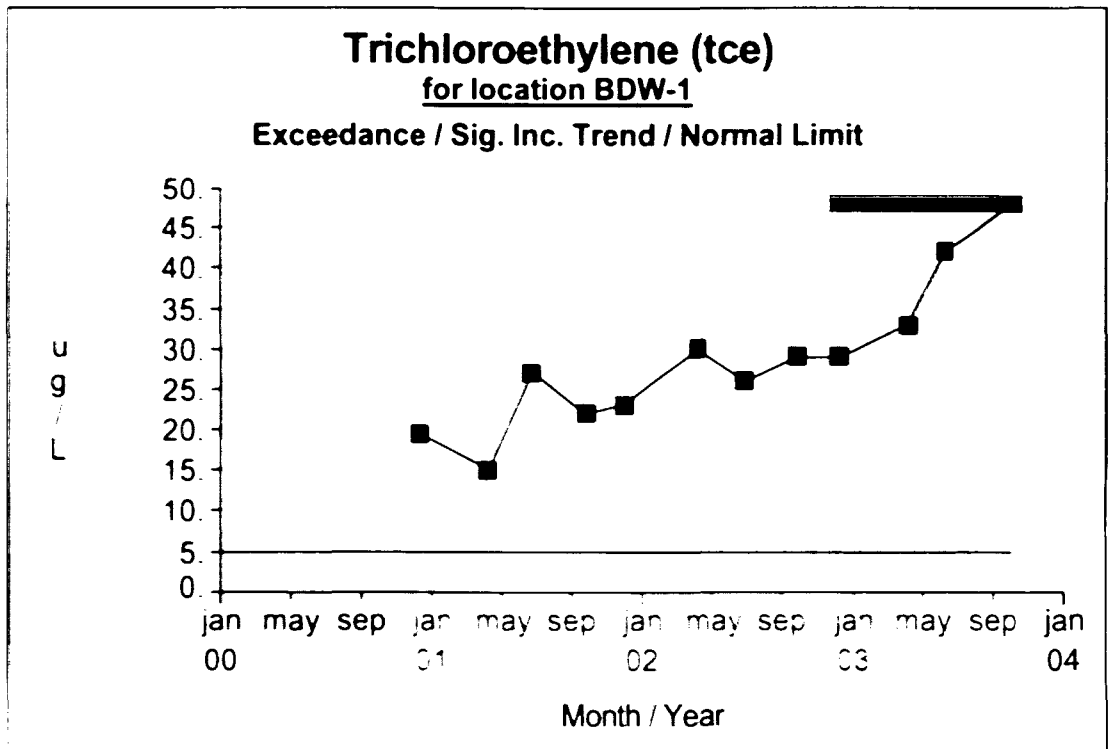
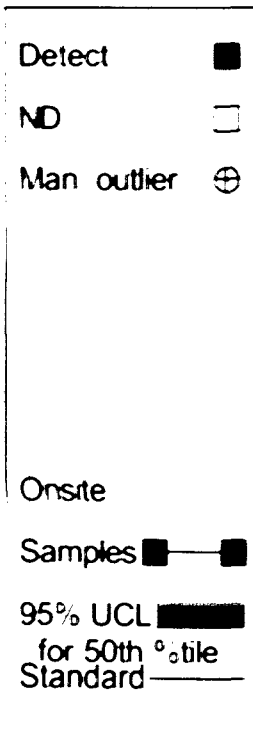


**Graph 145**

**Comparison to Standard**

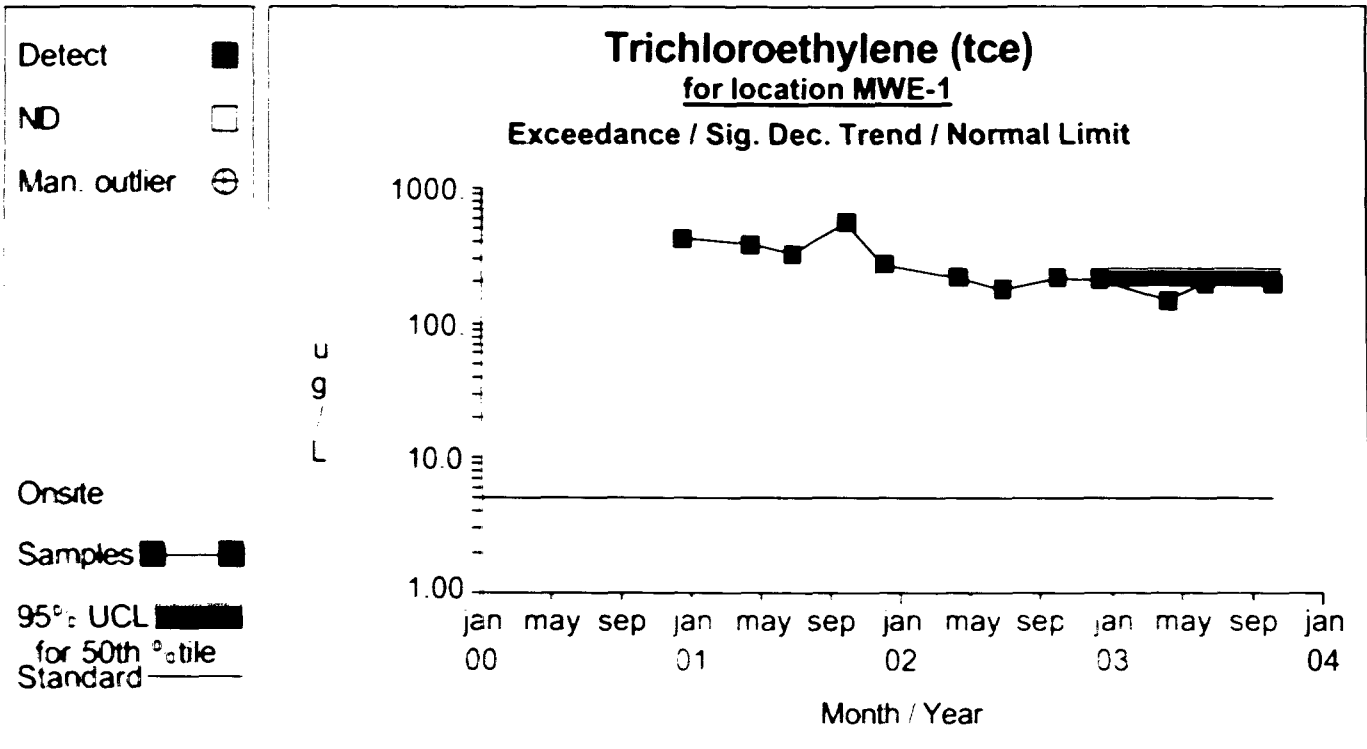


**Graph 156**

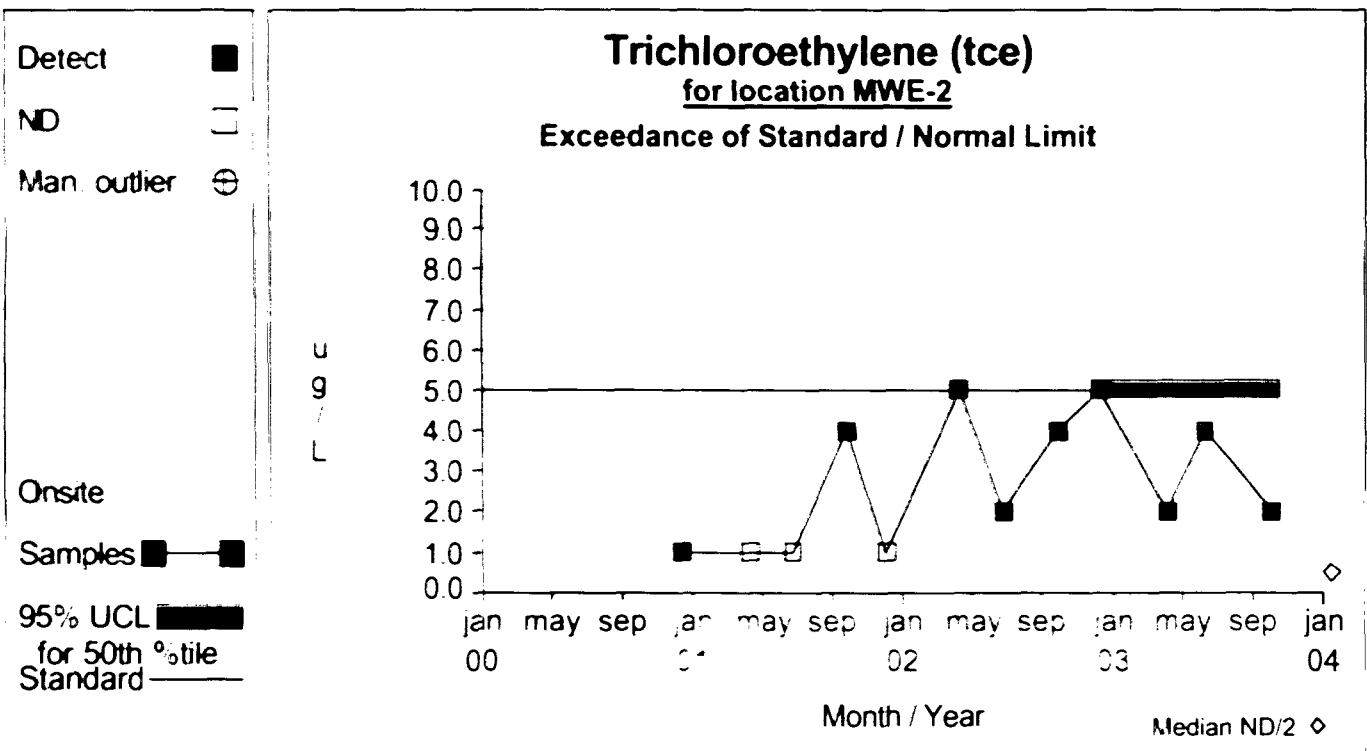


**Graph 163**

**Comparison to Standard**



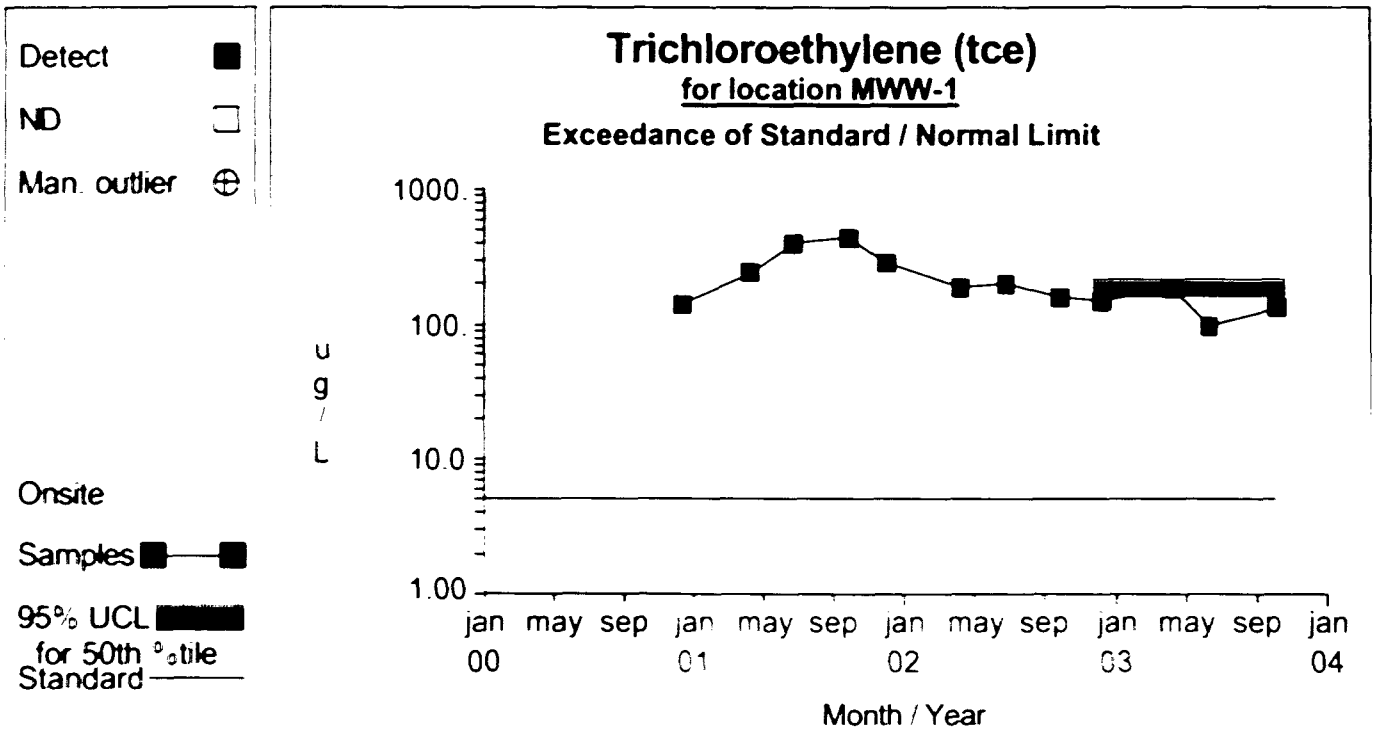
**Graph 167**



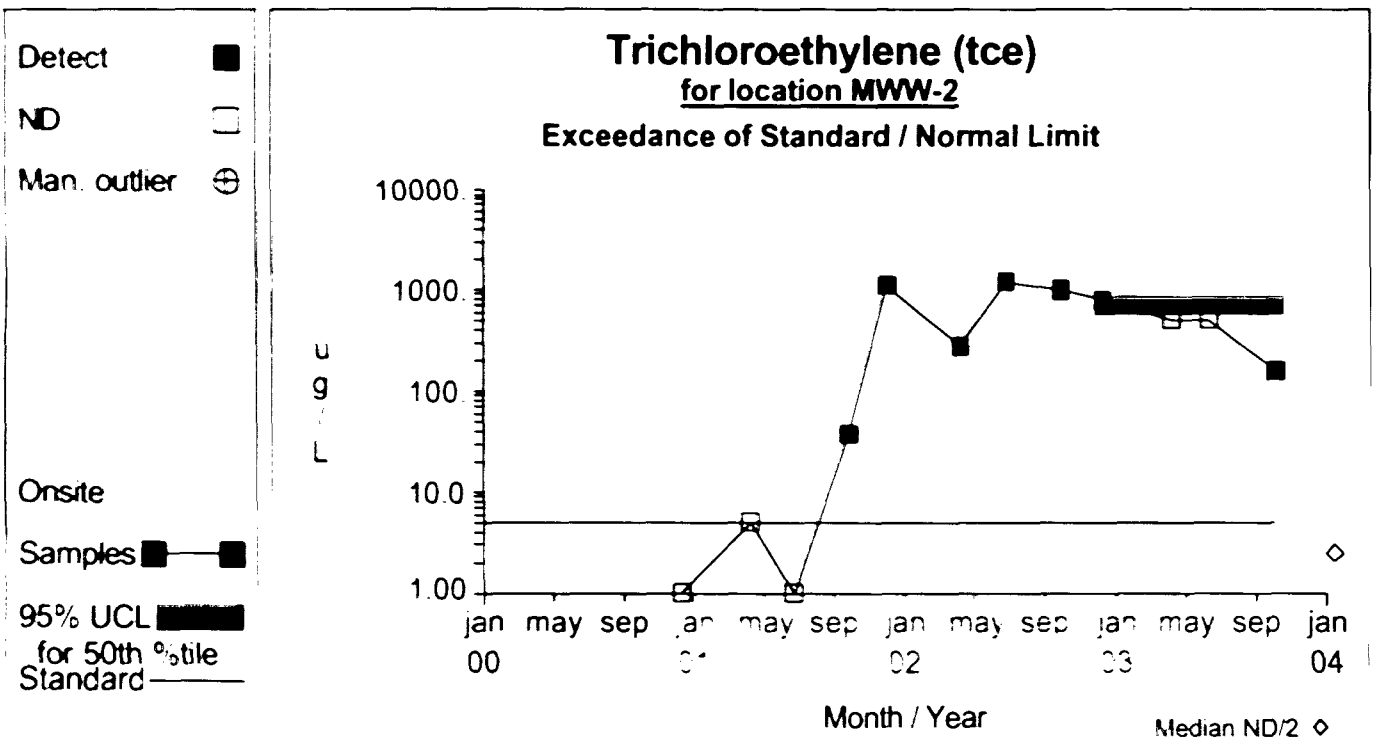
**Graph 168**



**Comparison to Standard**

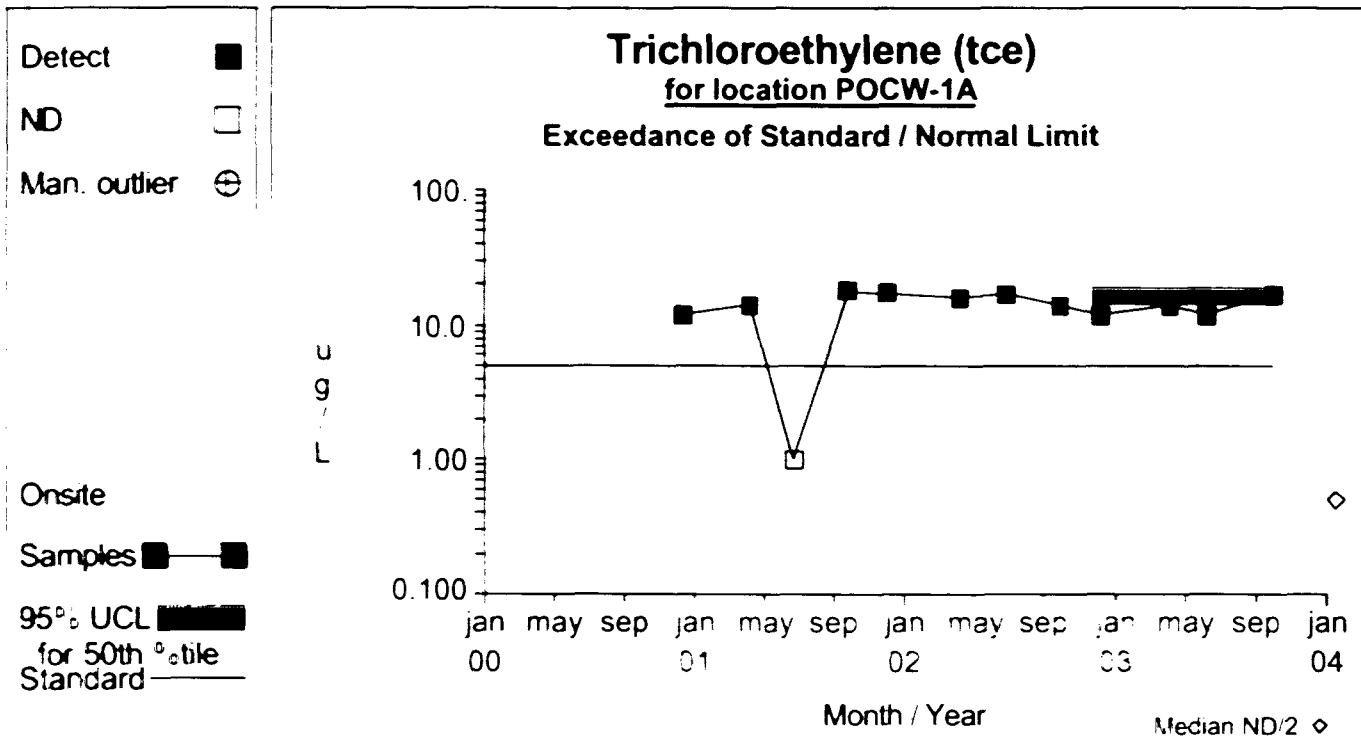


**Graph 169**

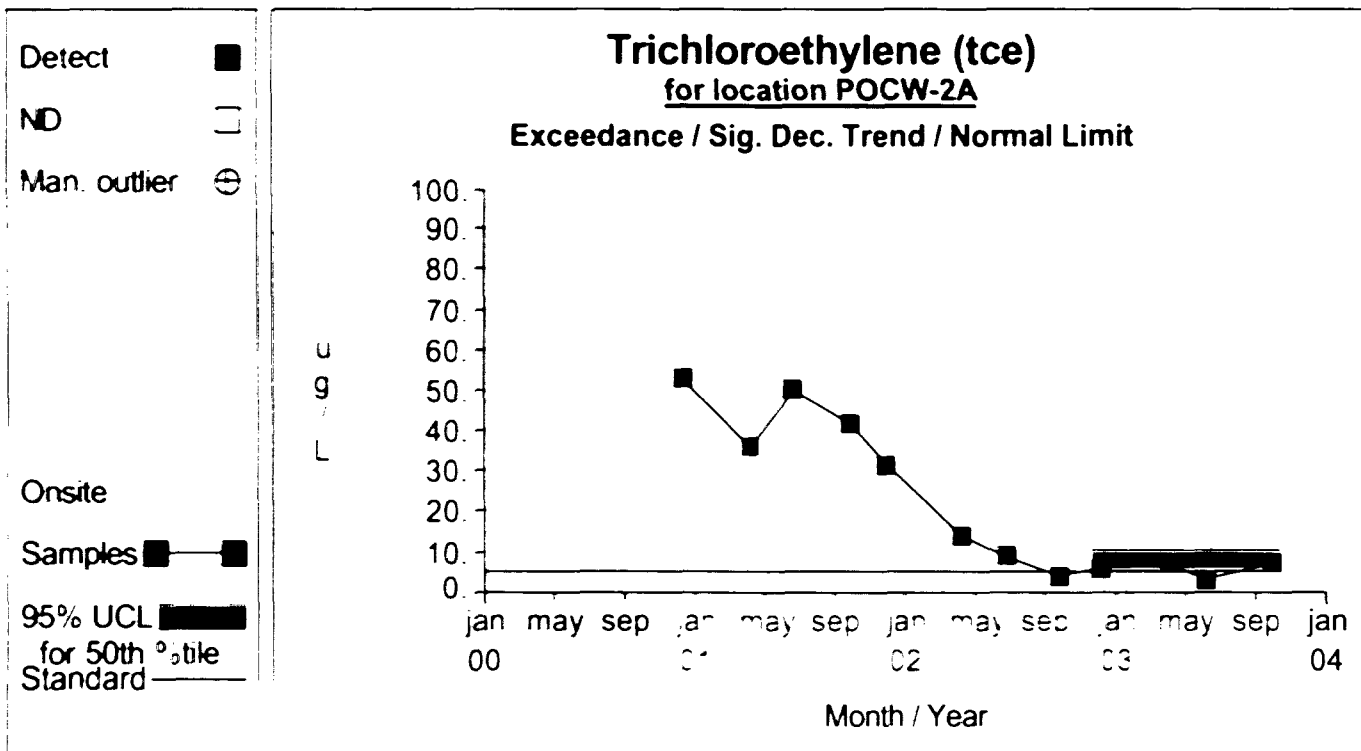


**Graph 170**

**Comparison to Standard**

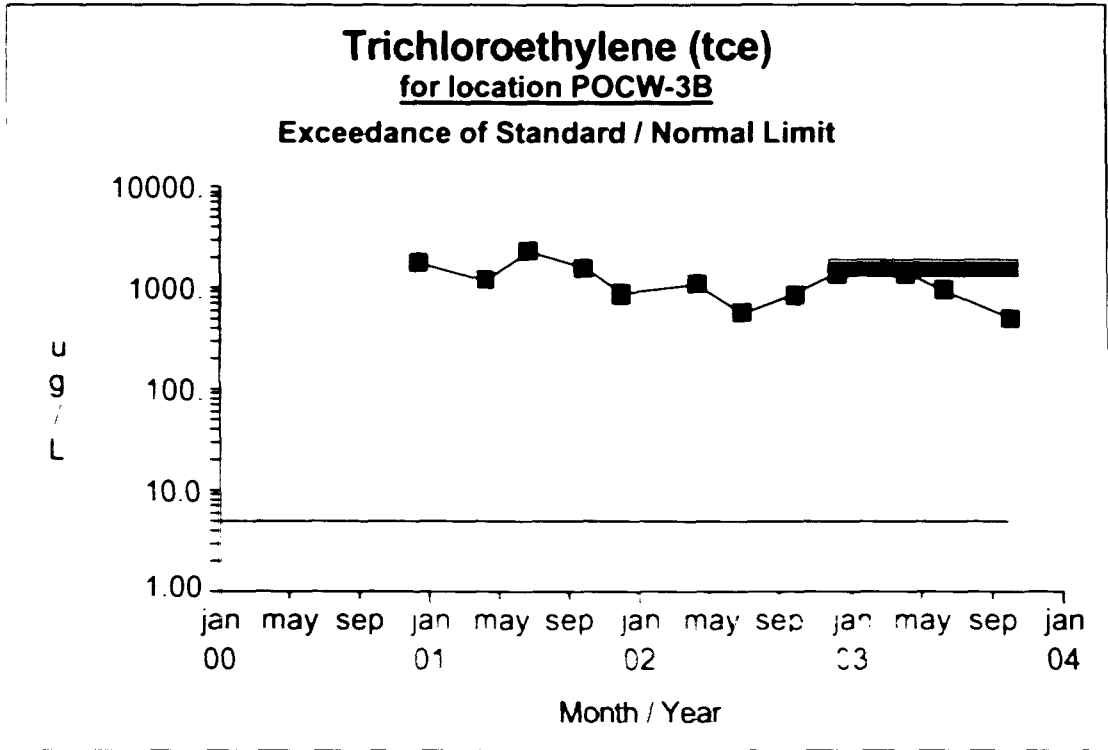


**Graph 181**

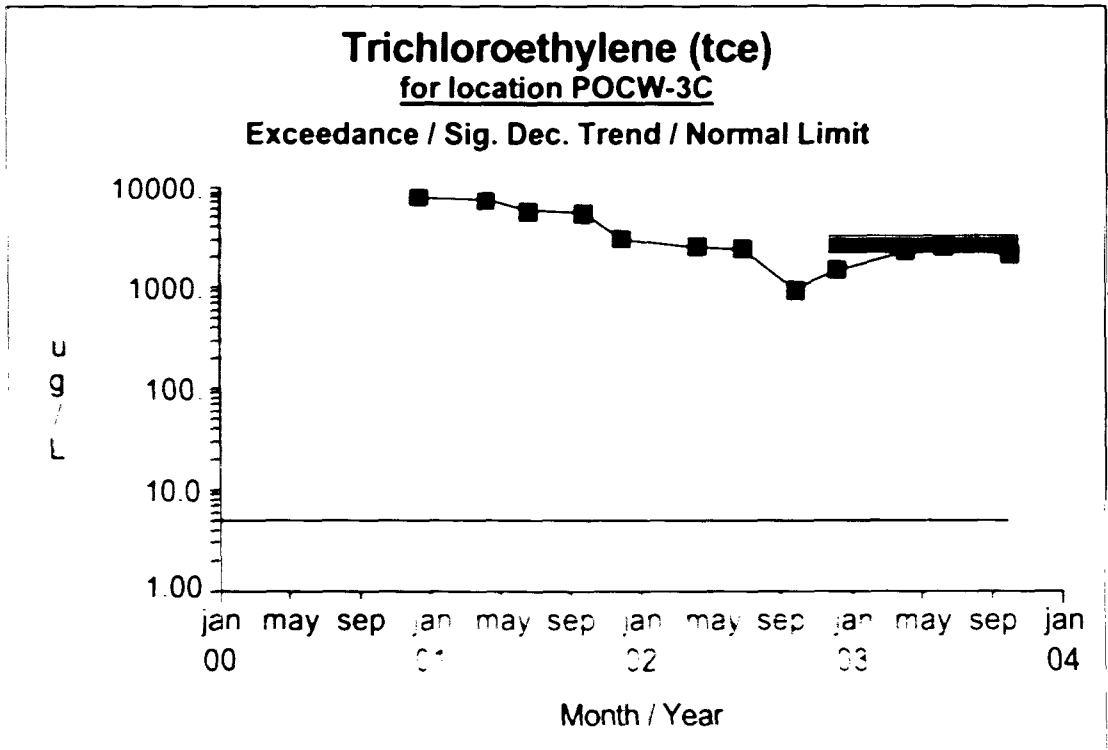
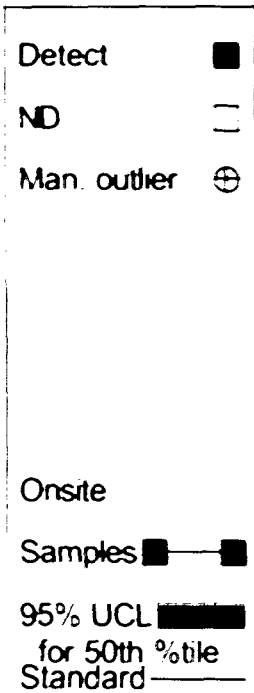


**Graph 183**

**Comparison to Standard**

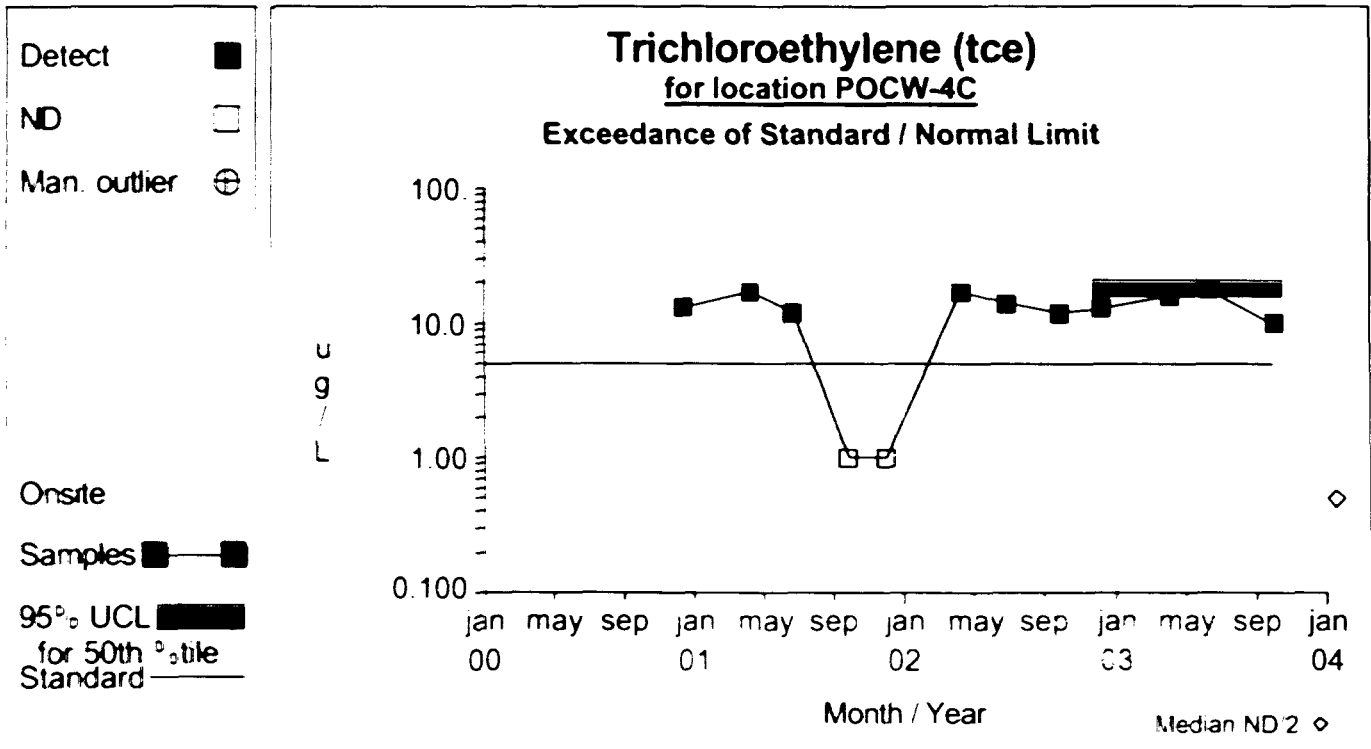


**Graph 186**

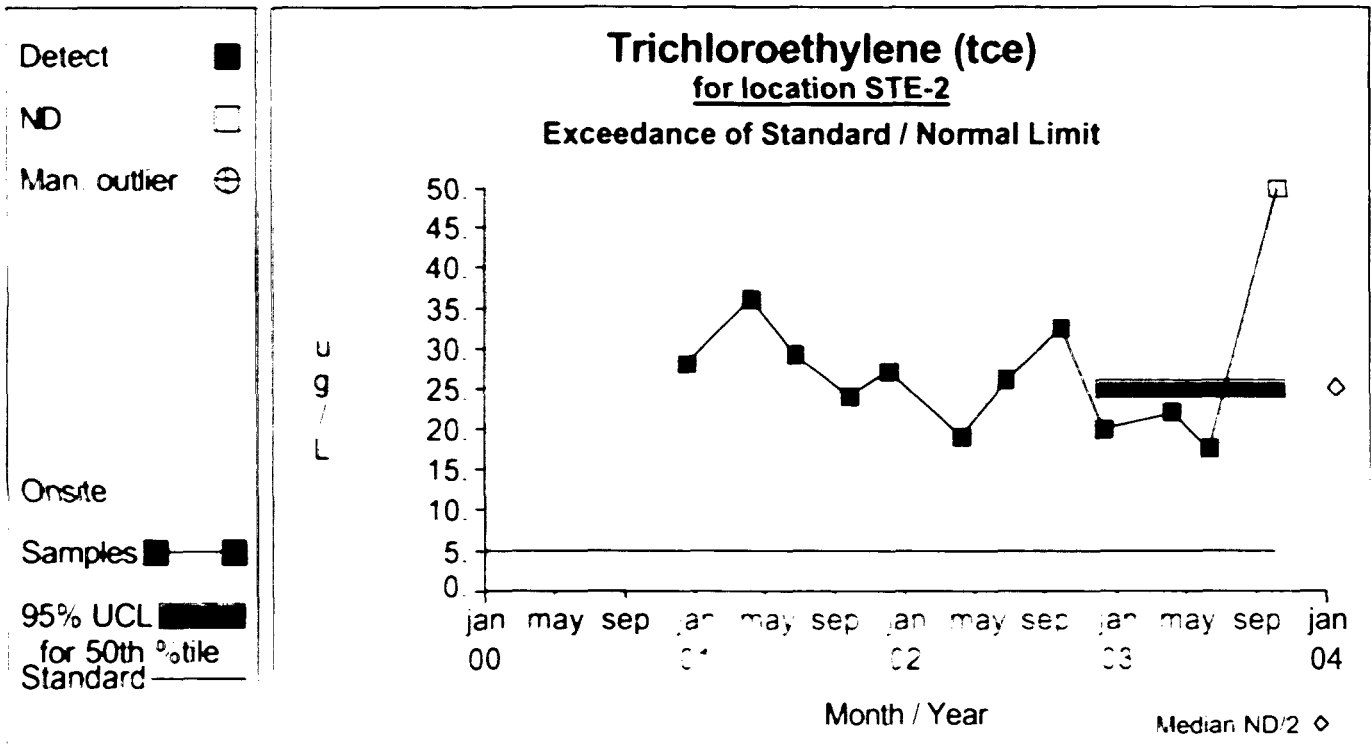


**Graph 187**

**Comparison to Standard**

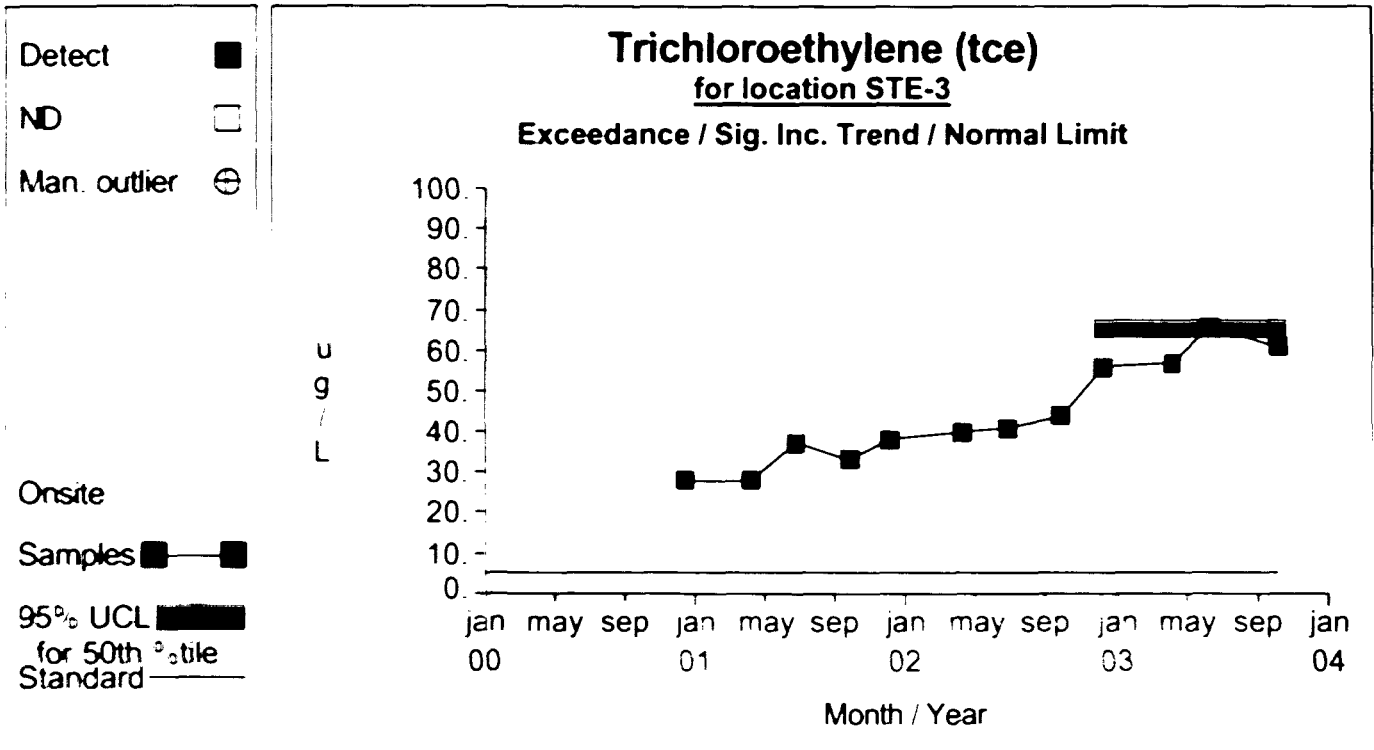


**Graph 190**

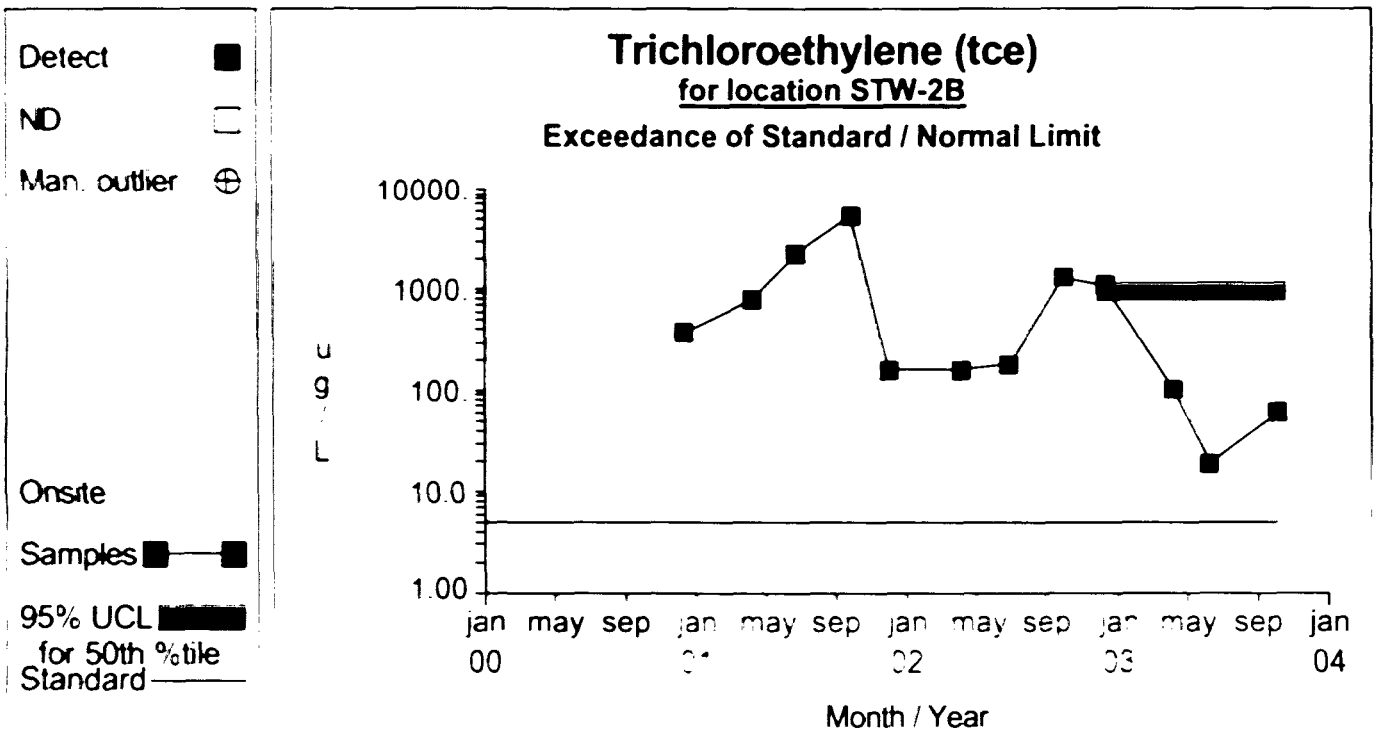


**Graph 195**

**Comparison to Standard**

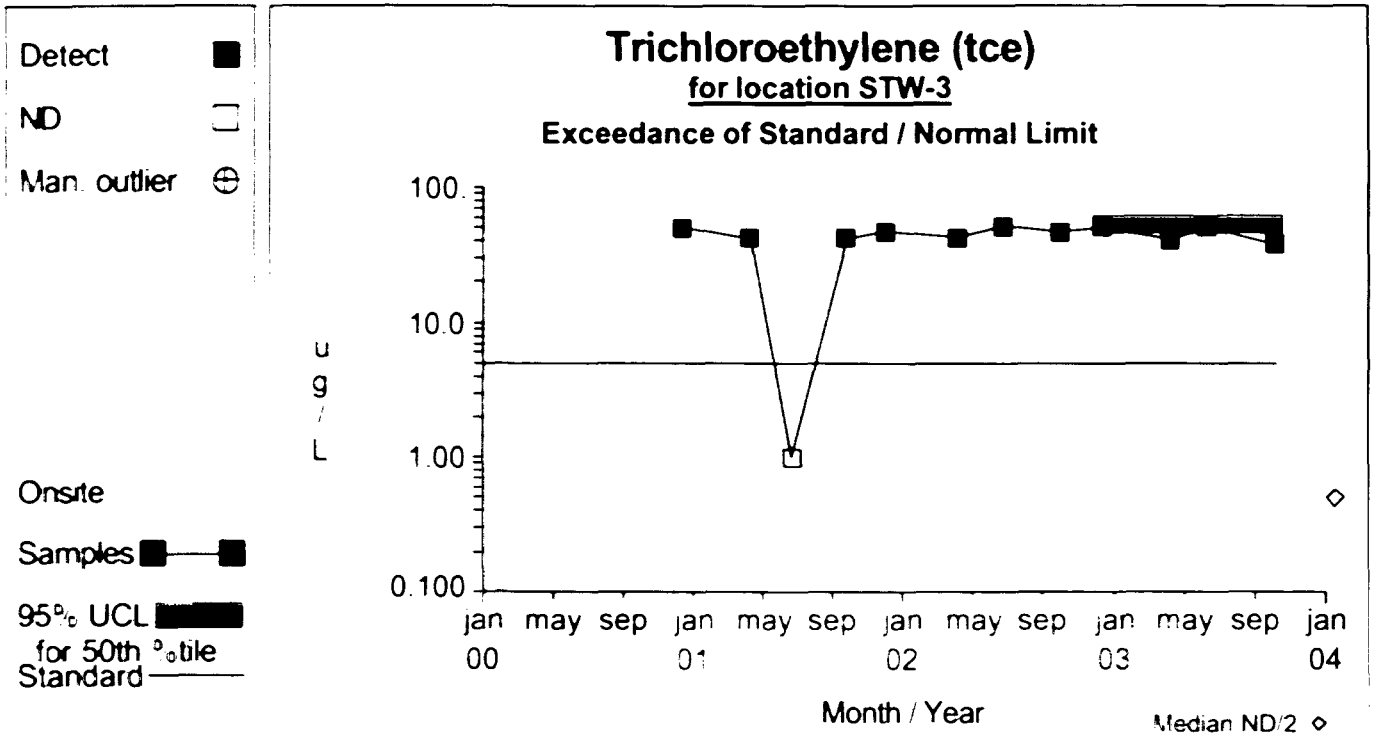


**Graph 196**



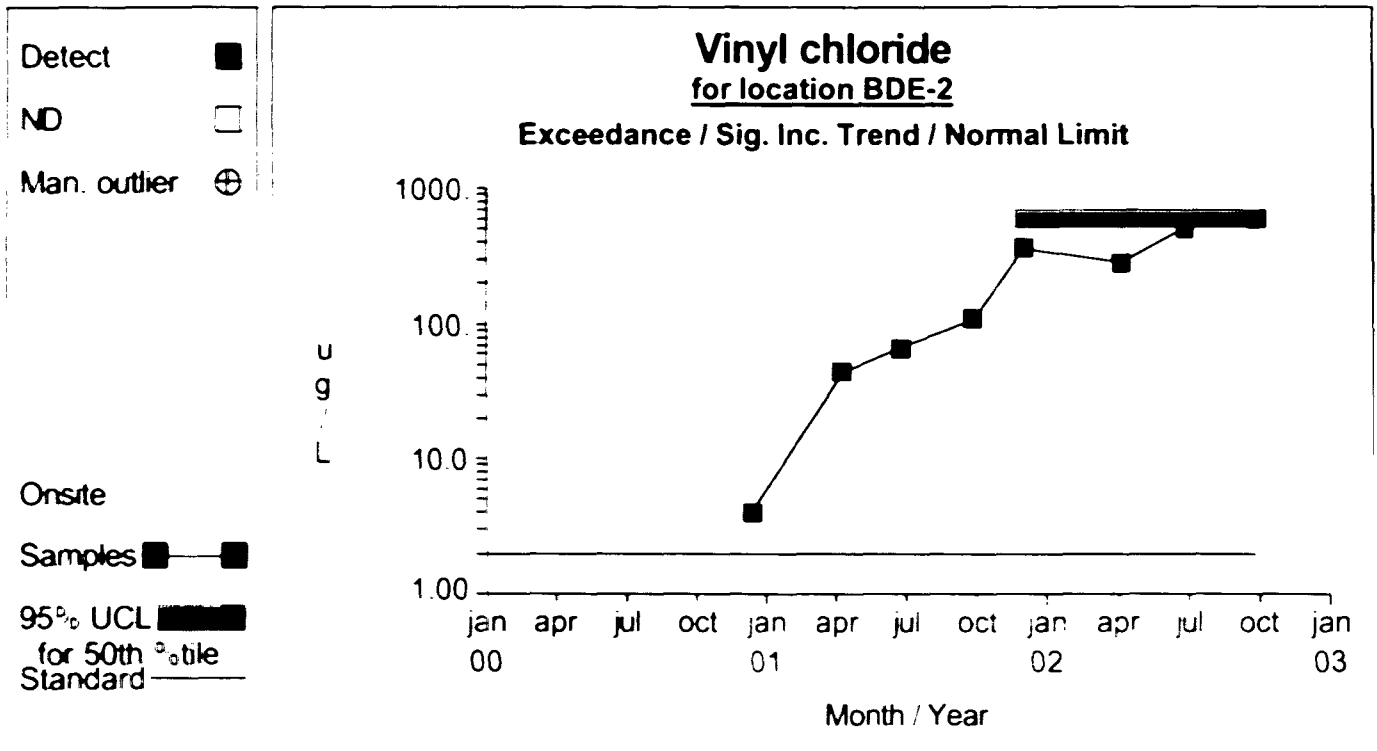
**Graph 199**

### Comparison to Standard

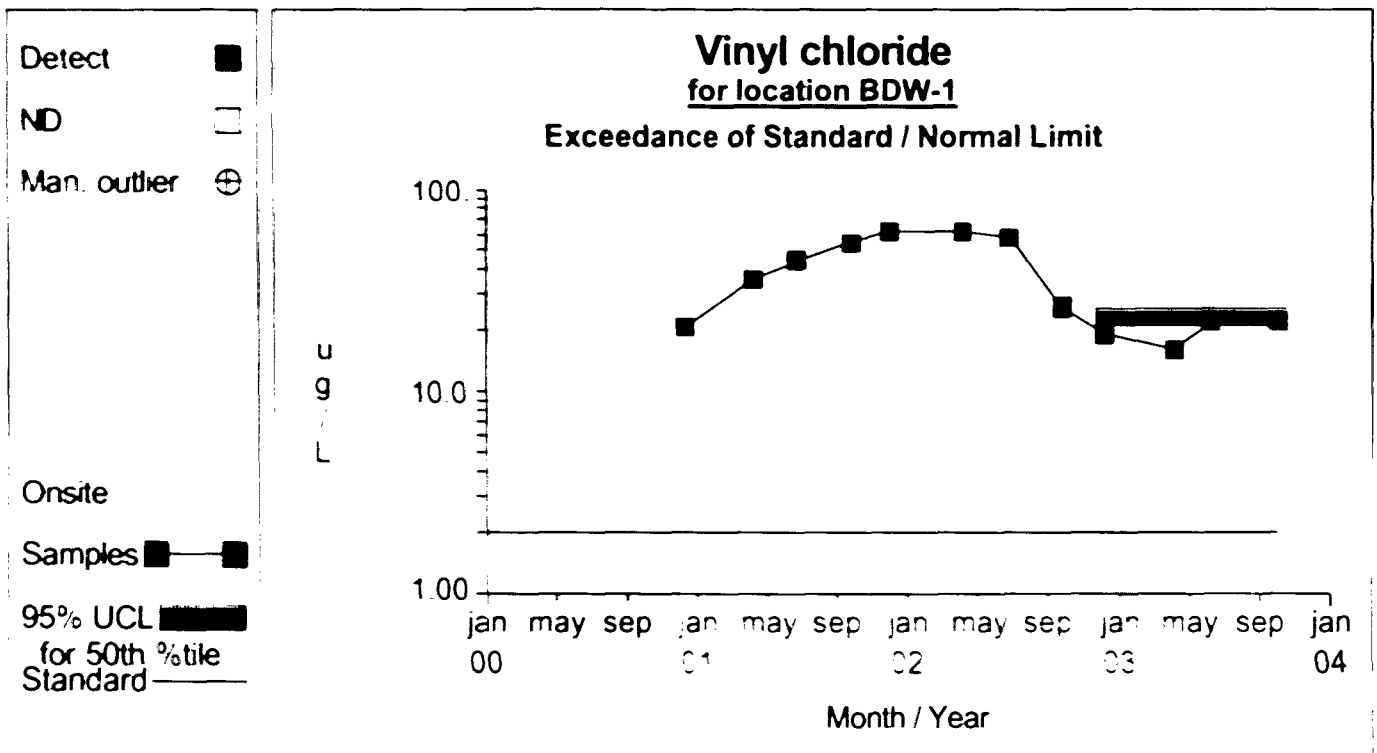


**Graph 200**

**Comparison to Standard**

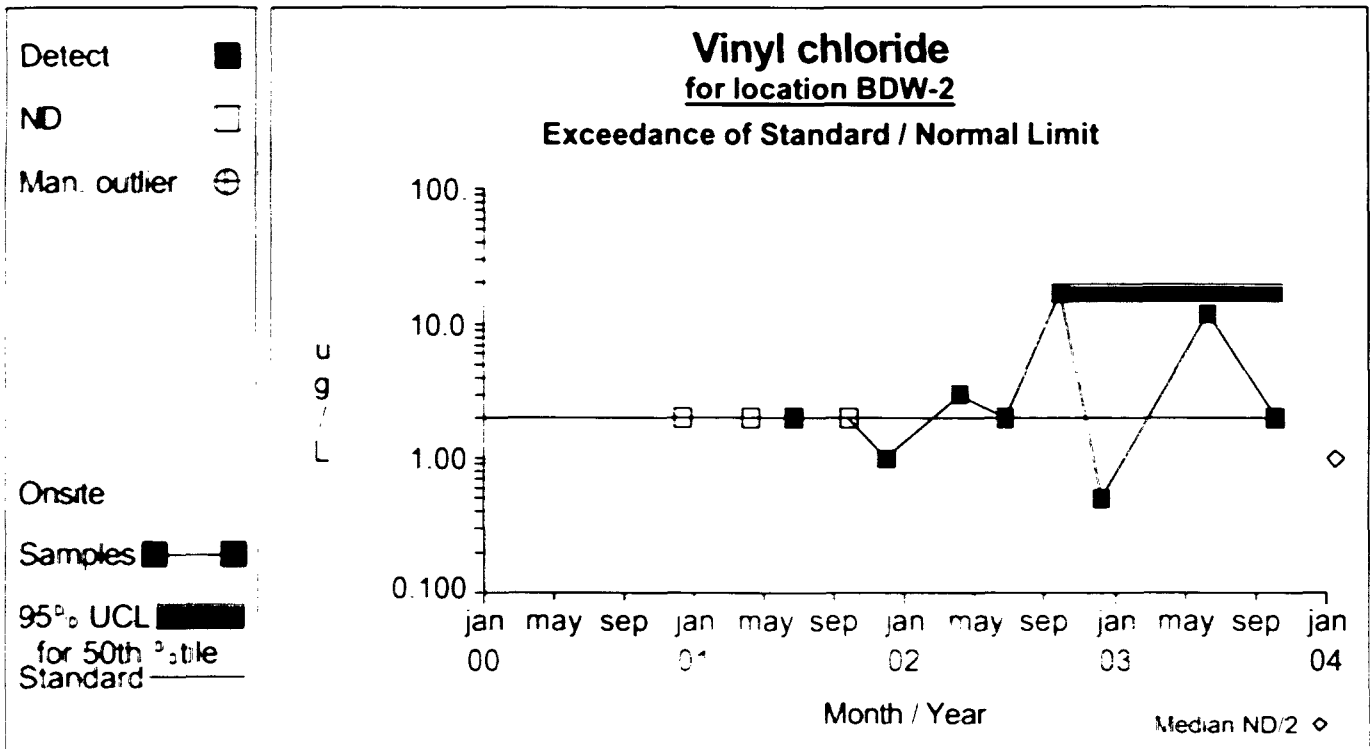


**Graph 202**

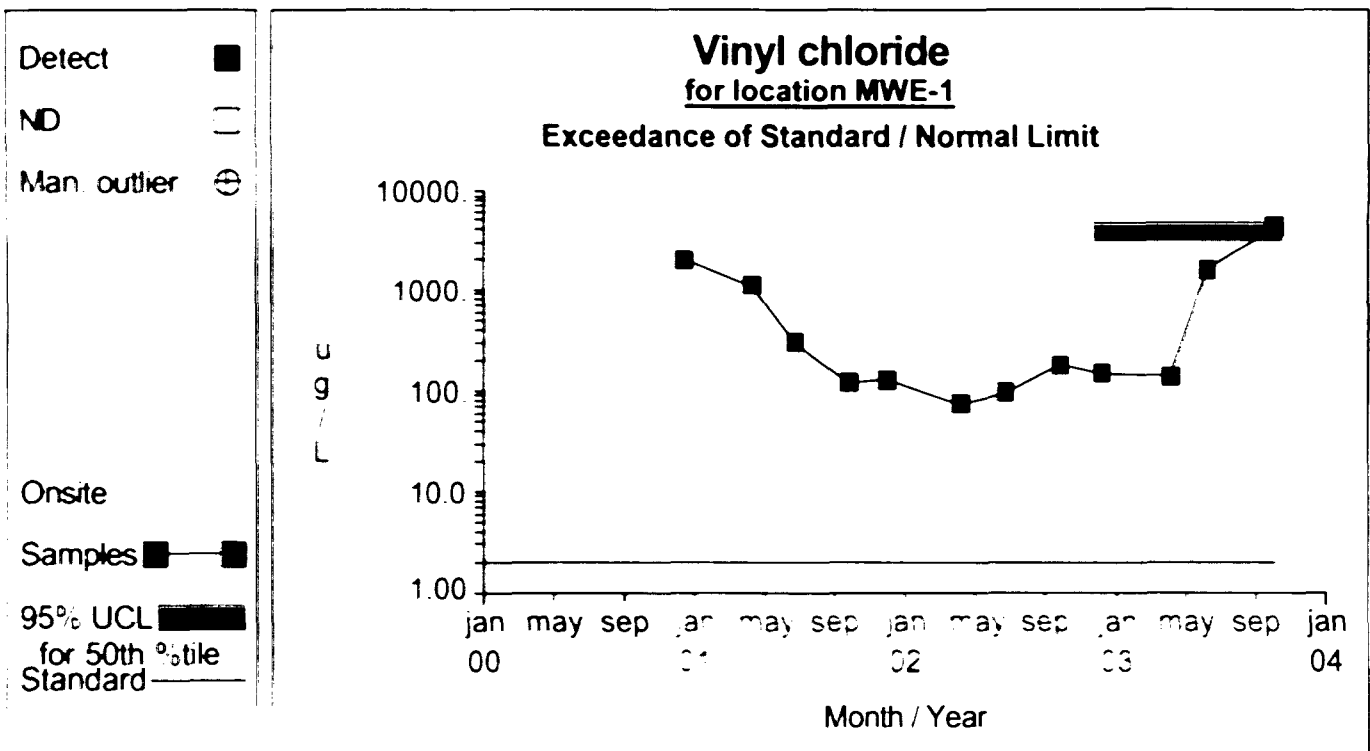


**Graph 203**

**Comparison to Standard**



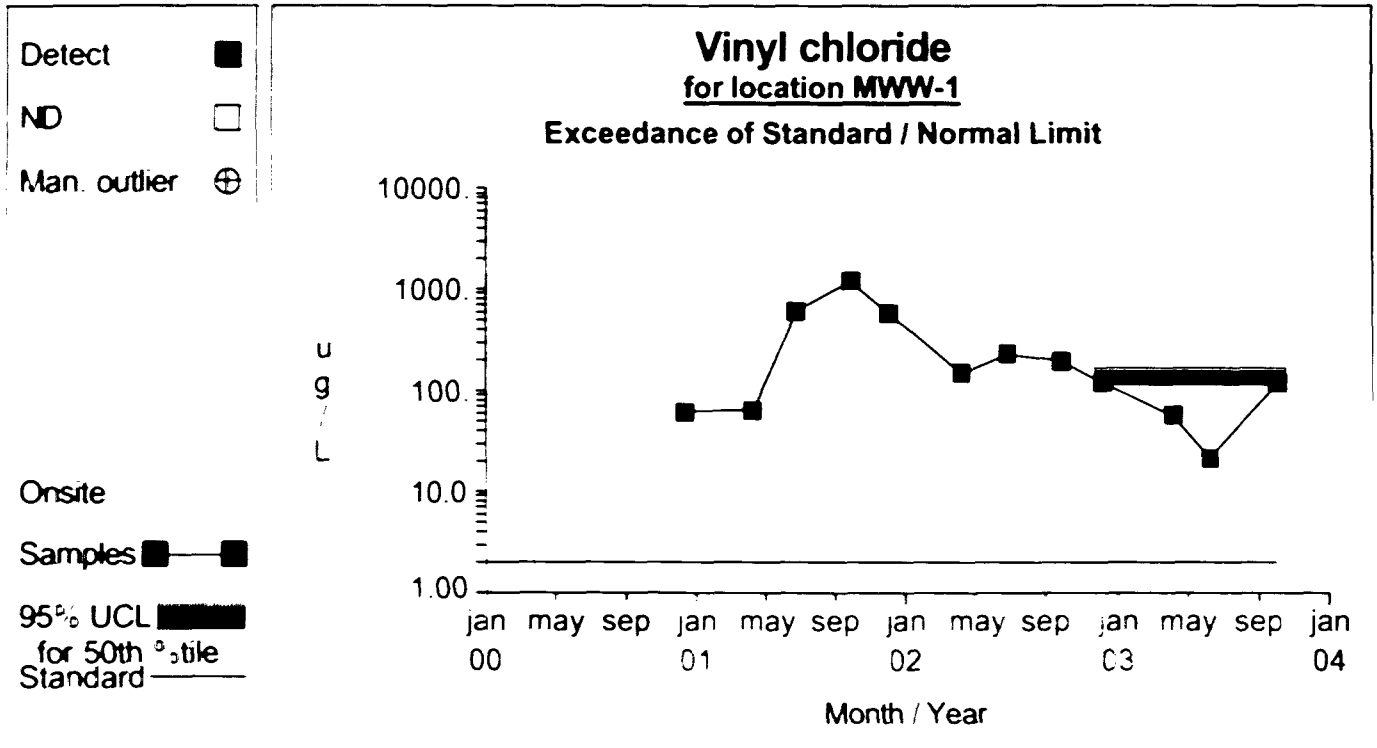
**Graph 204**



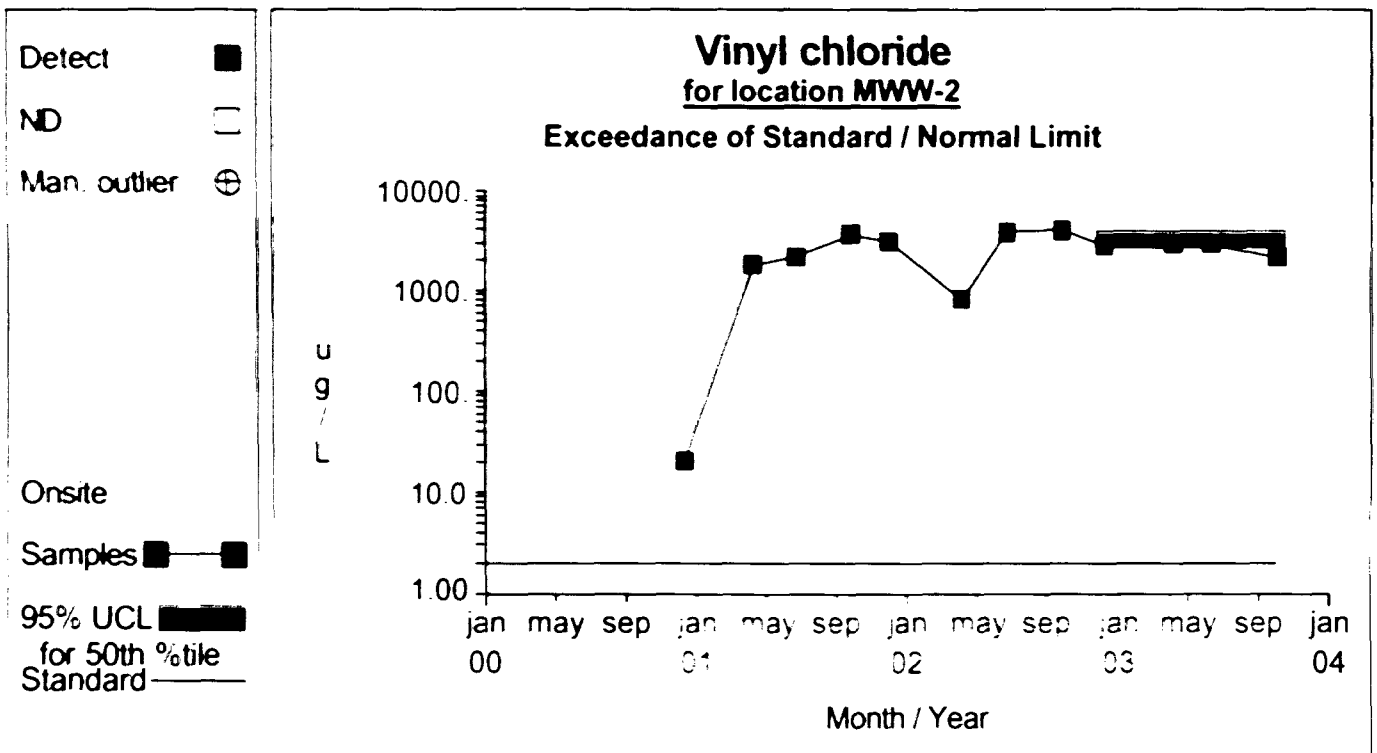
**Graph 207**



### Comparison to Standard

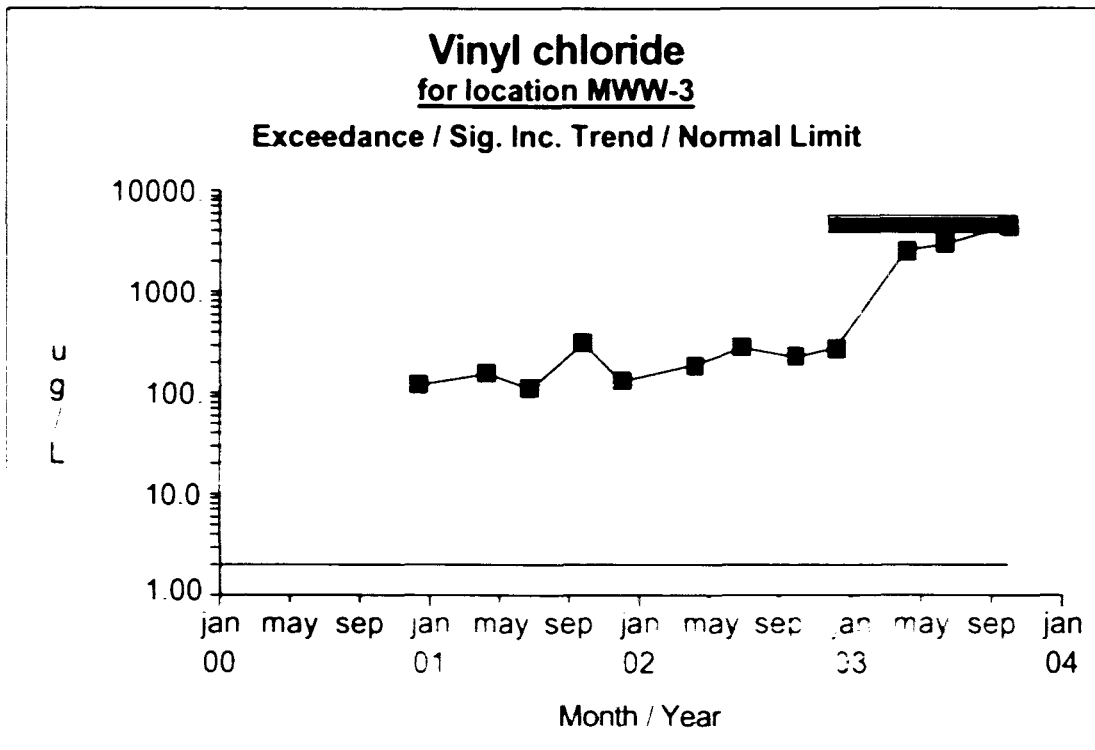


**Graph 209**

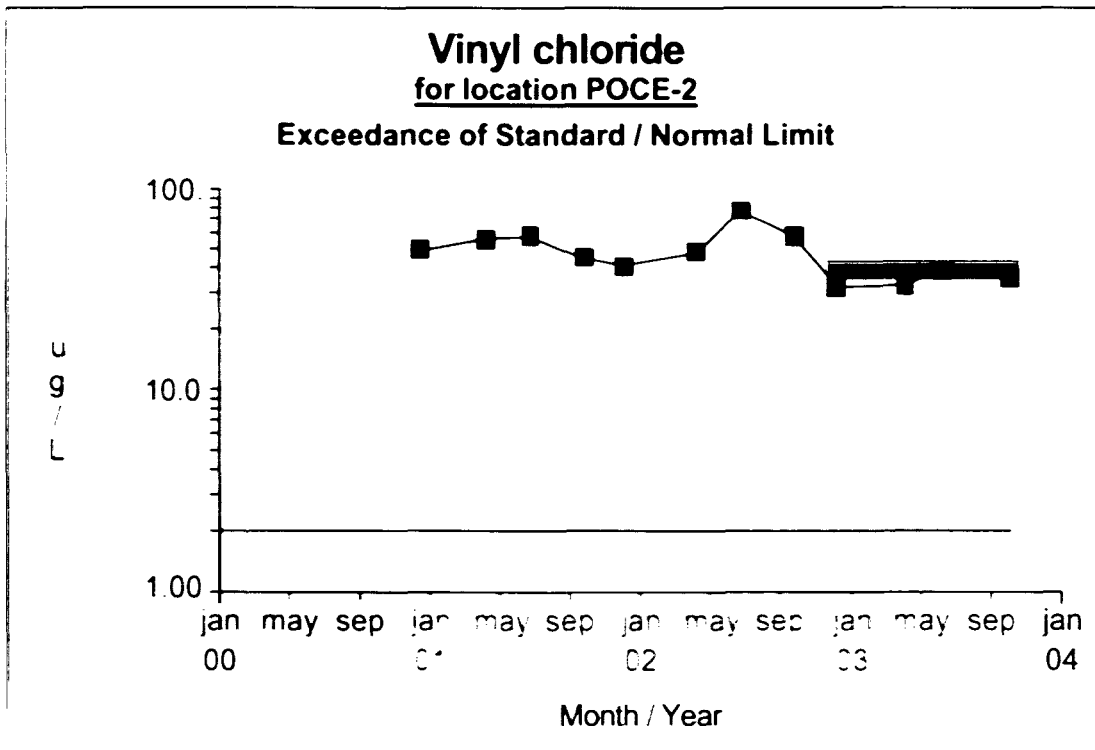
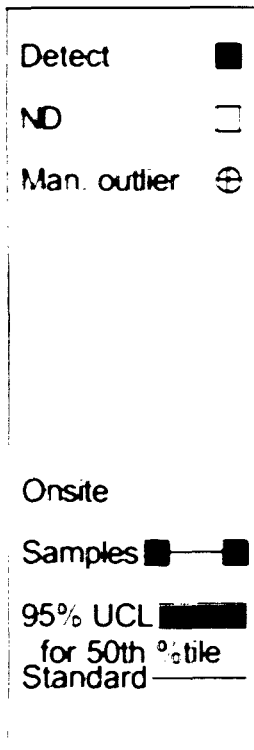


**Graph 210**

**Comparison to Standard**

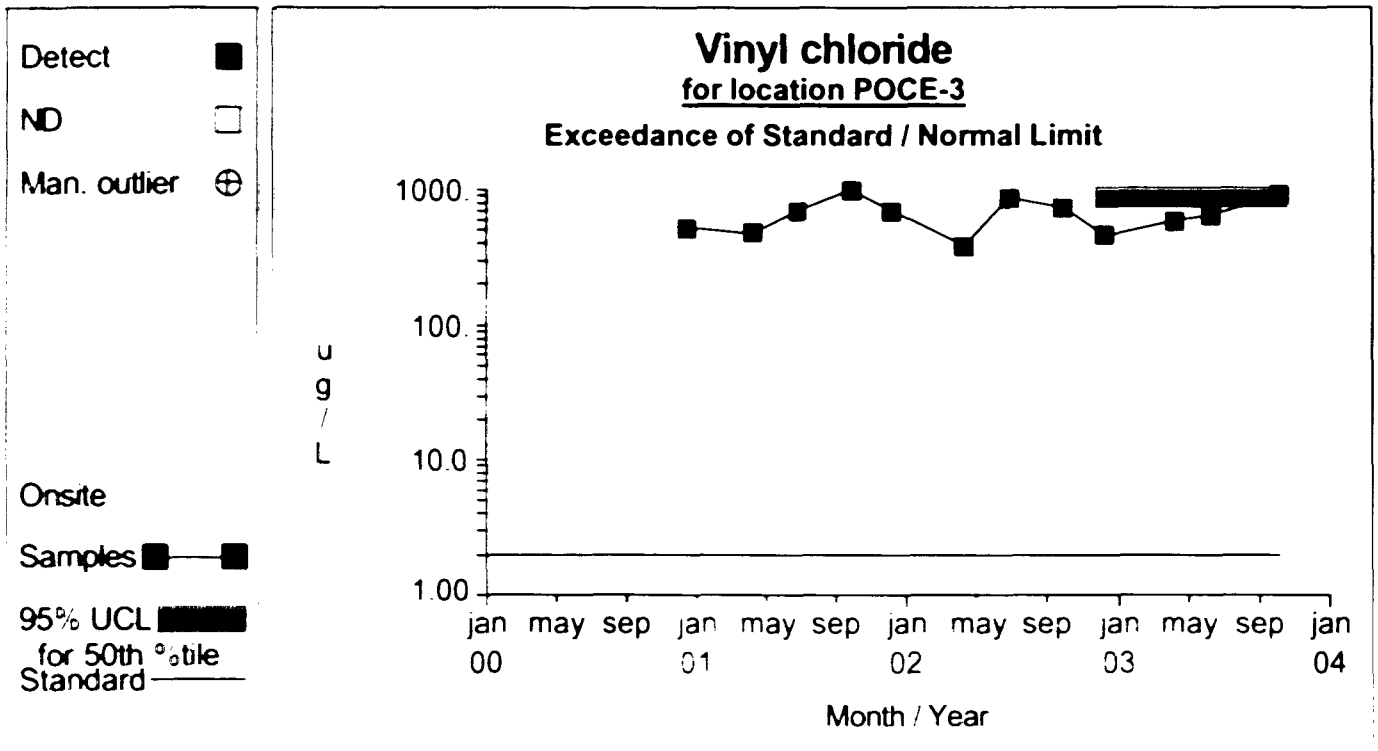


**Graph 211**

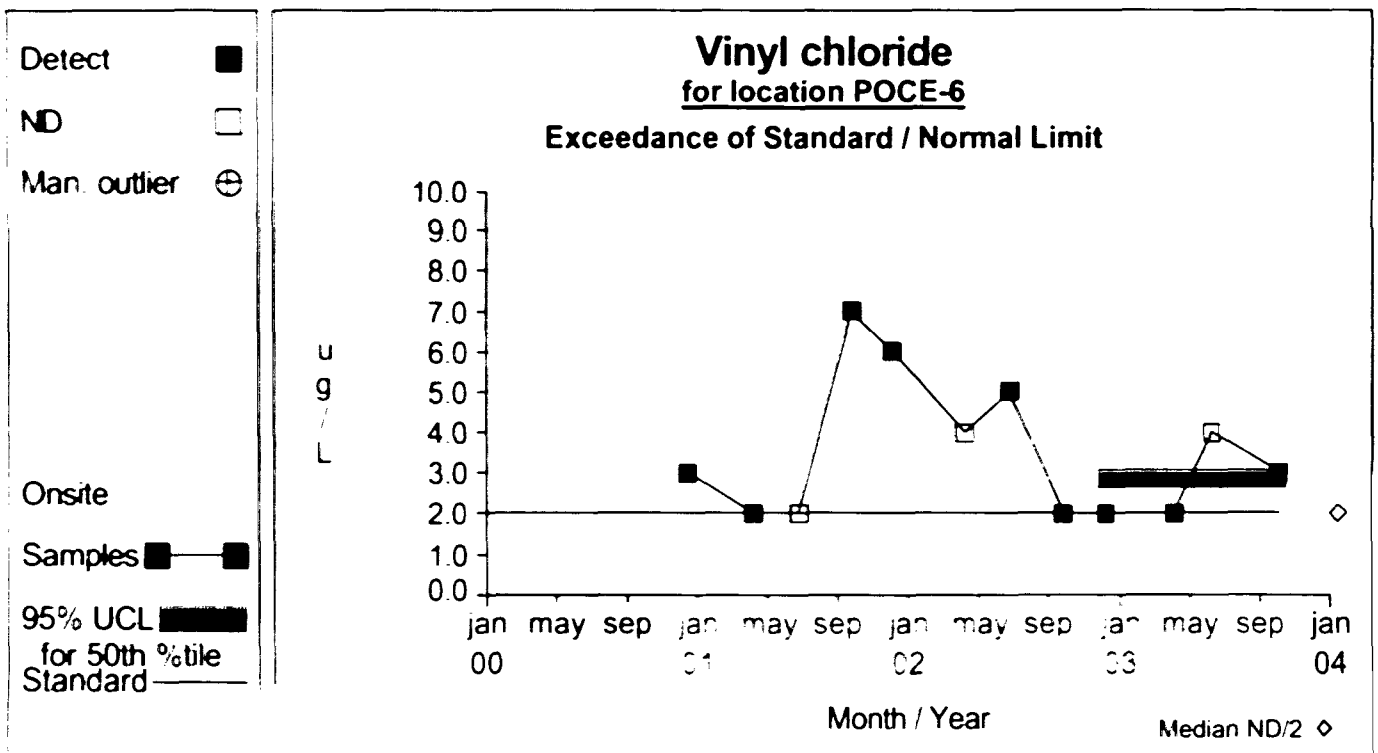


**Graph 215**

**Comparison to Standard**

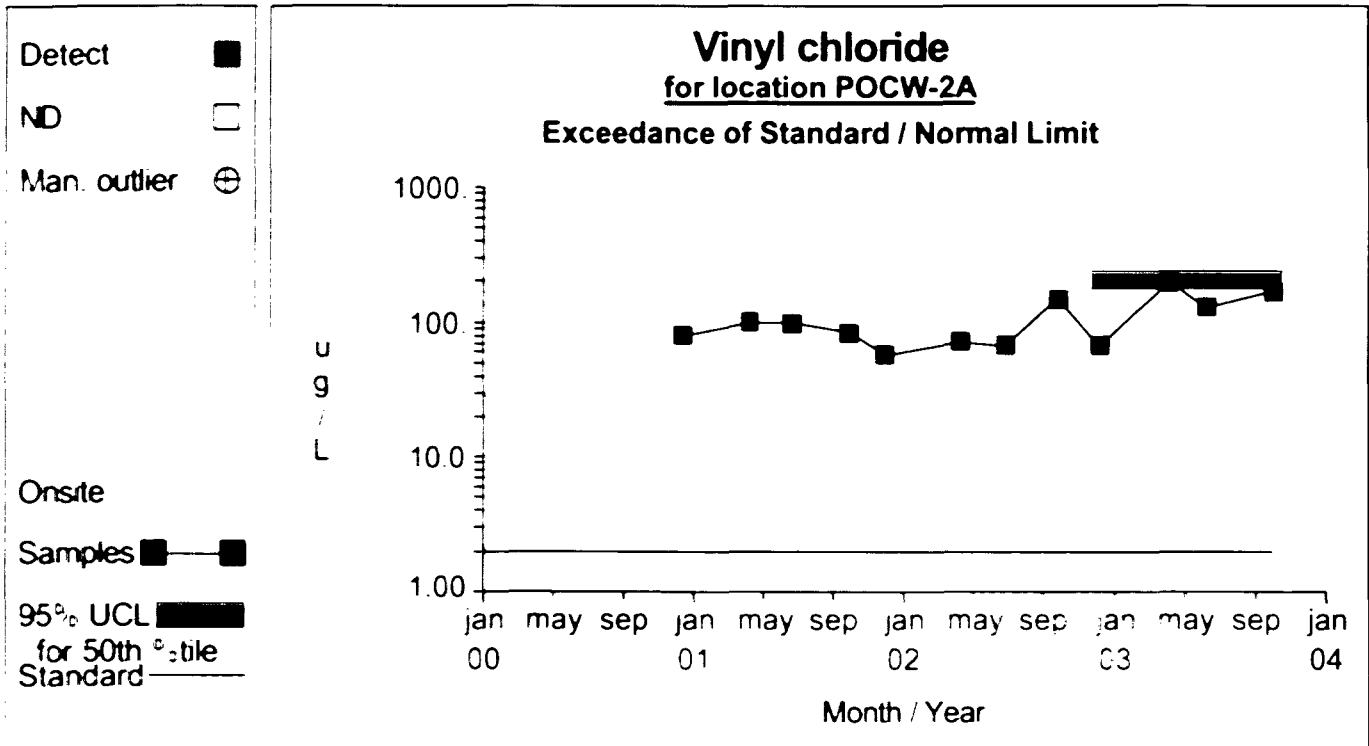


**Graph 216**

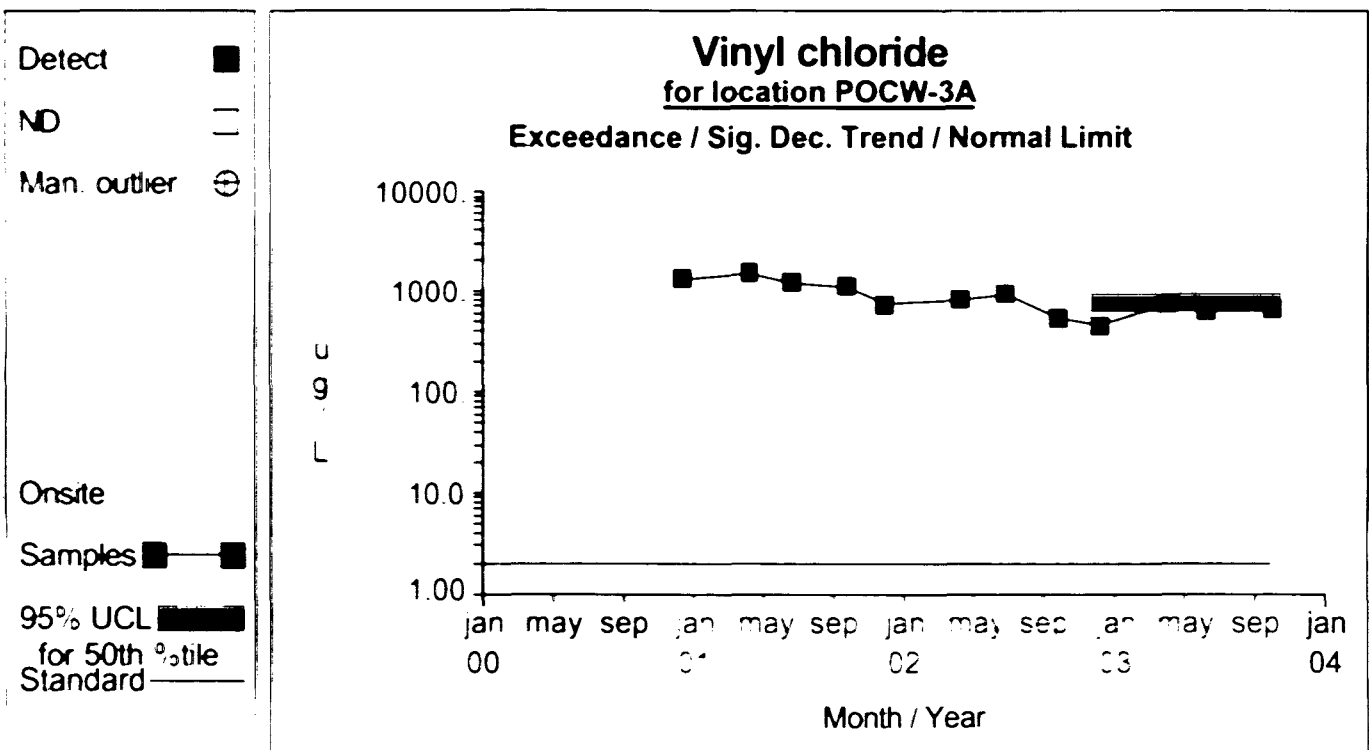


**Graph 219**

**Comparison to Standard**

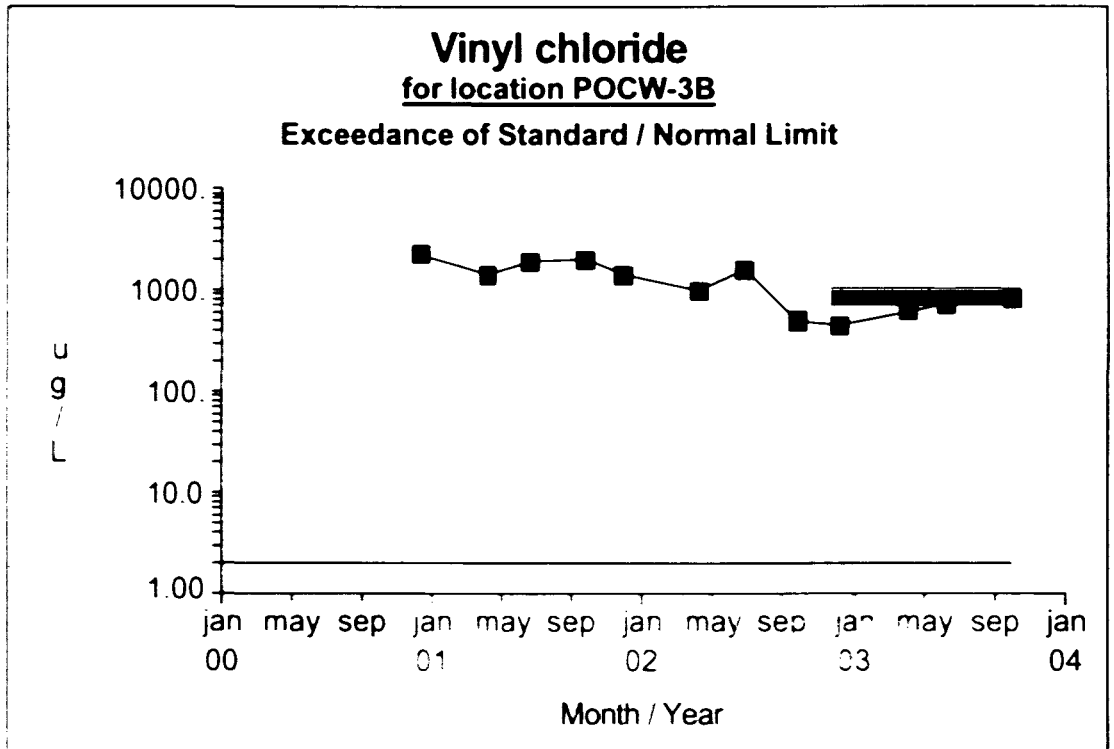


**Graph 223**

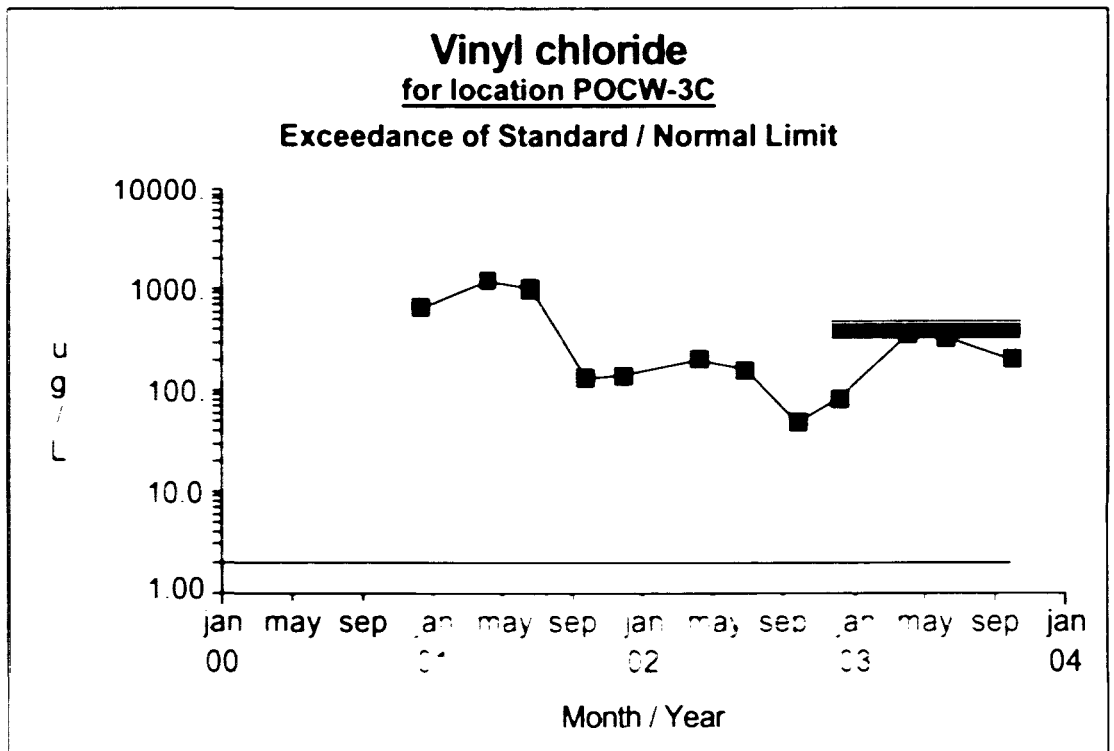
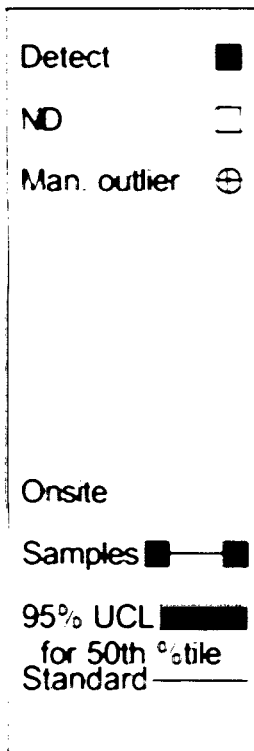


**Graph 225**

**Comparison to Standard**



**Graph 226**

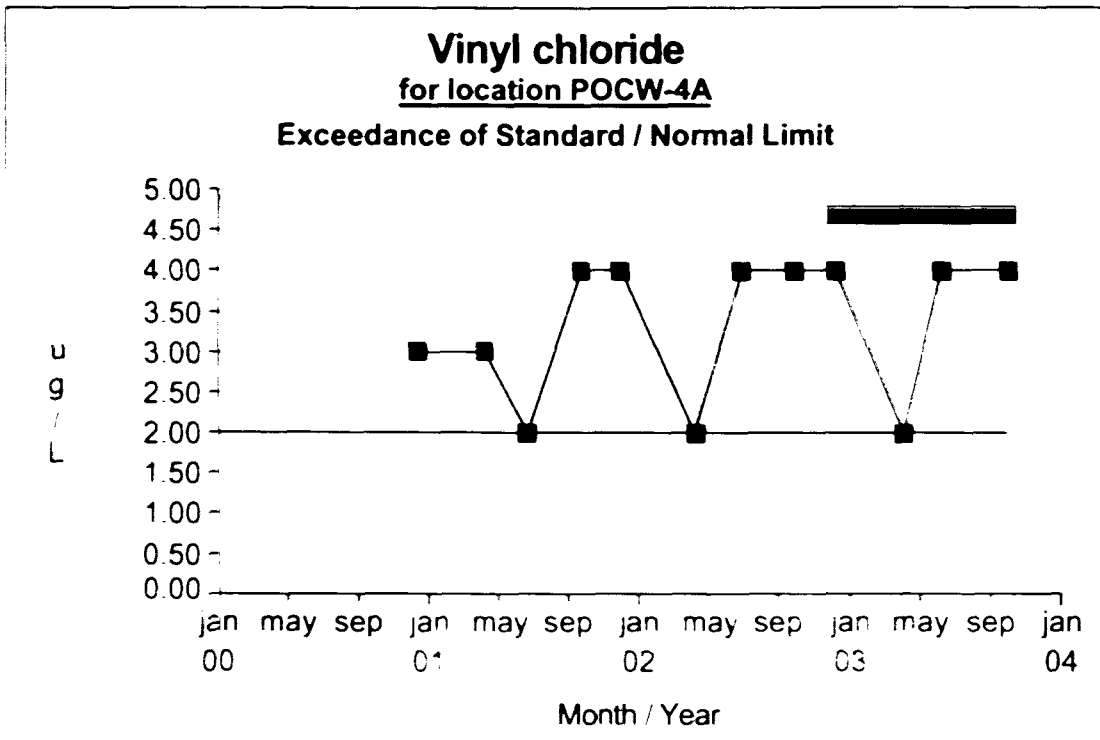


**Graph 227**

### Comparison to Standard

Detect   
 ND   
 Man. outlier

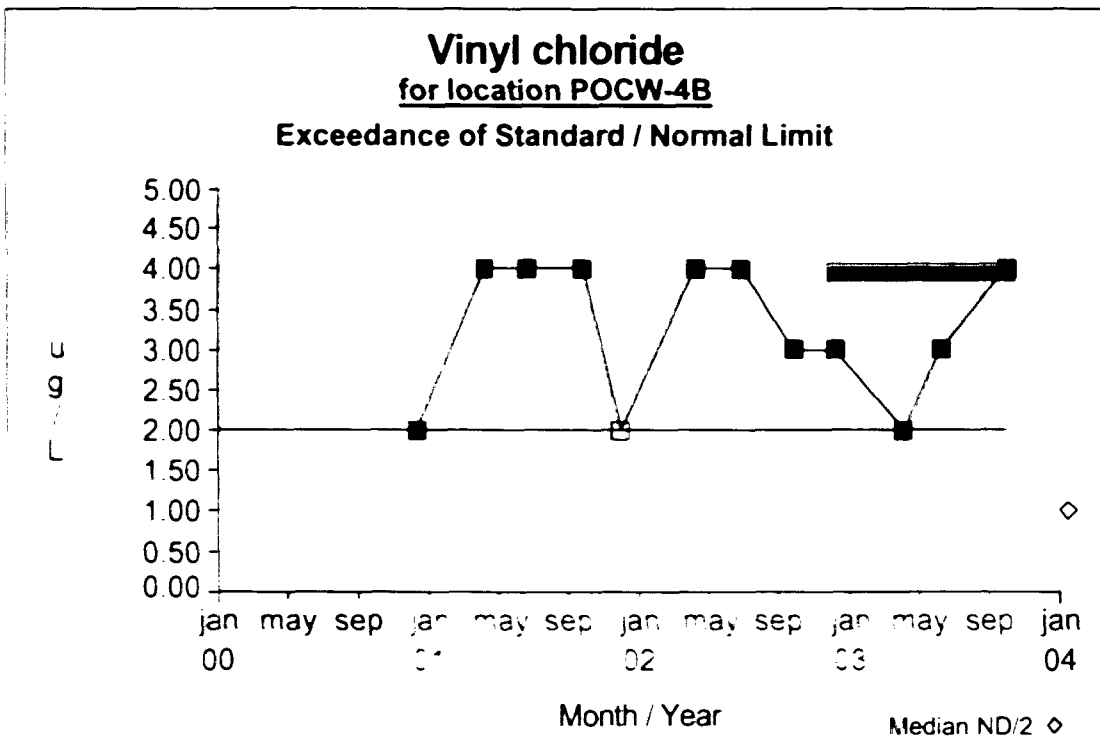
Onsite  
 Samples  —   
 95% UCL for 50th %tile   
 Standard



**Graph 228**

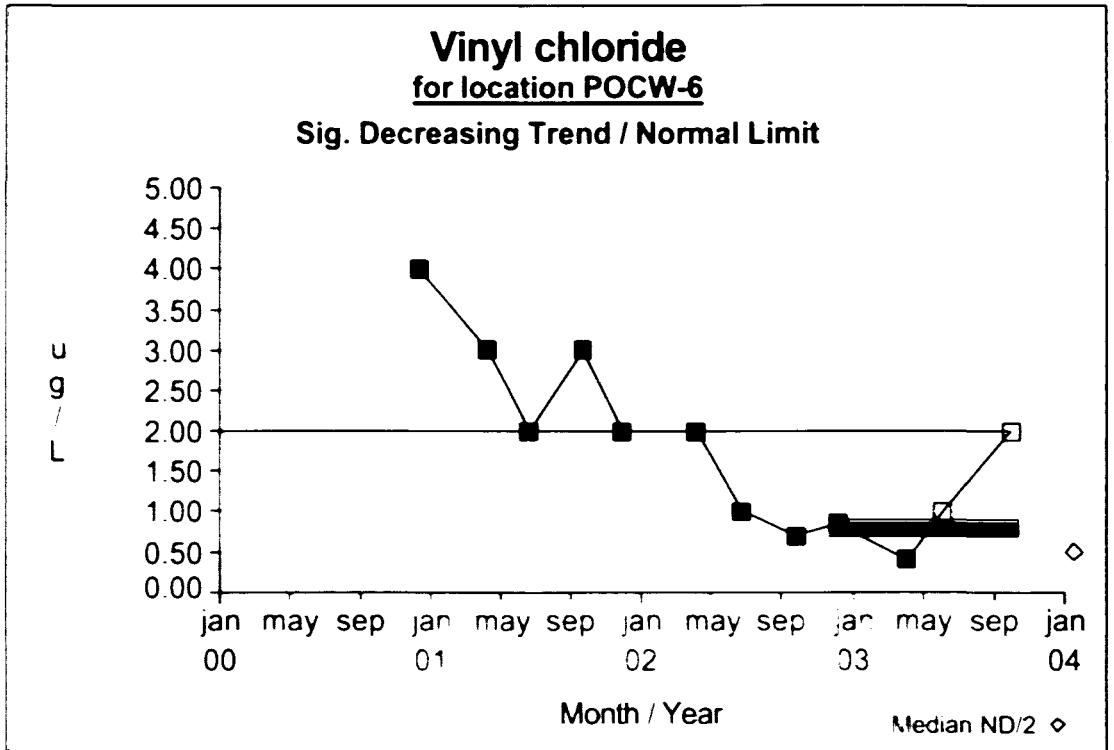
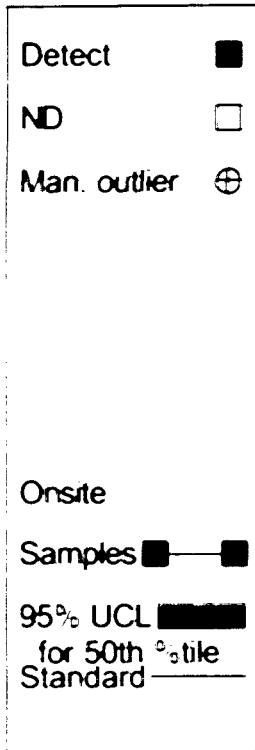
Detect   
 ND   
 Man. outlier

Onsite  
 Samples  —   
 95% UCL for 50th %tile   
 Standard

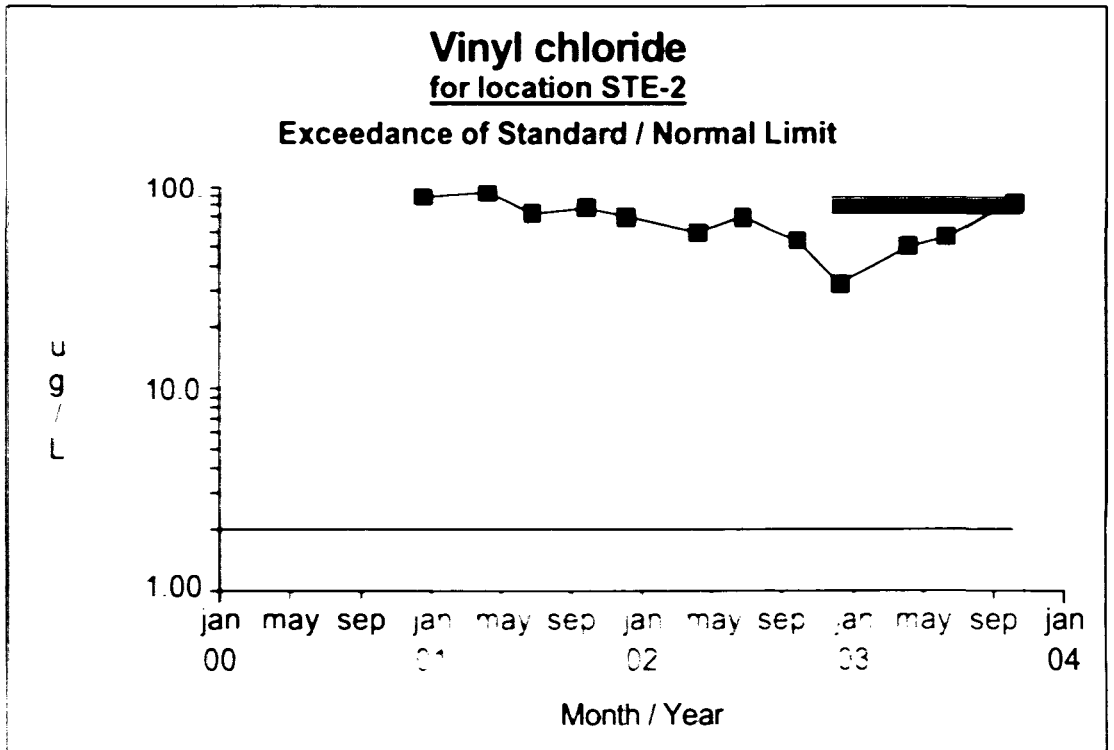


**Graph 229**

**Comparison to Standard**

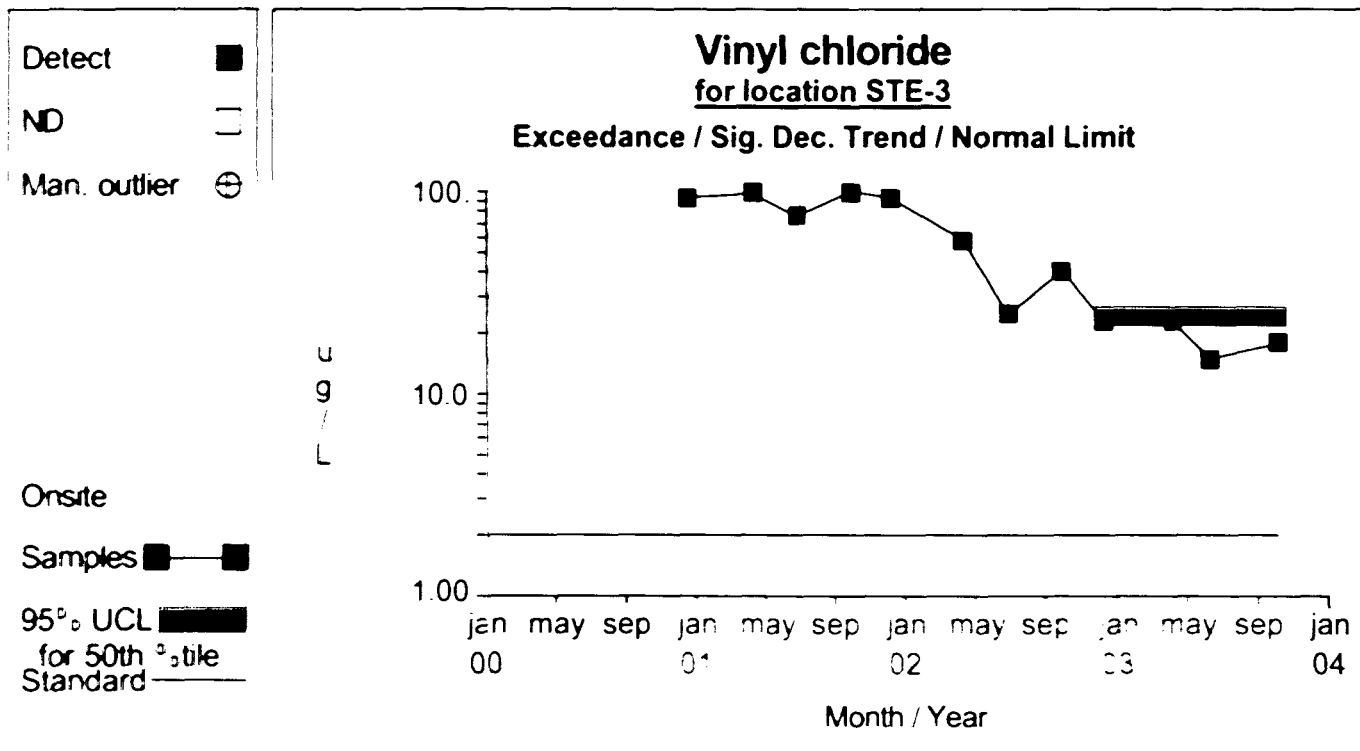


**Graph 233**

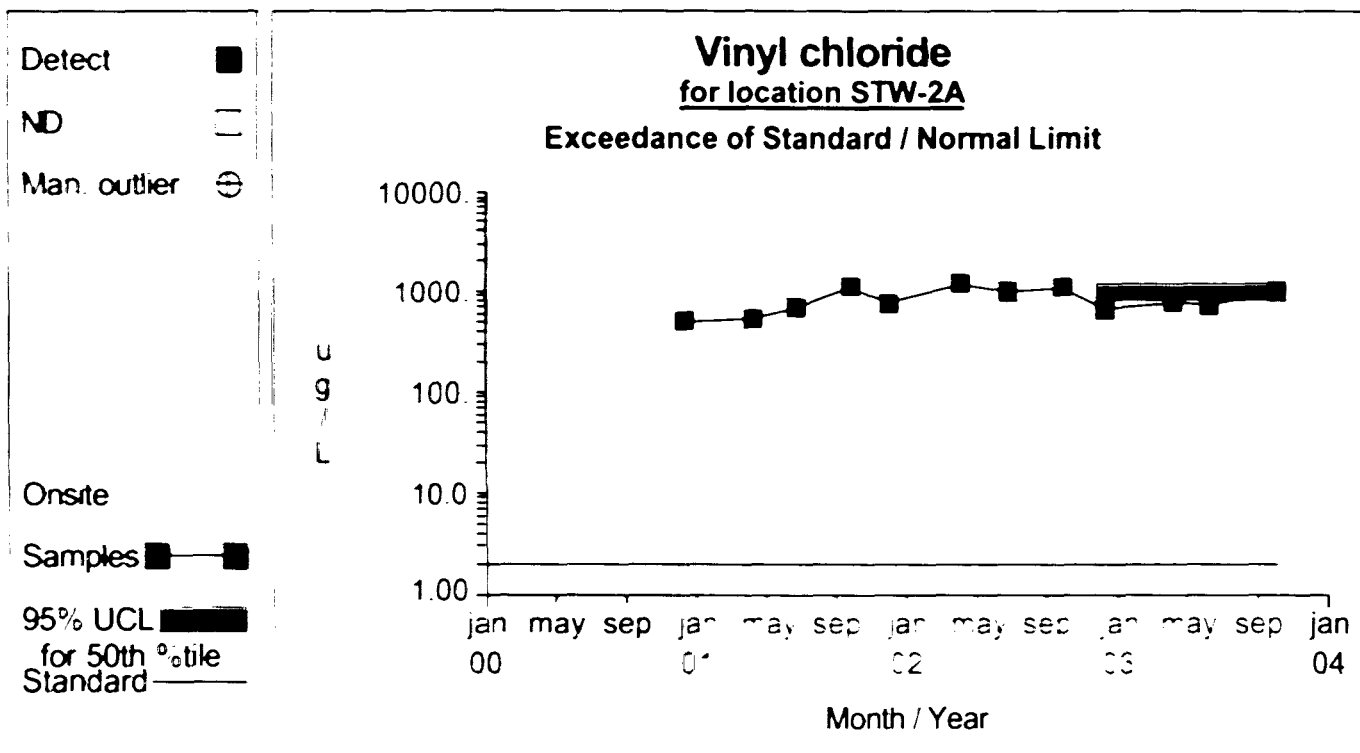


**Graph 235**

### Comparison to Standard



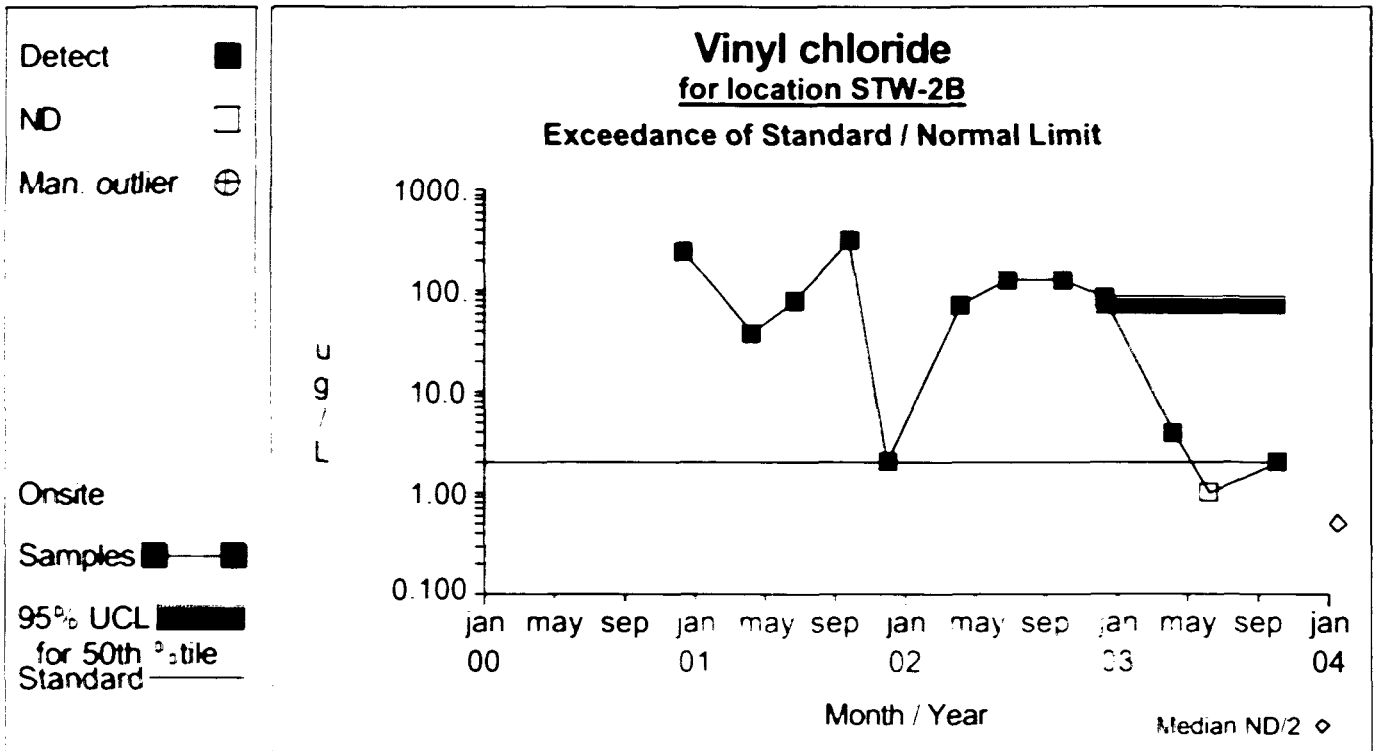
**Graph 236**



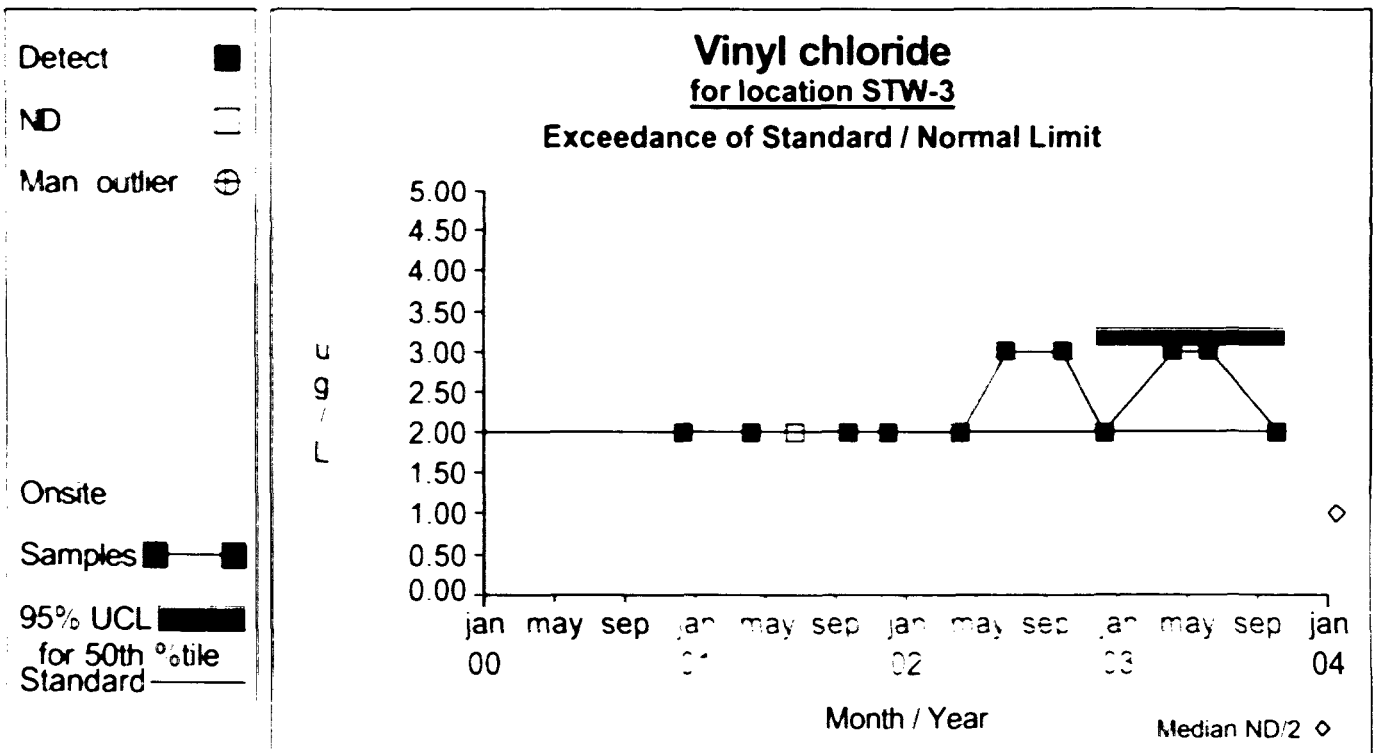
**Graph 238**



**Comparison to Standard**

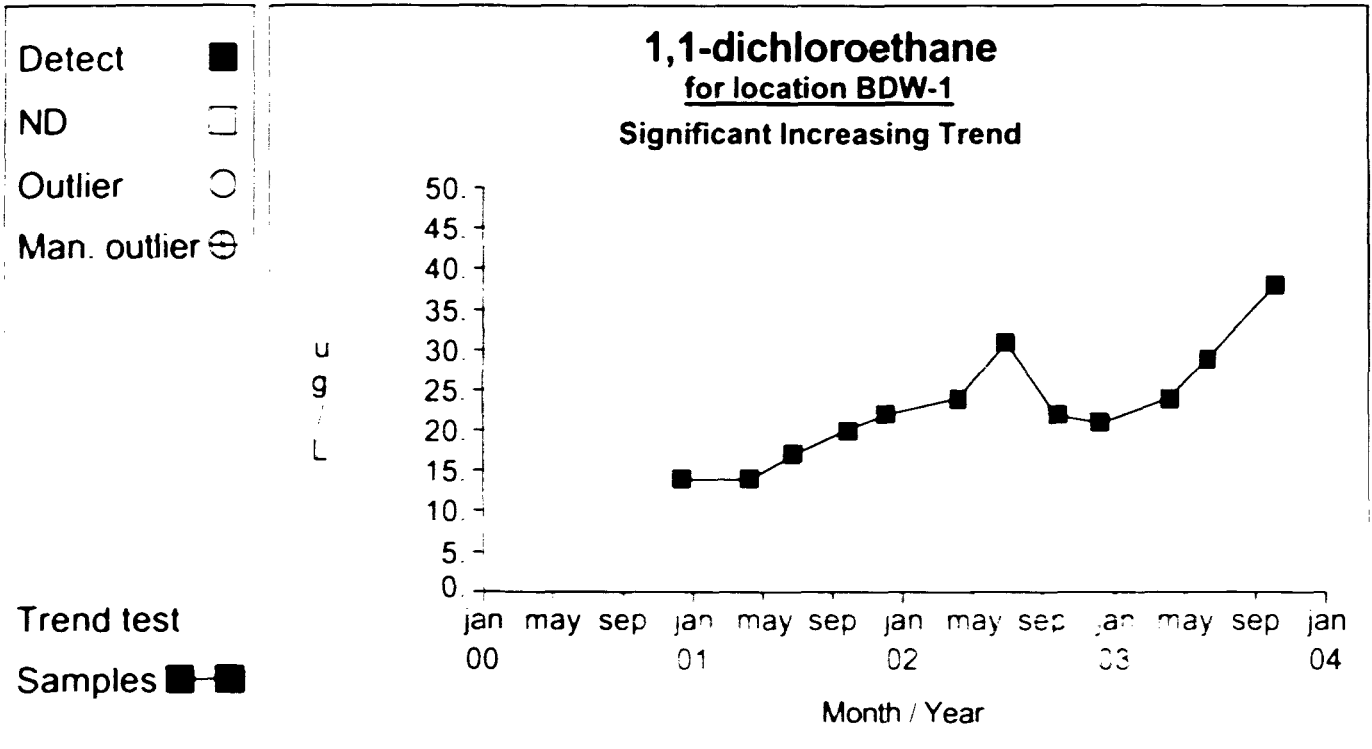


**Graph 239**

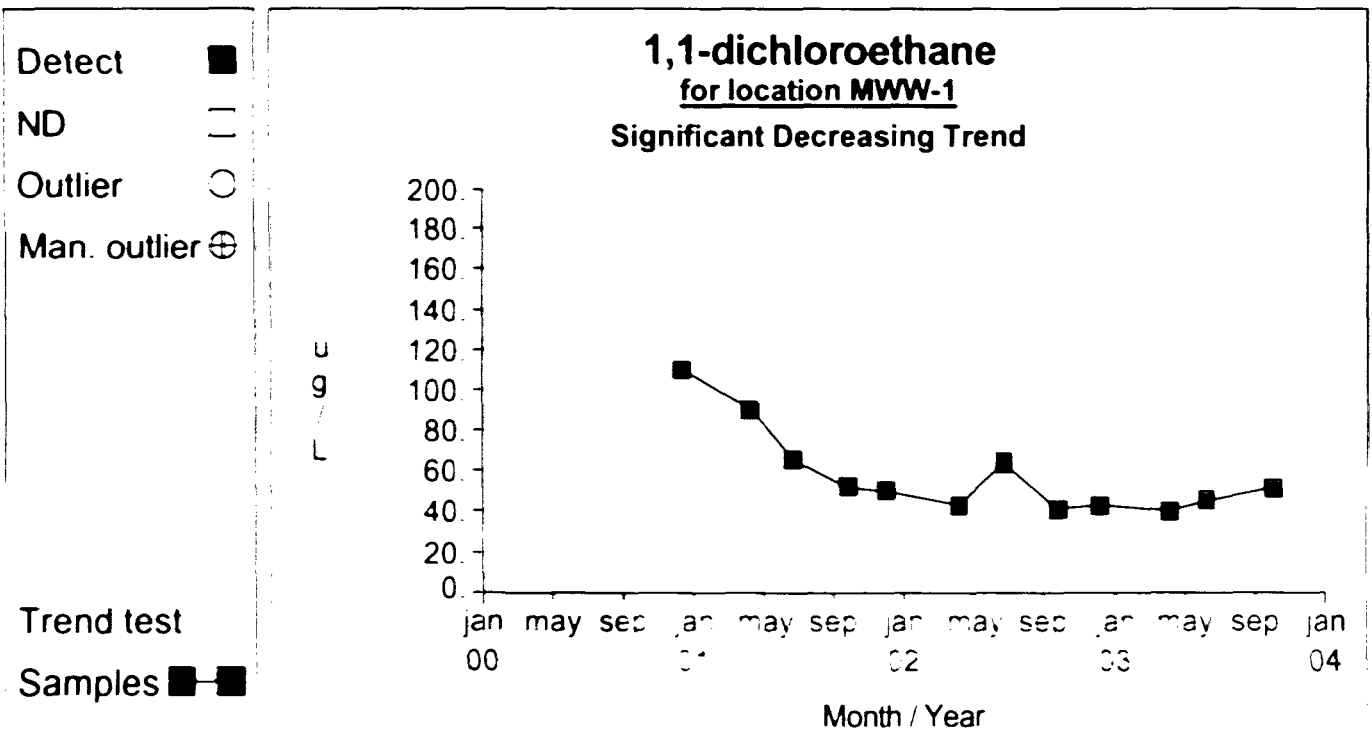


**Graph 240**

### Time Series



Graph 43

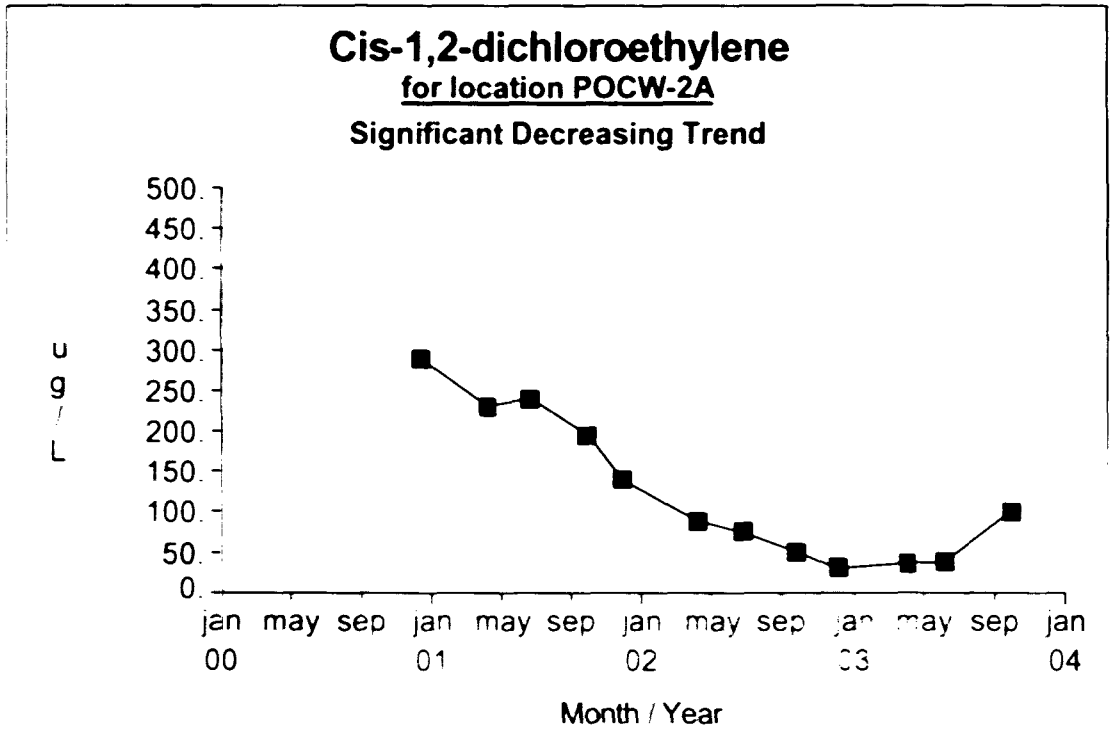


Graph 49

### Time Series

Detect    
 ND    
 Outlier    
 Man. outlier

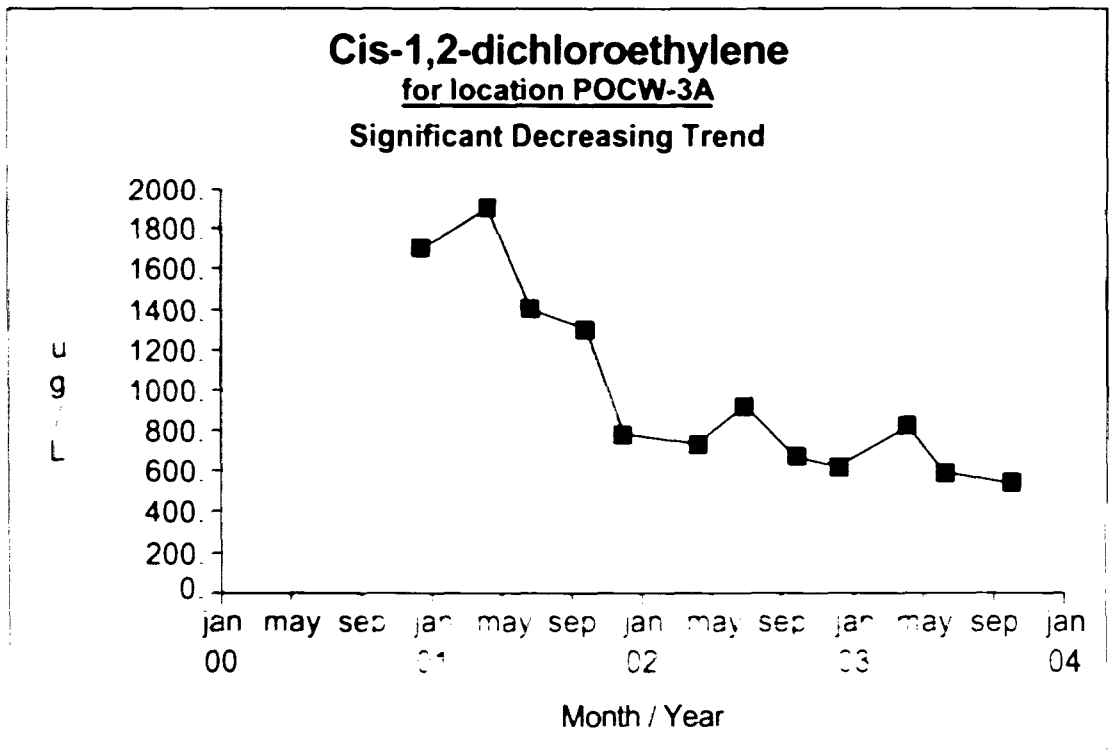
Trend test   
 Samples



Graph 143

Detect    
 ND    
 Outlier    
 Man. outlier

Trend test   
 Samples



Graph 145

**Time Series**

Detect

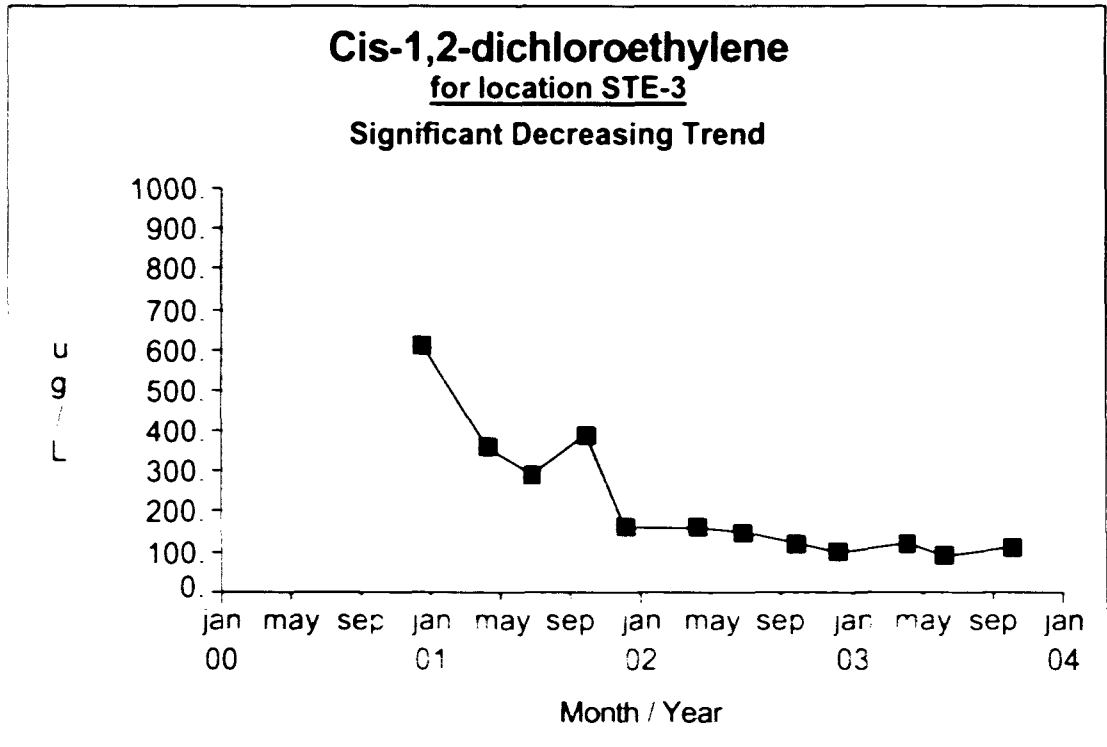
ND

Outlier

Man. outlier

Trend test

Samples



**Graph 156**

Detect

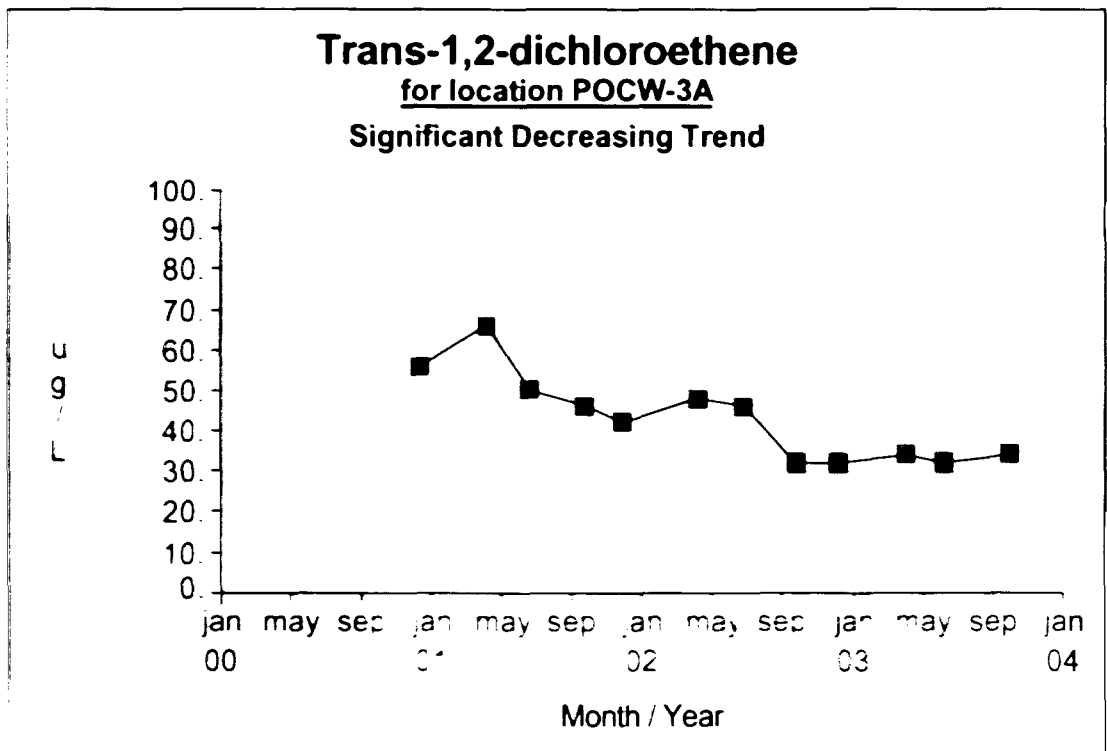
ND

Outlier

Man. outlier

Trend test

Samples



**Graph 185**

**Time Series**

Detect

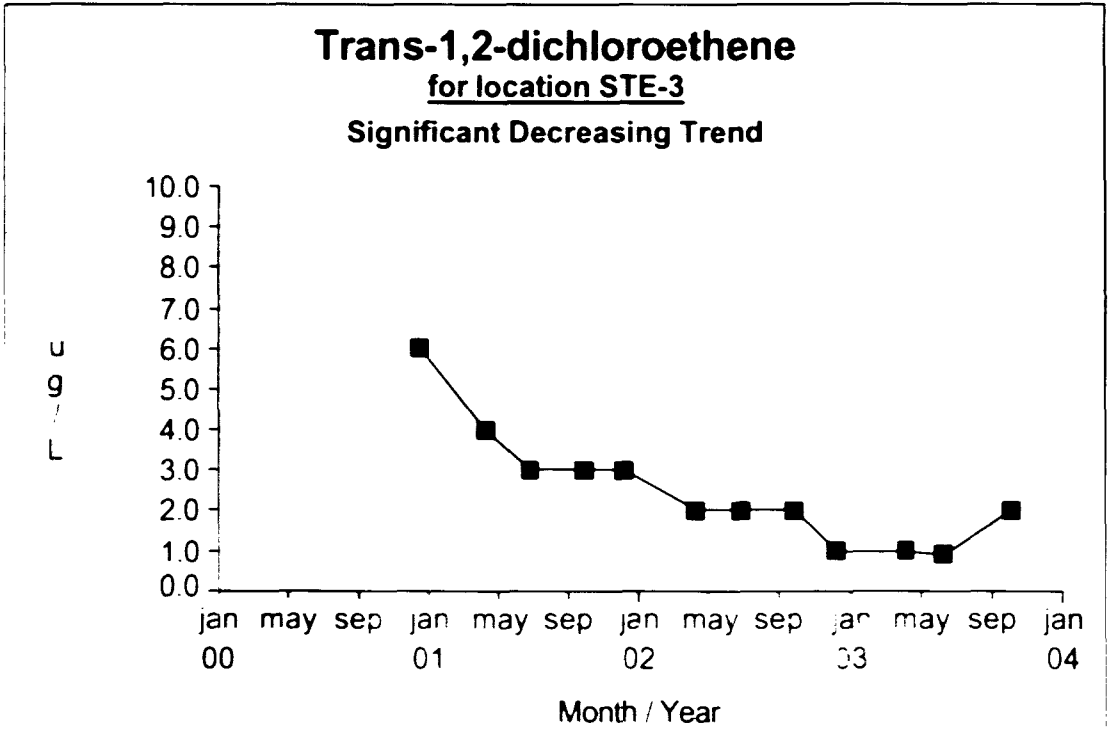
ND

Outlier

Man. outlier

Trend test

Samples



**Graph 196**

Detect

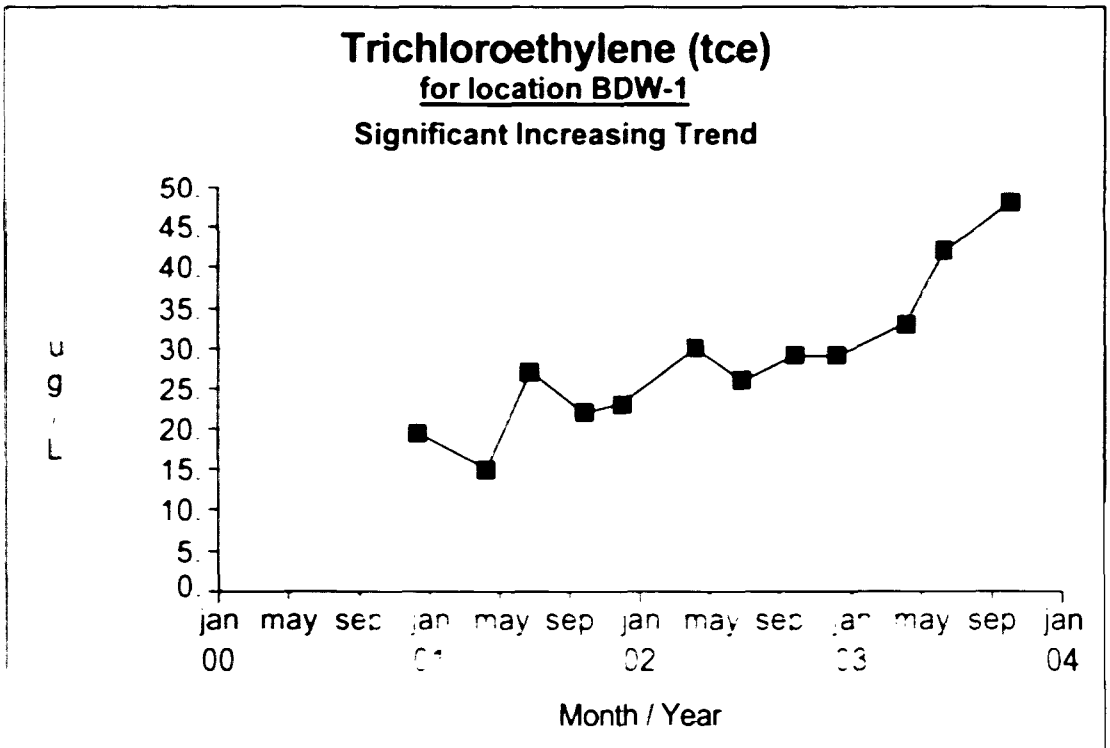
ND

Outlier

Man. outlier

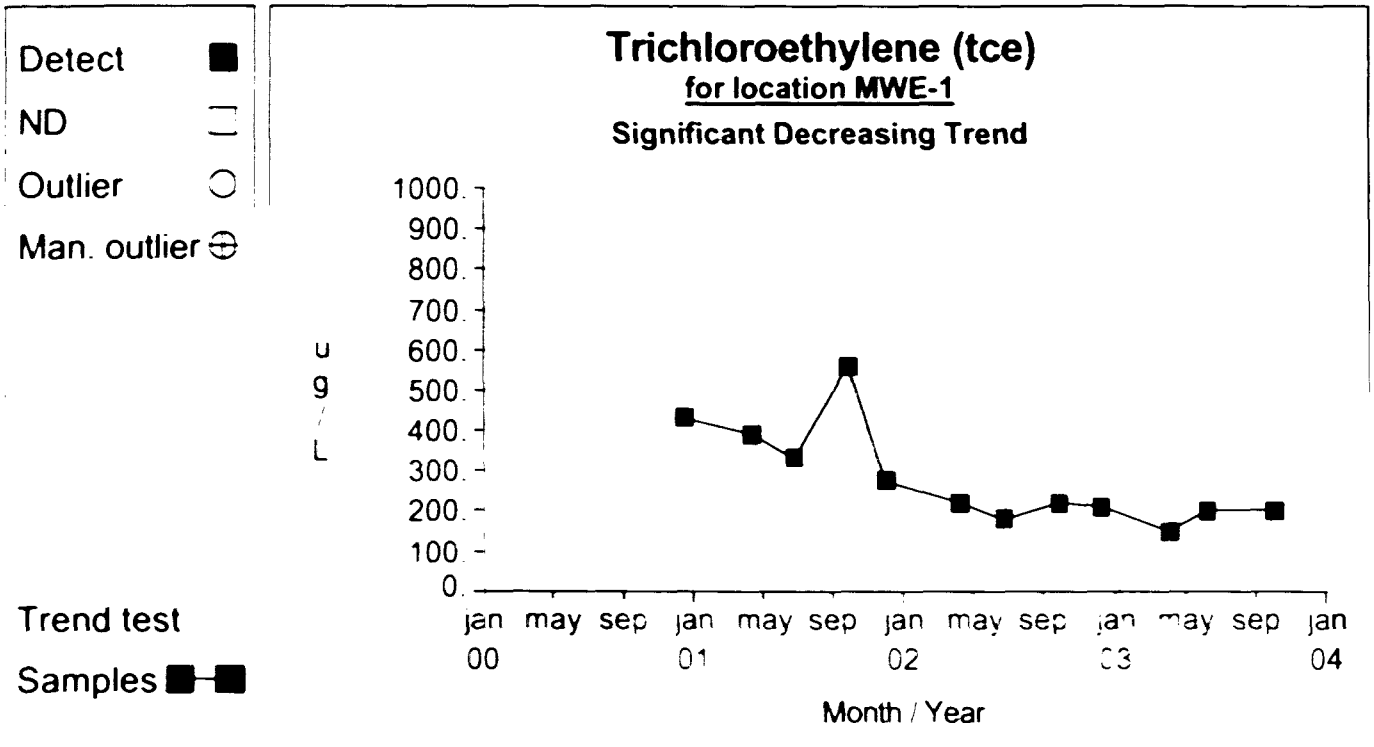
Trend test

Samples

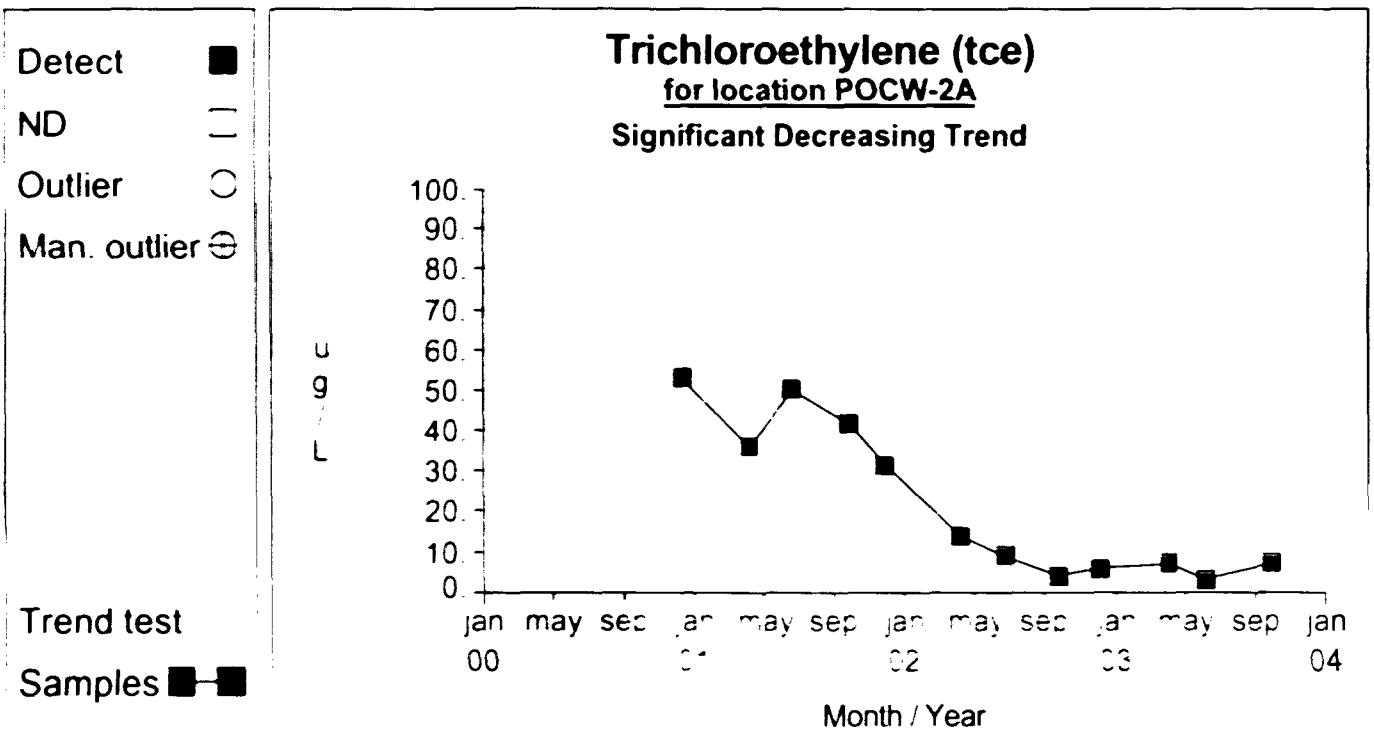


**Graph 203**

**Time Series**



**Graph 207**



**Graph 223**

**Time Series**

Detect

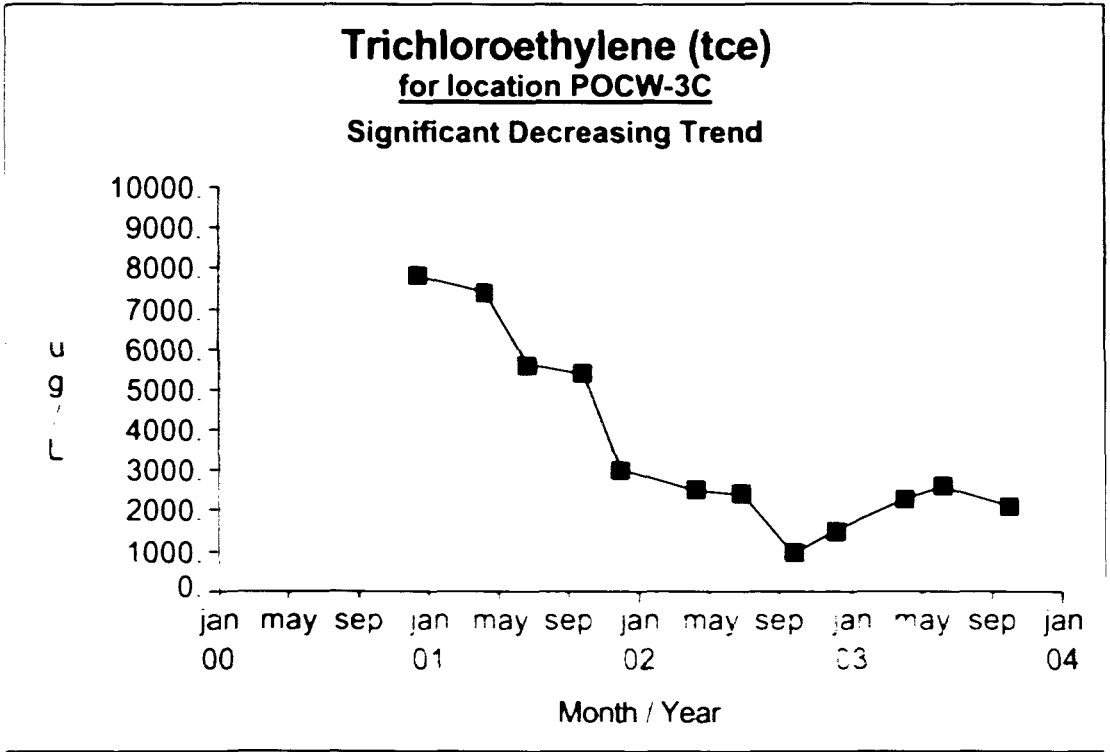
ND

Outlier

Man. outlier

Trend test

Samples



**Graph 227**

Detect

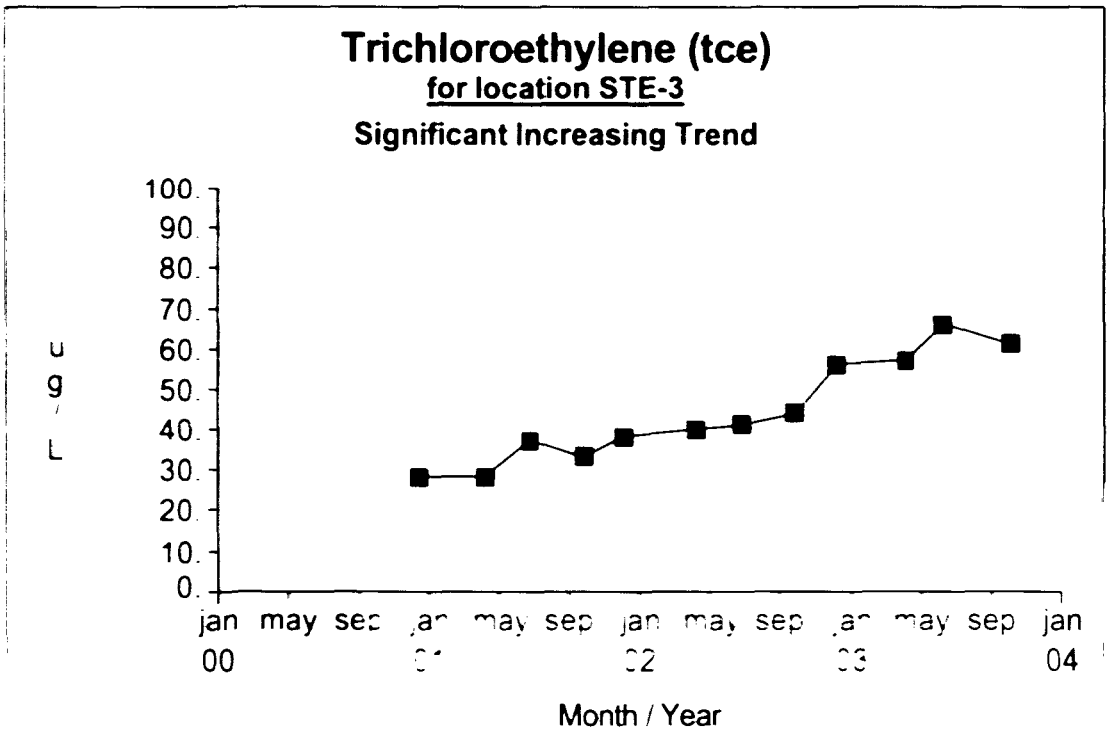
ND

Outlier

Man. outlier

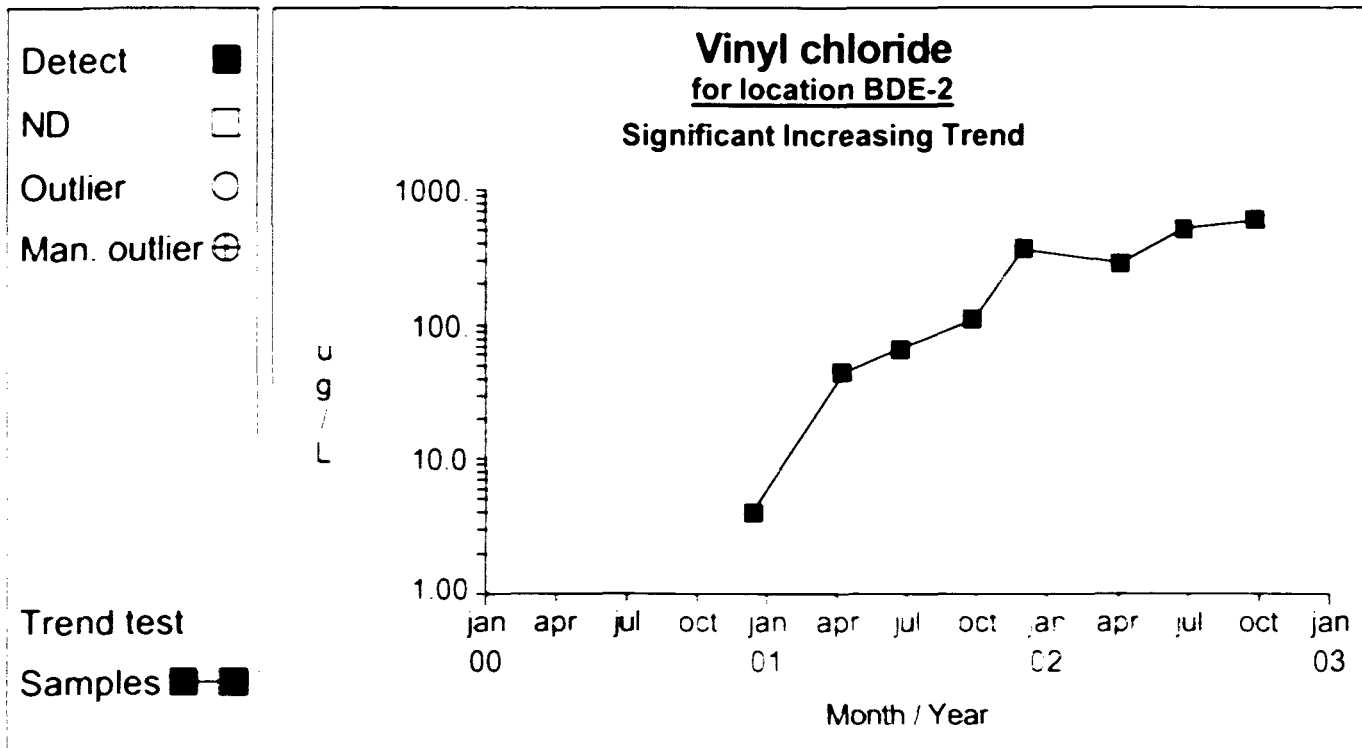
Trend test

Samples

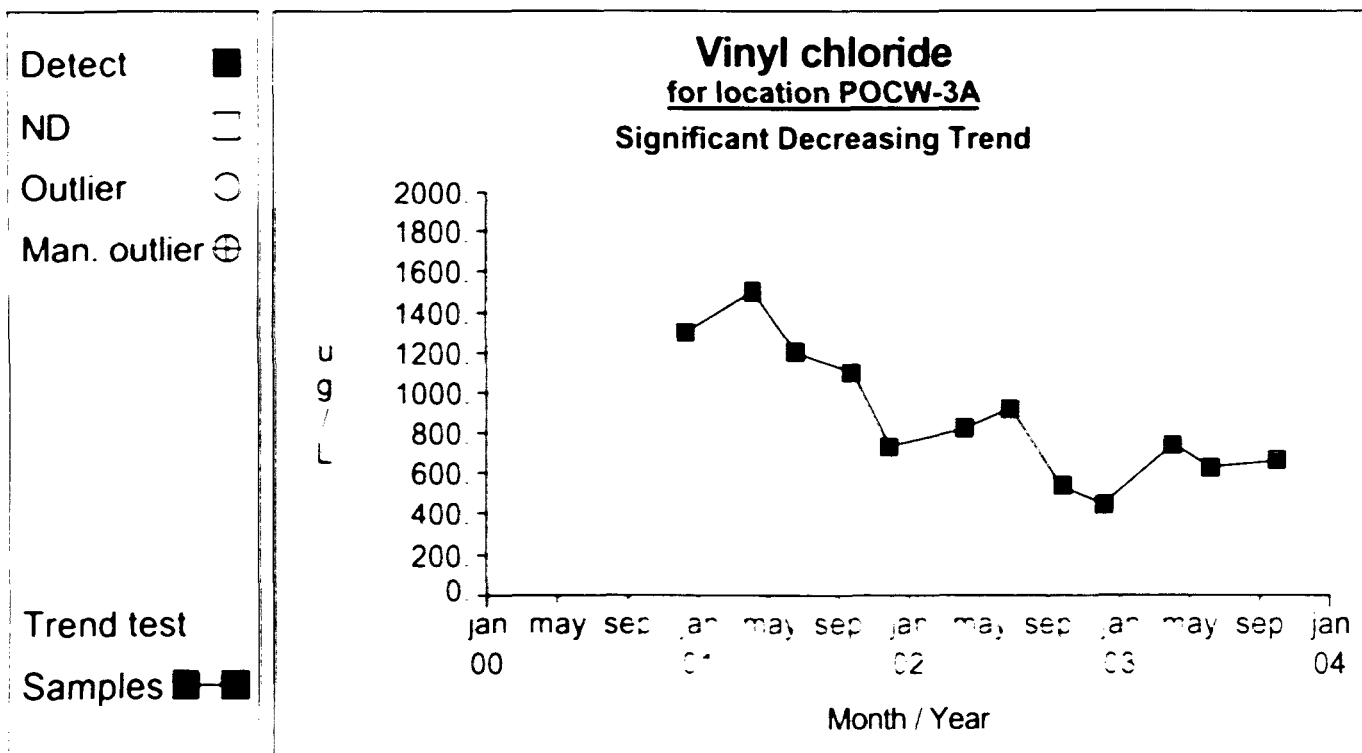


**Graph 236**

**Time Series**



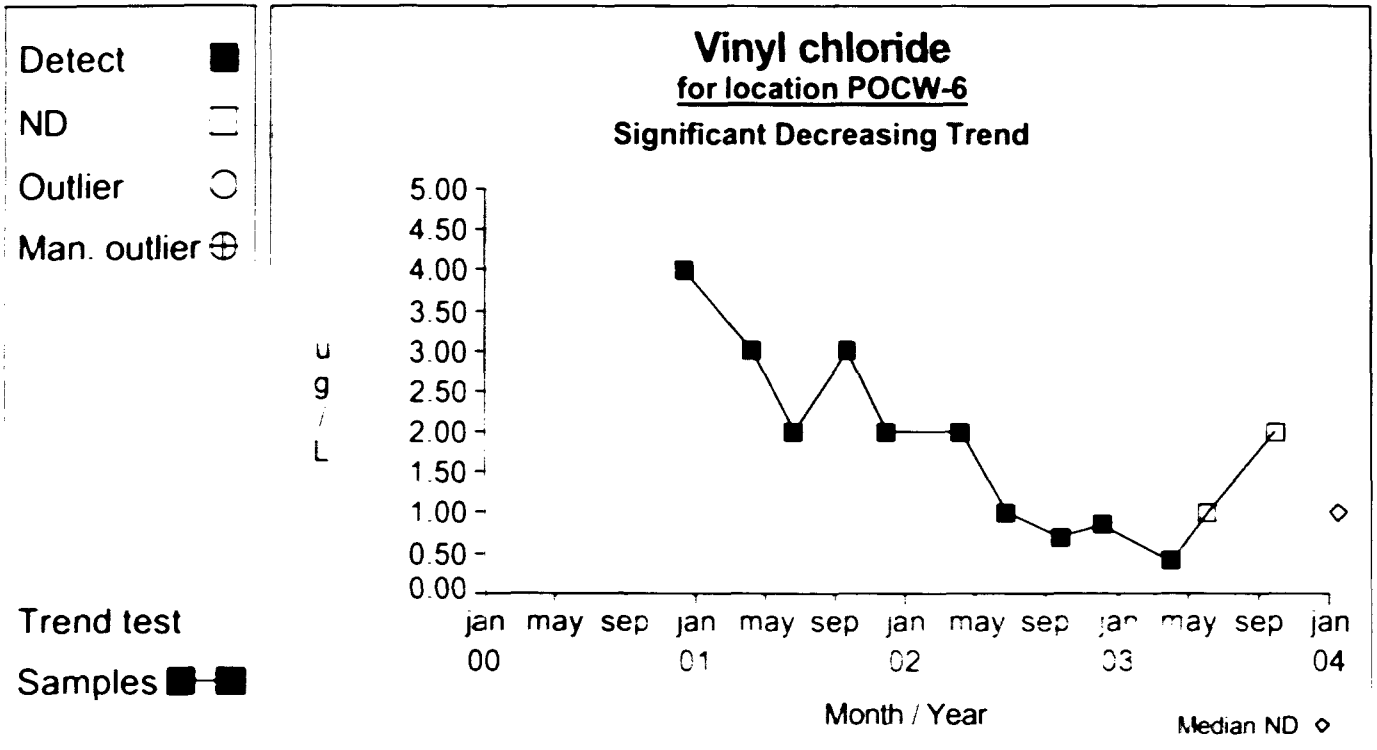
**Graph 242**



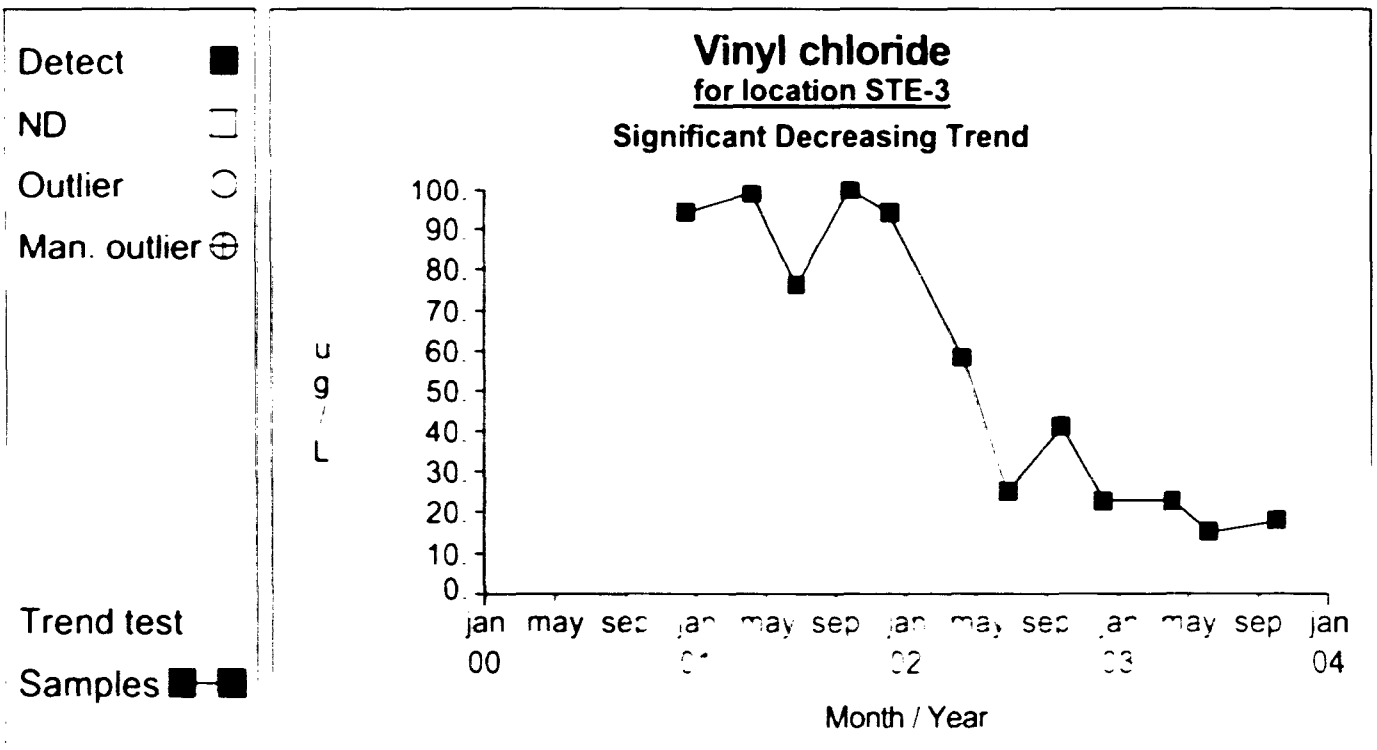
**Graph 265**



**Time Series**

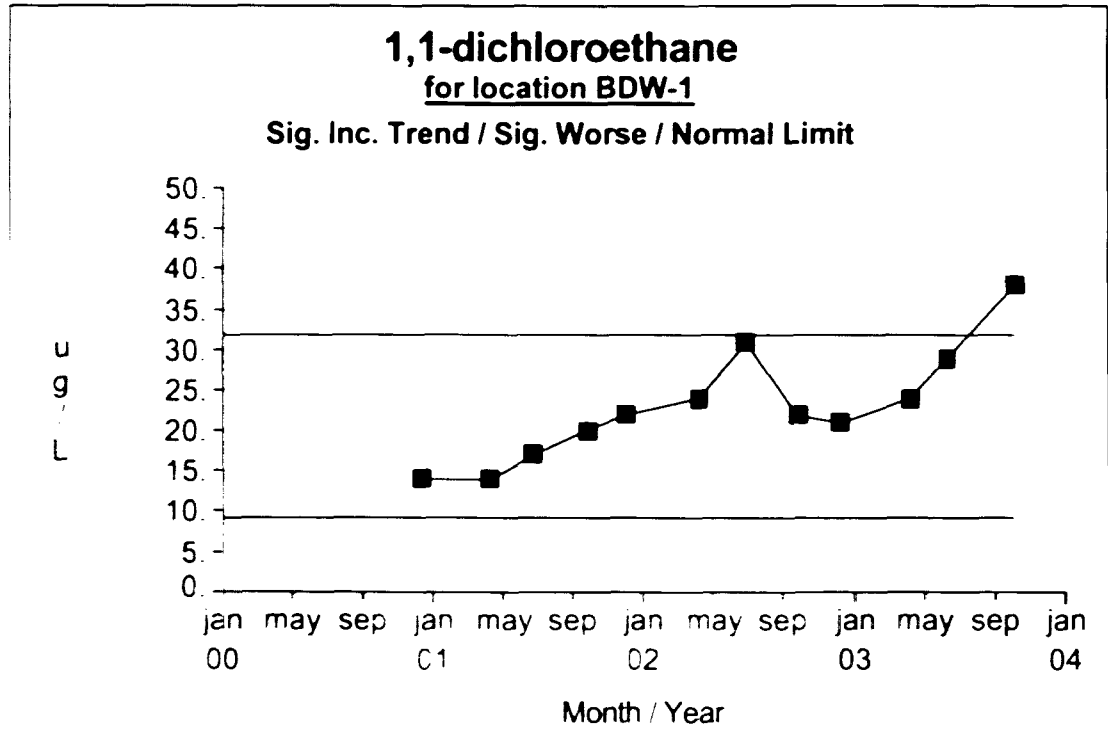
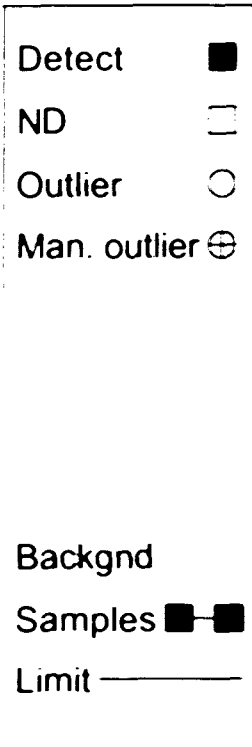


**Graph 273**

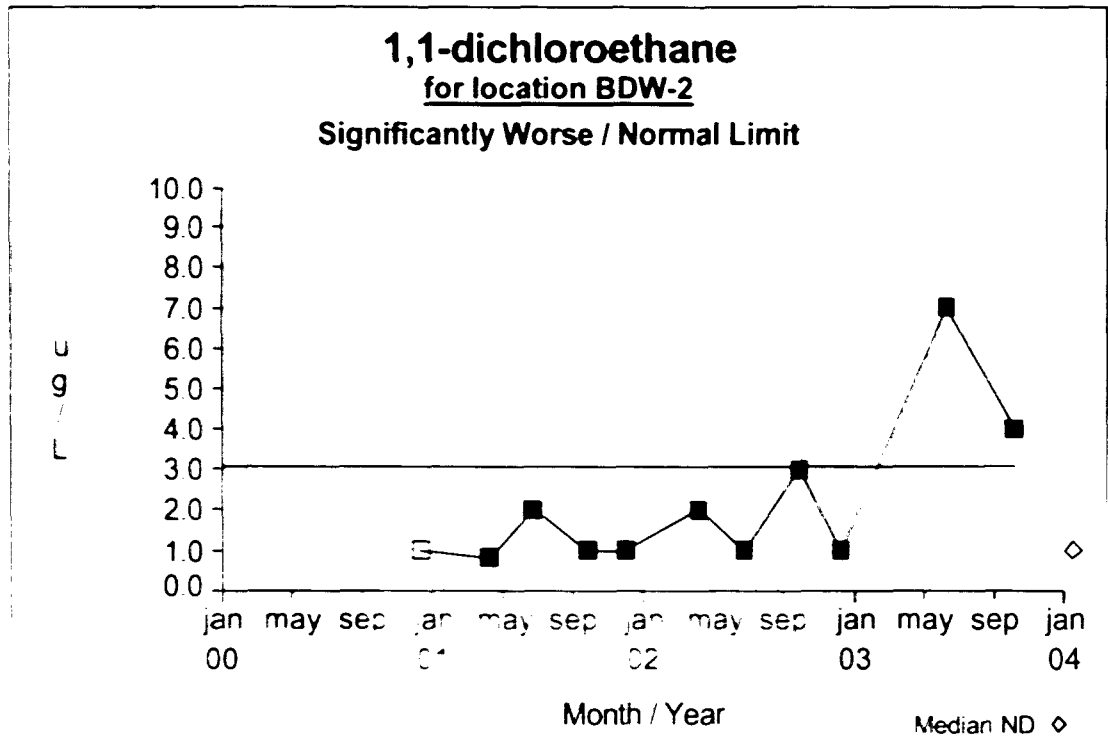
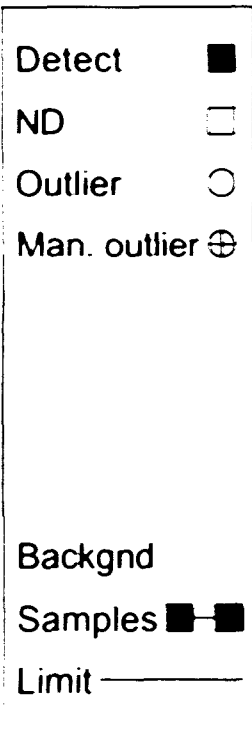


**Graph 276**

### Comparison to Baseline

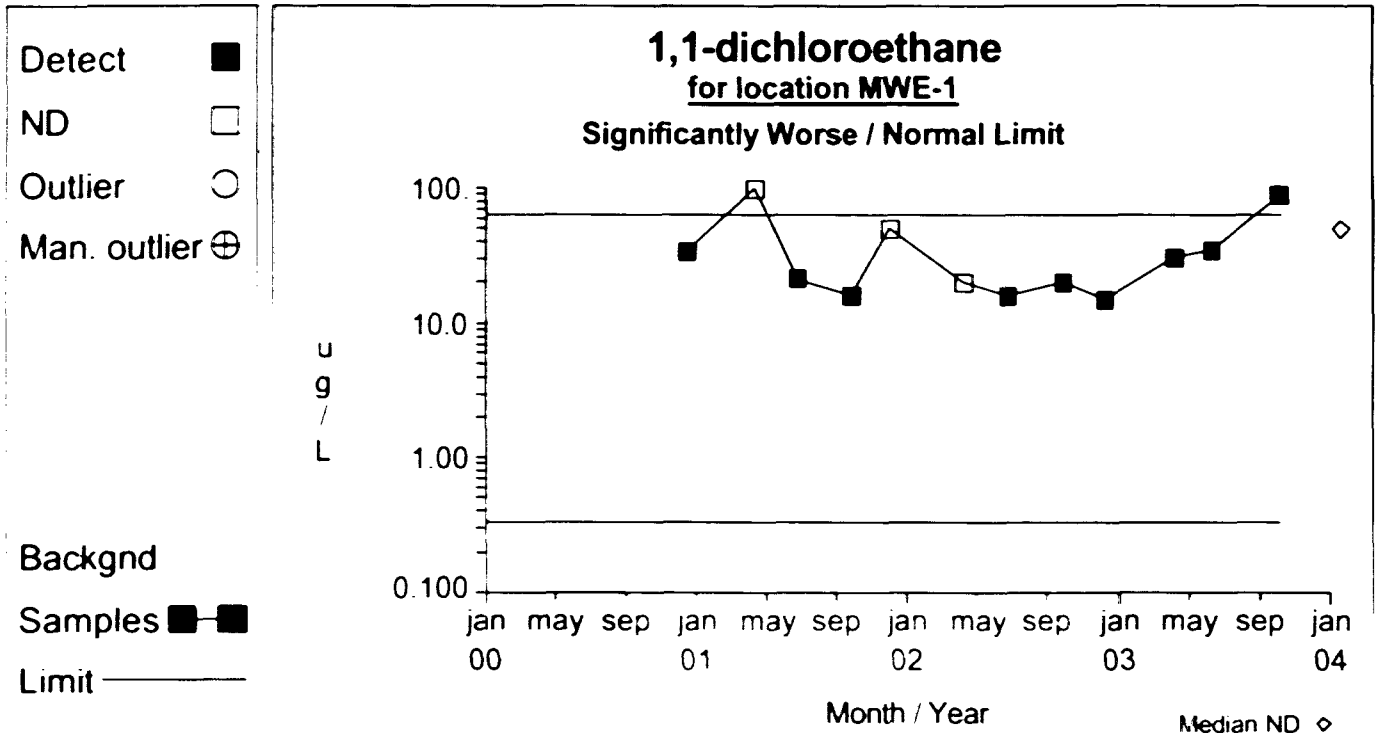


**Graph 48**

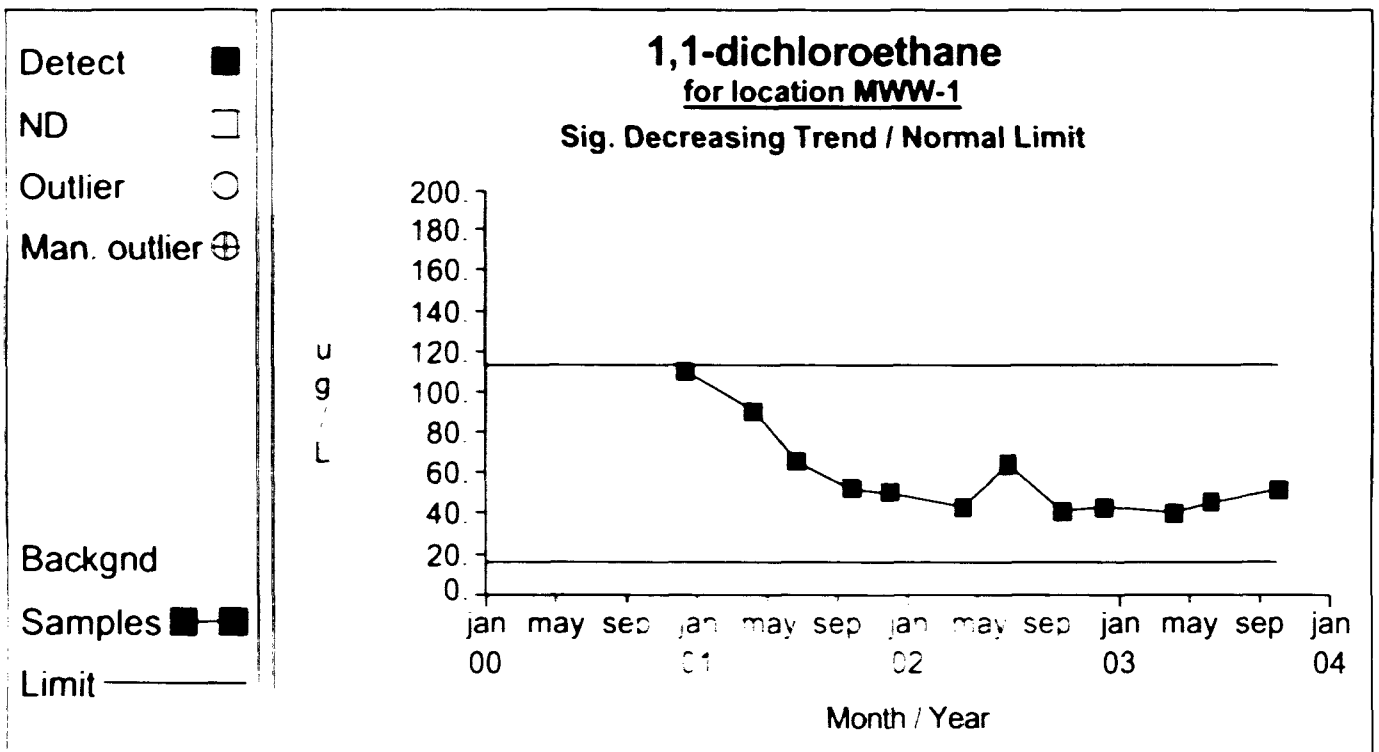


**Graph 49**

### Comparison to Baseline

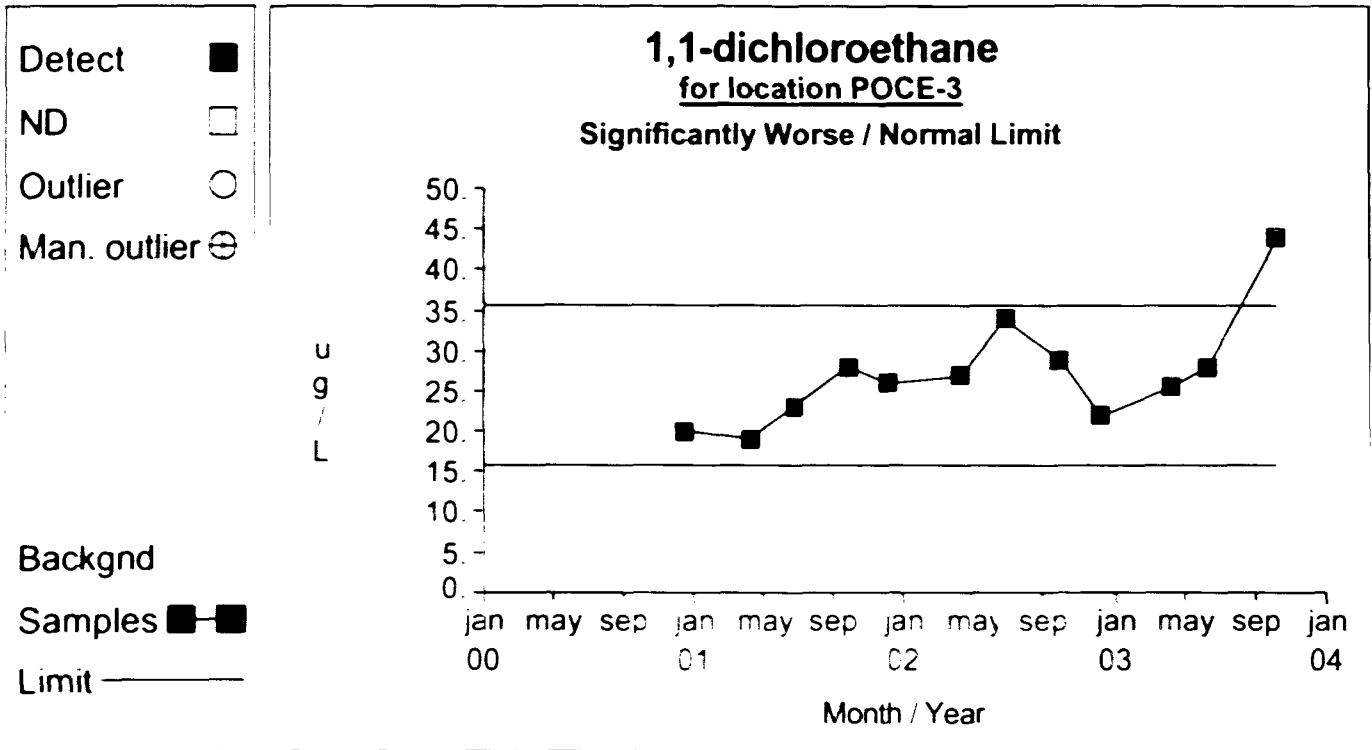


**Graph 53**

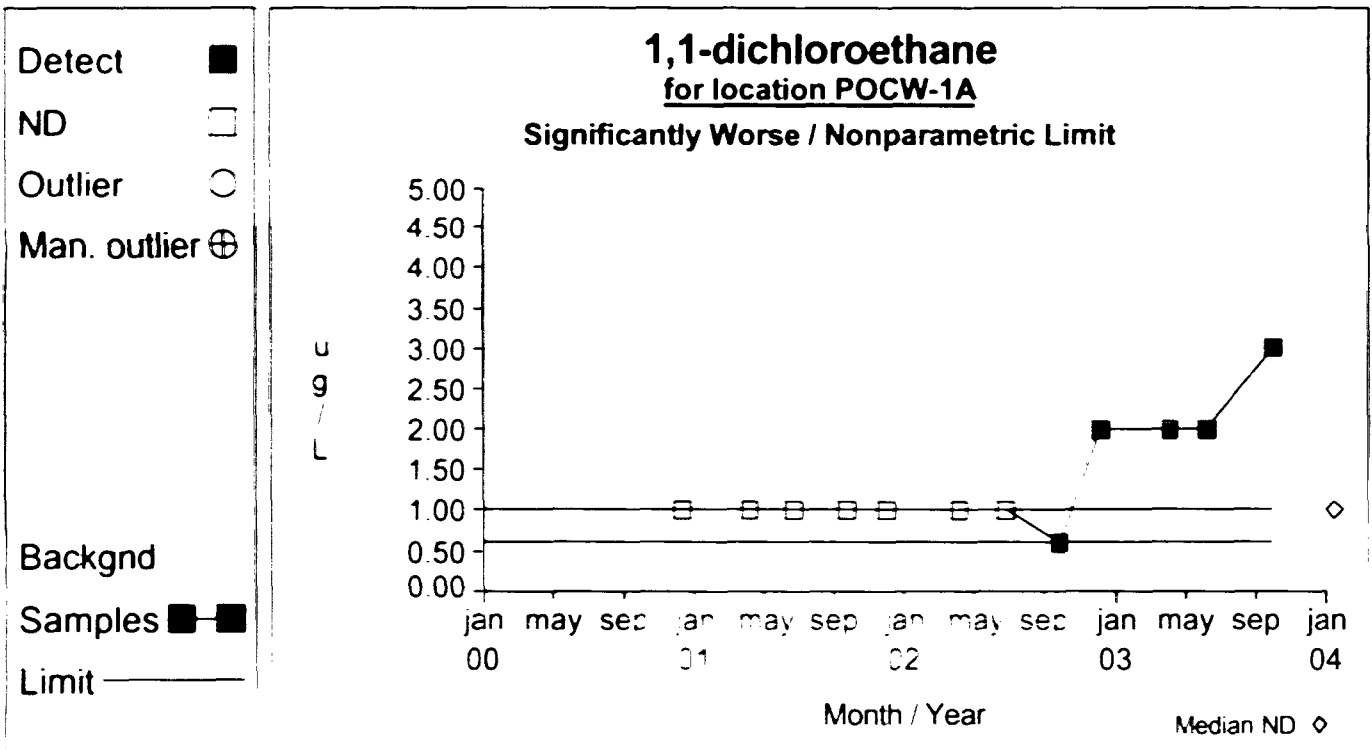


**Graph 55**

### Comparison to Baseline

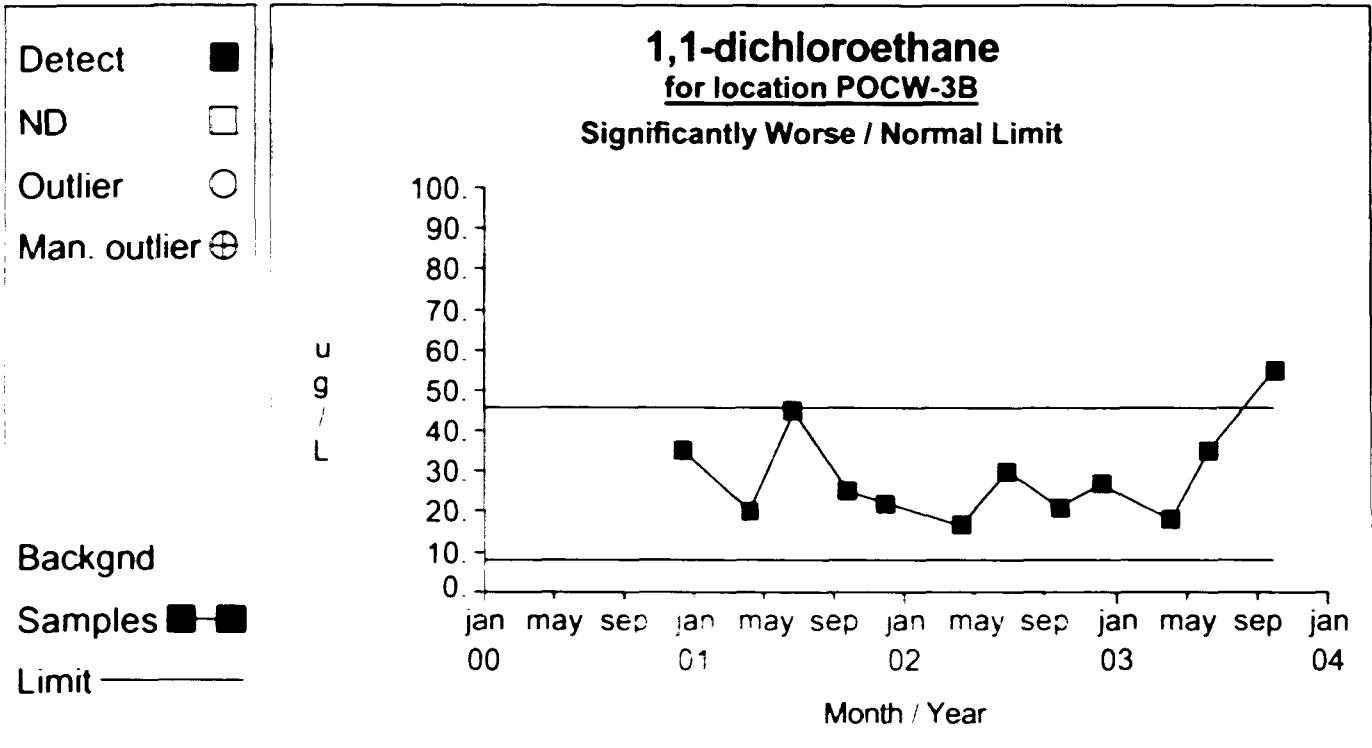


**Graph 63**

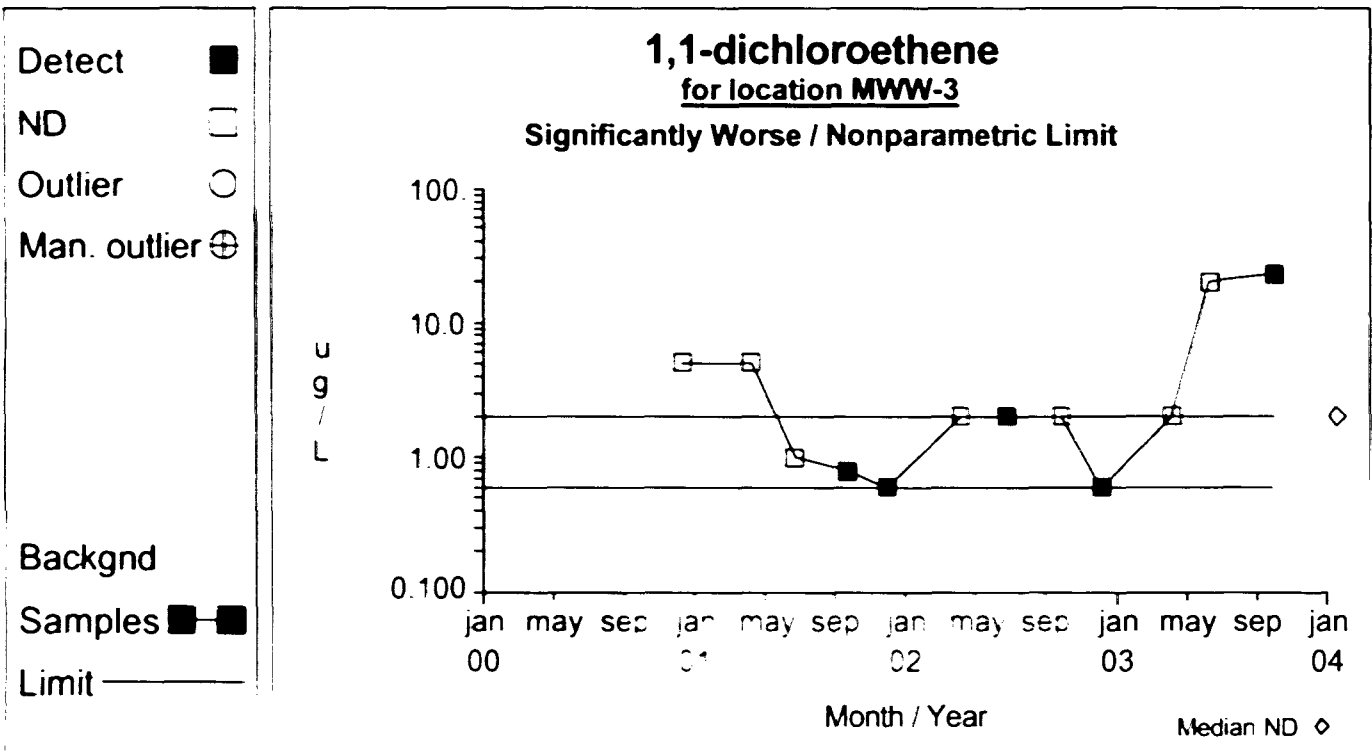


**Graph 68**

### Comparison to Baseline

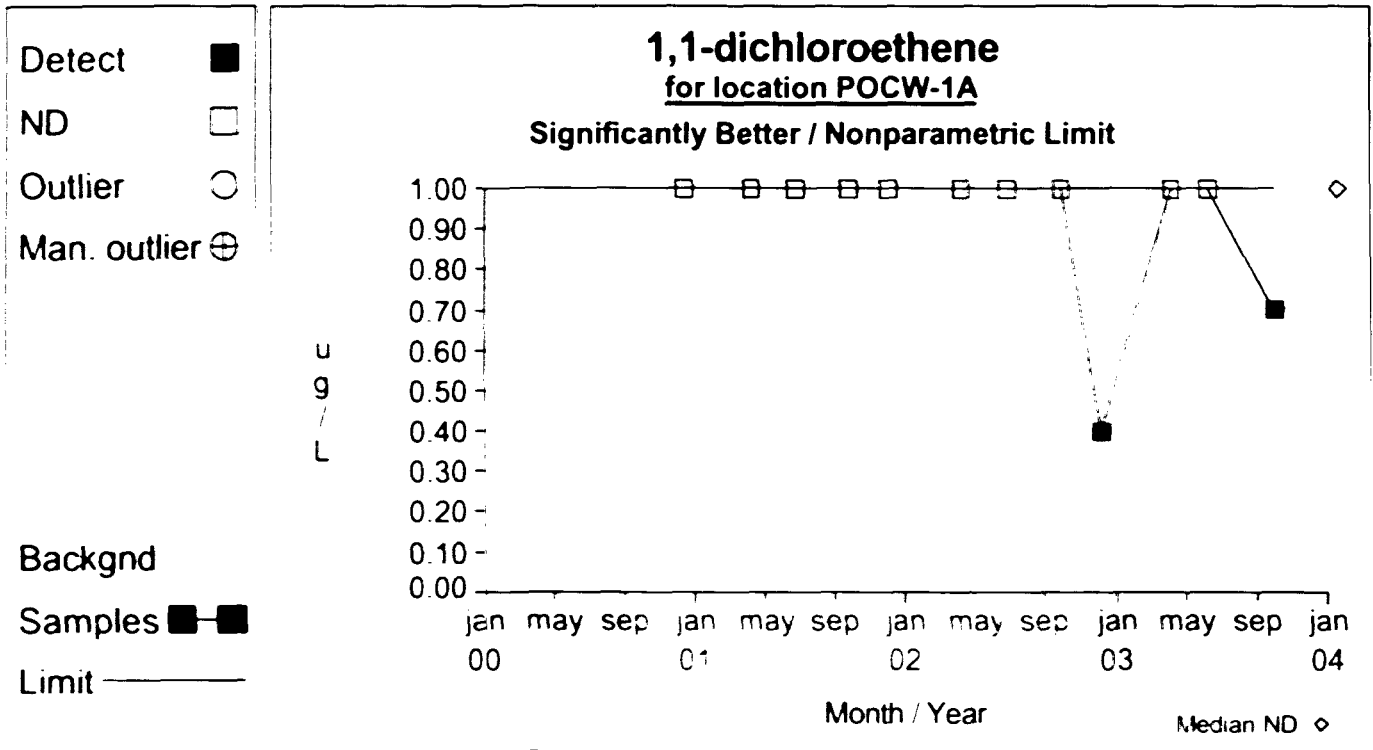


**Graph 73**

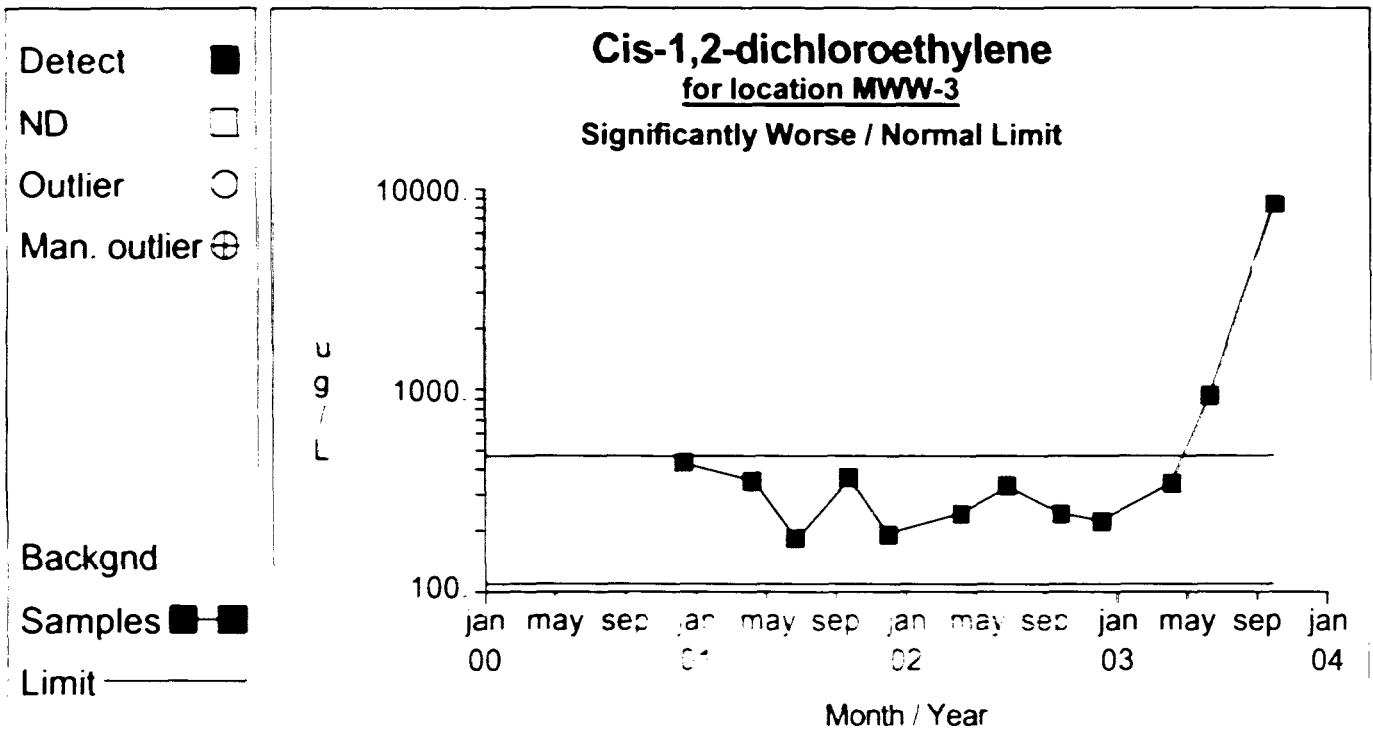


**Graph 101**

### Comparison to Baseline

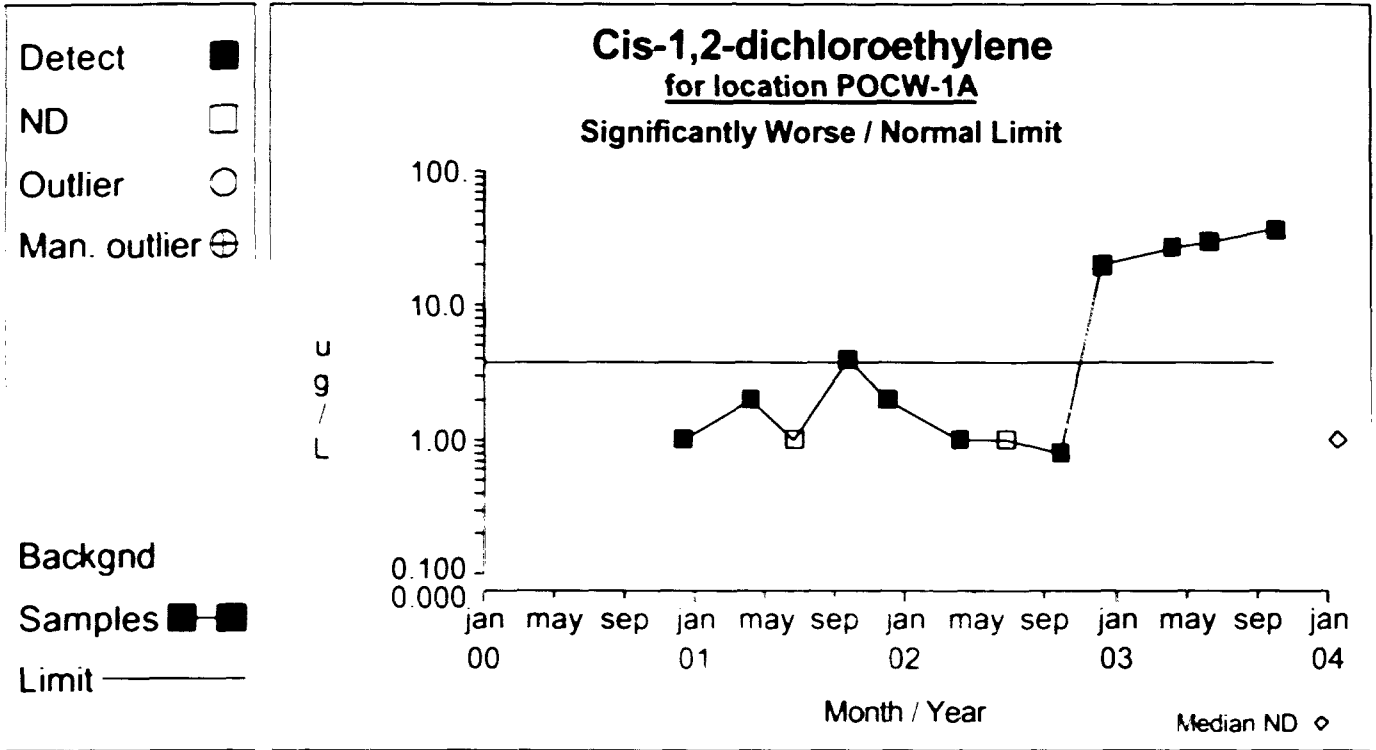


**Graph 112**

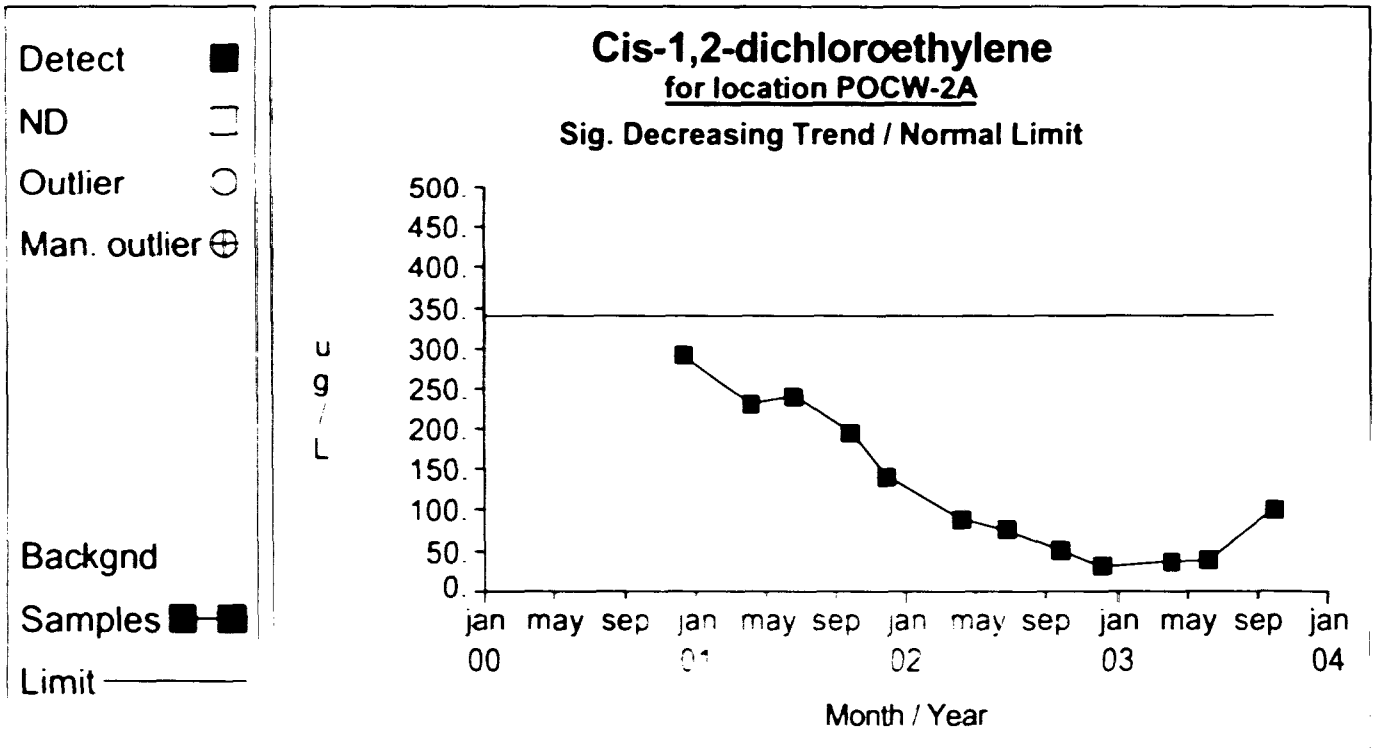


**Graph 145**

**Comparison to Baseline**

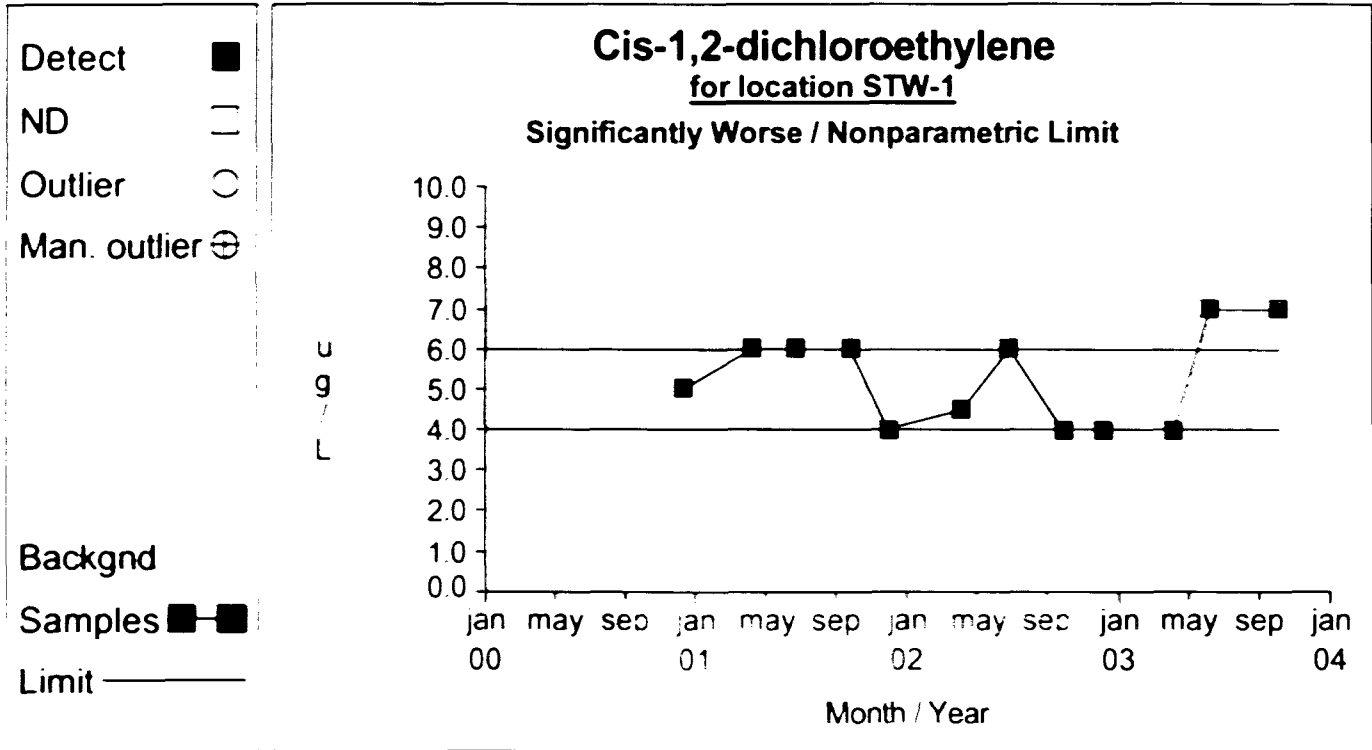


**Graph 156**

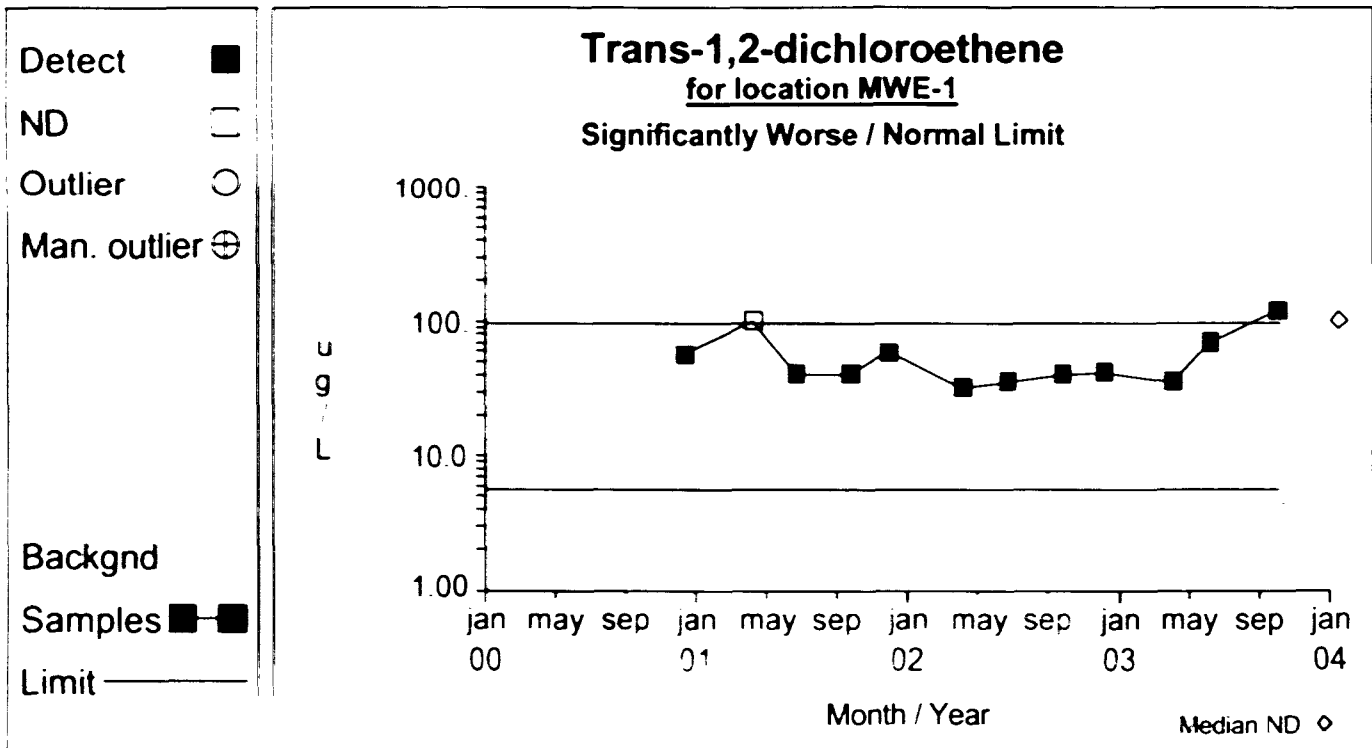


**Graph 158**

### Comparison to Baseline



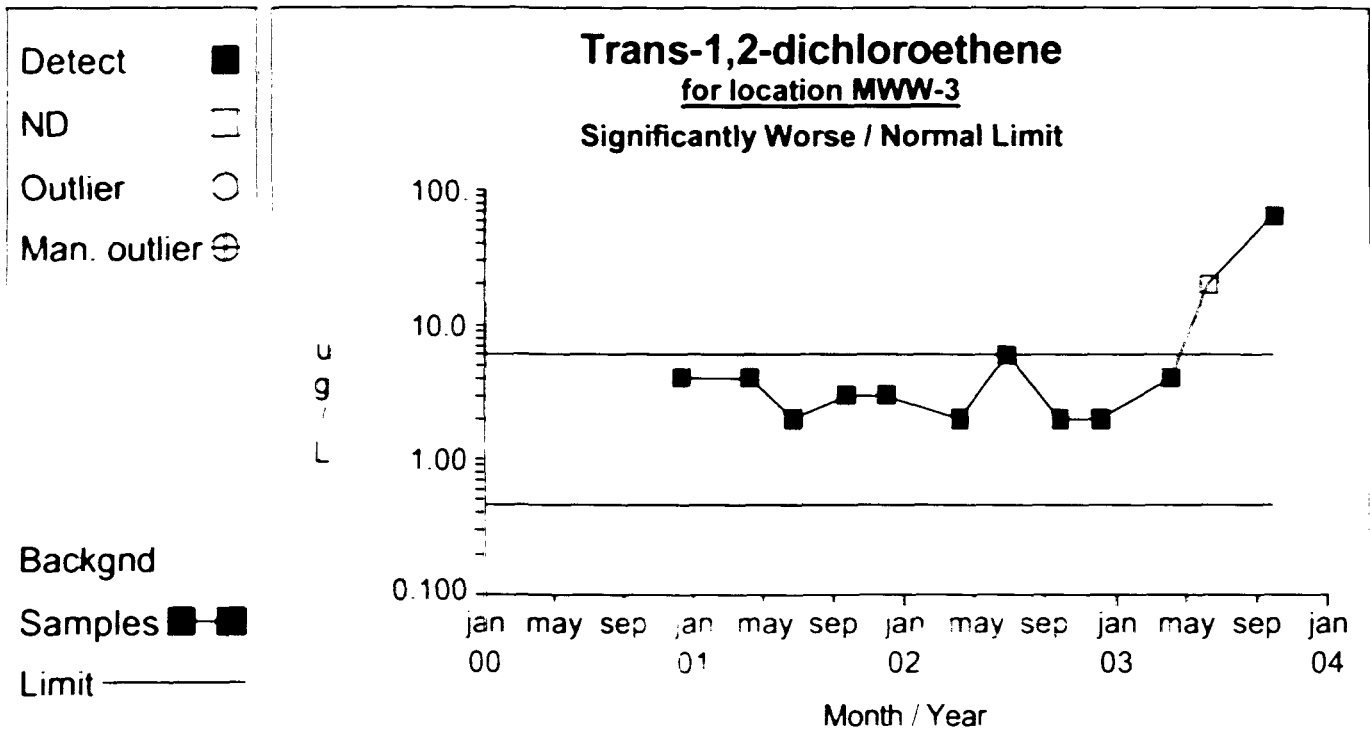
**Graph 173**



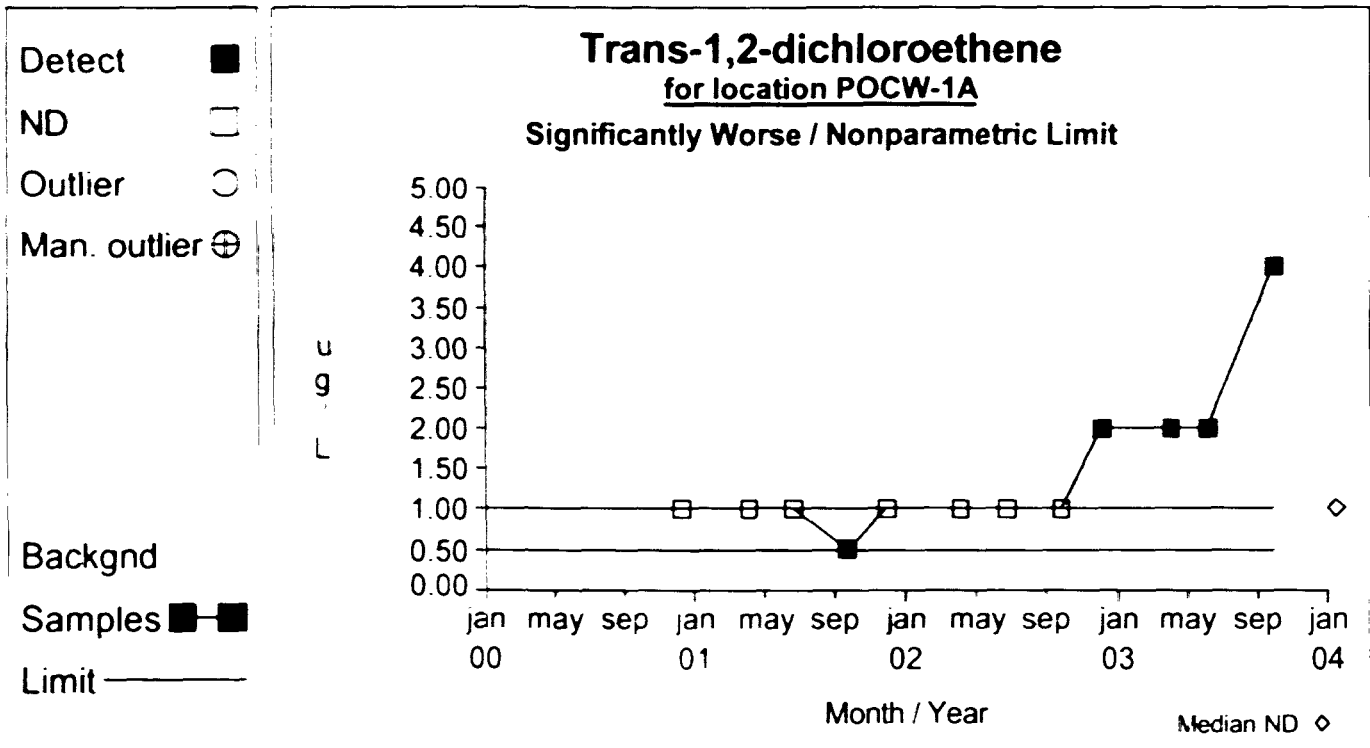
**Graph 185**



### Comparison to Baseline

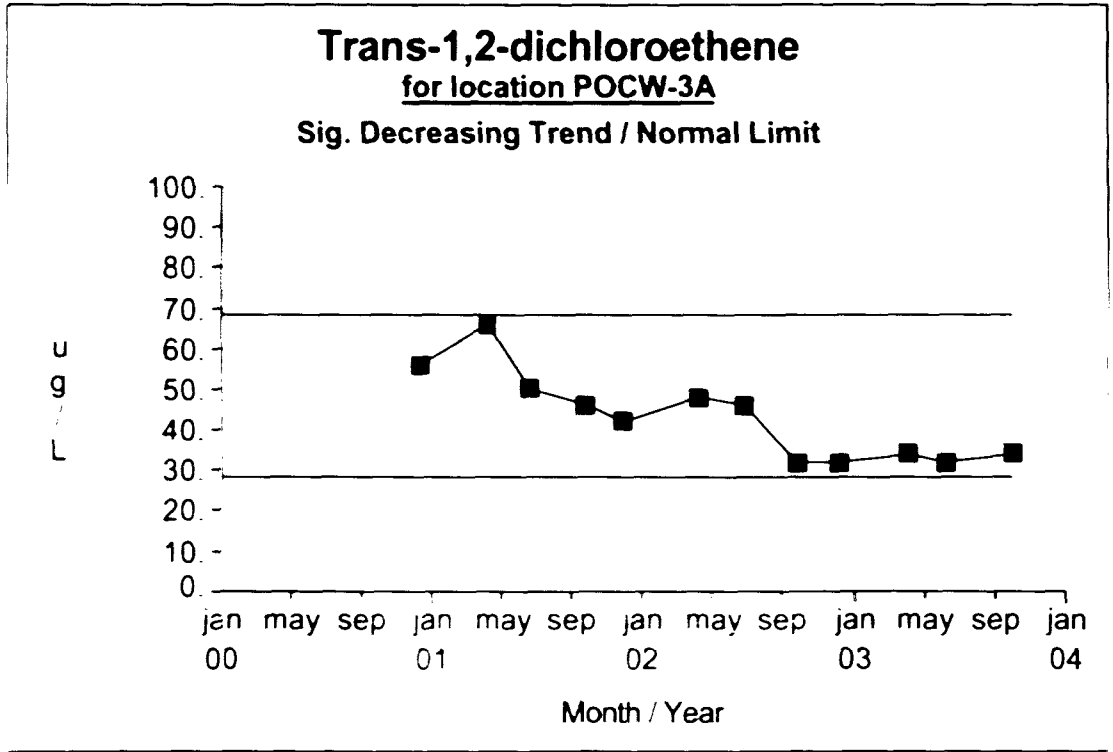
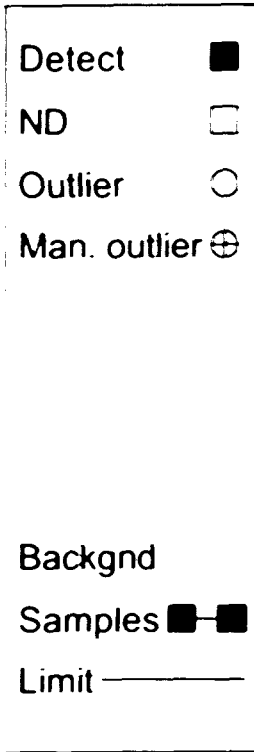


Graph 189

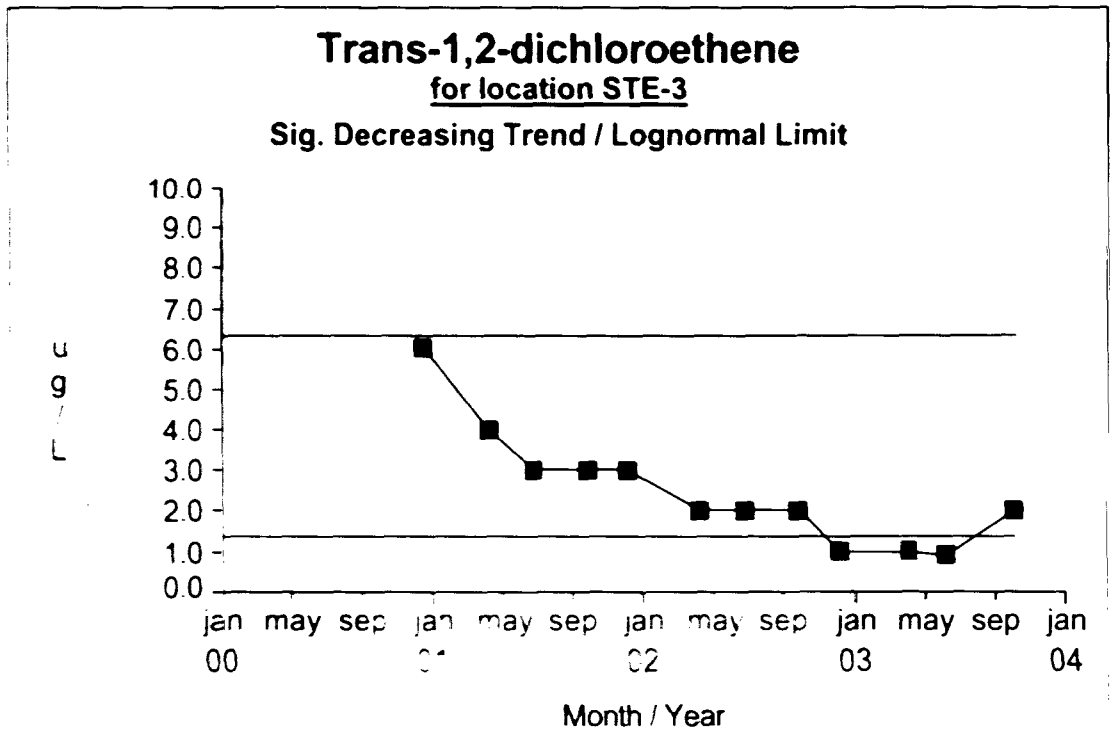
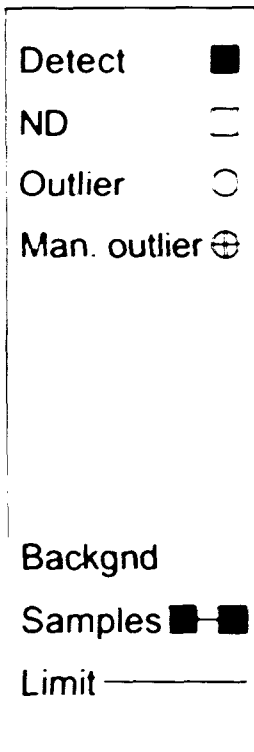


Graph 200

Comparison to Baseline



Graph 204



Graph 216

**Comparison to Baseline**

Detect

ND

Outlier

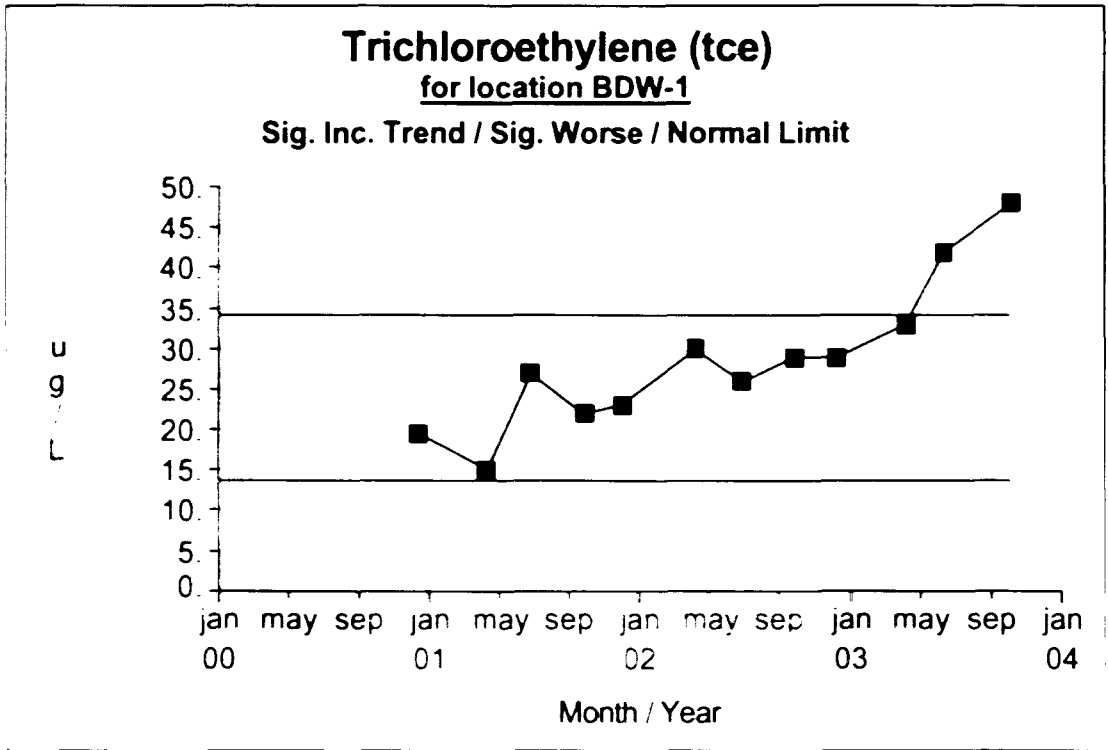
Man. outlier ⊕

Backgnd

Samples —

Limit



**Graph 224**

Detect

ND

Outlier

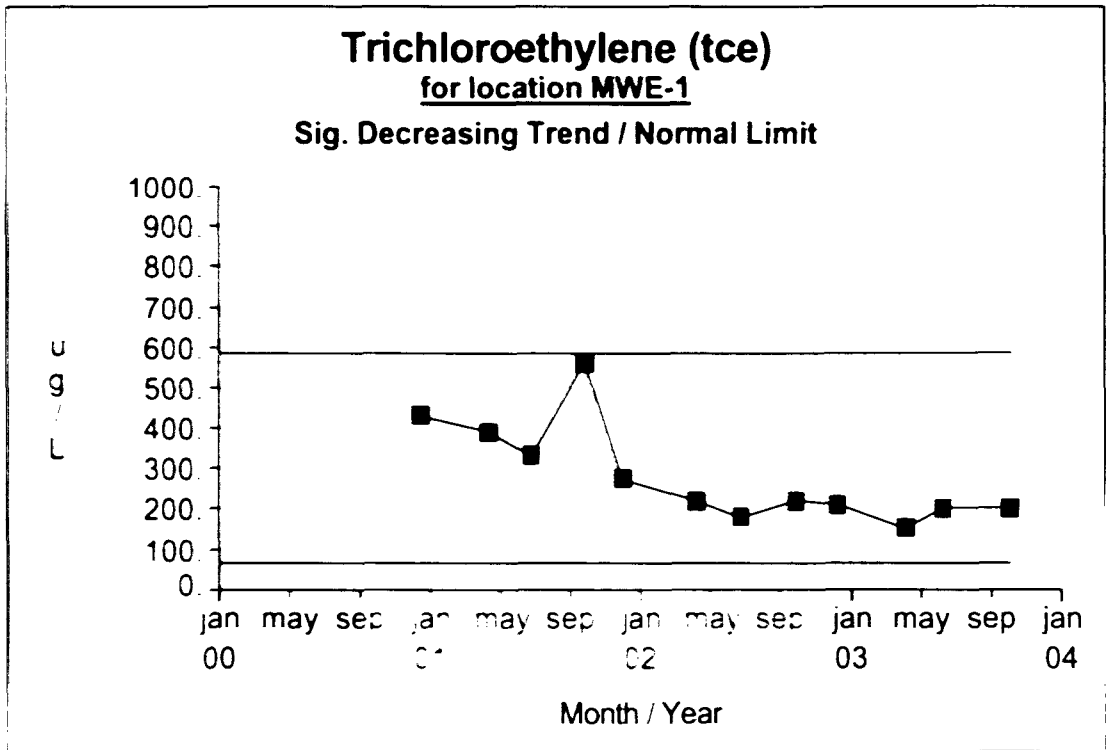
Man. outlier ⊕

Backgnd

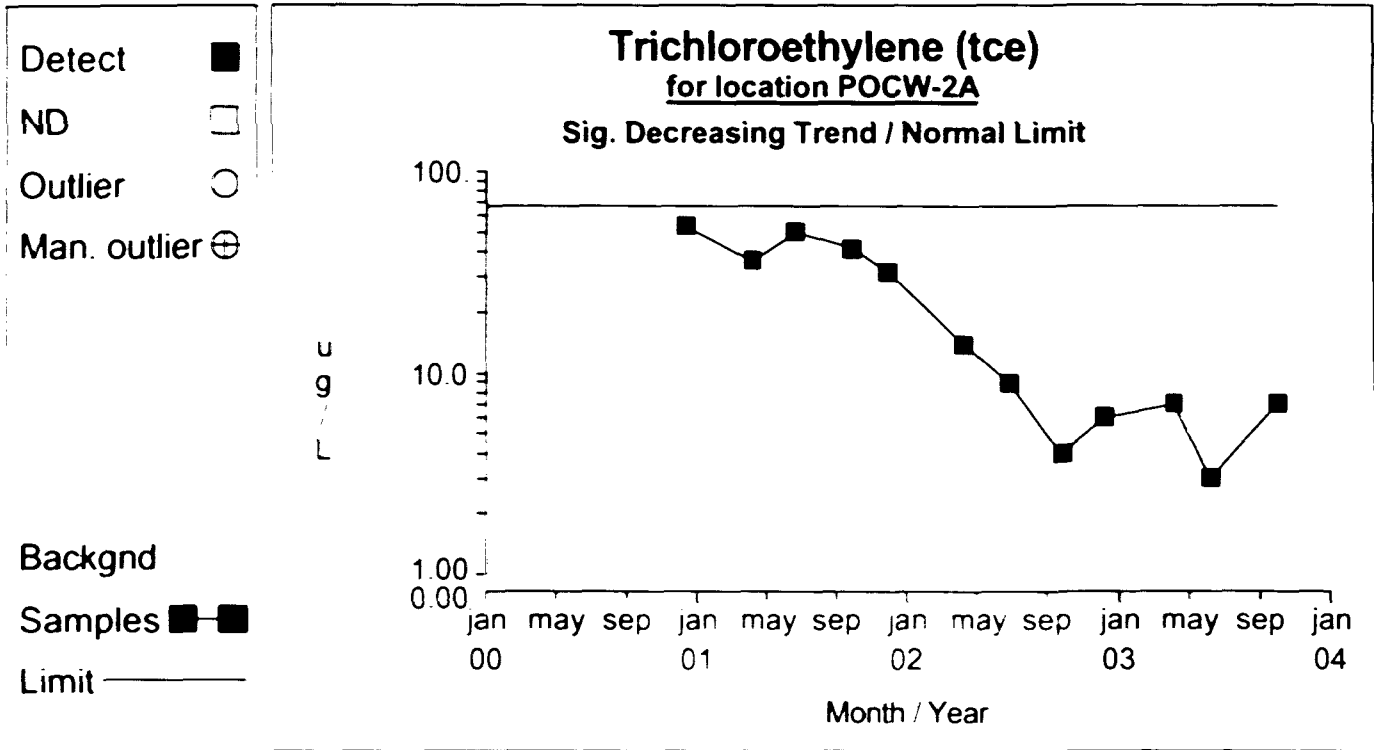
Samples —

Limit

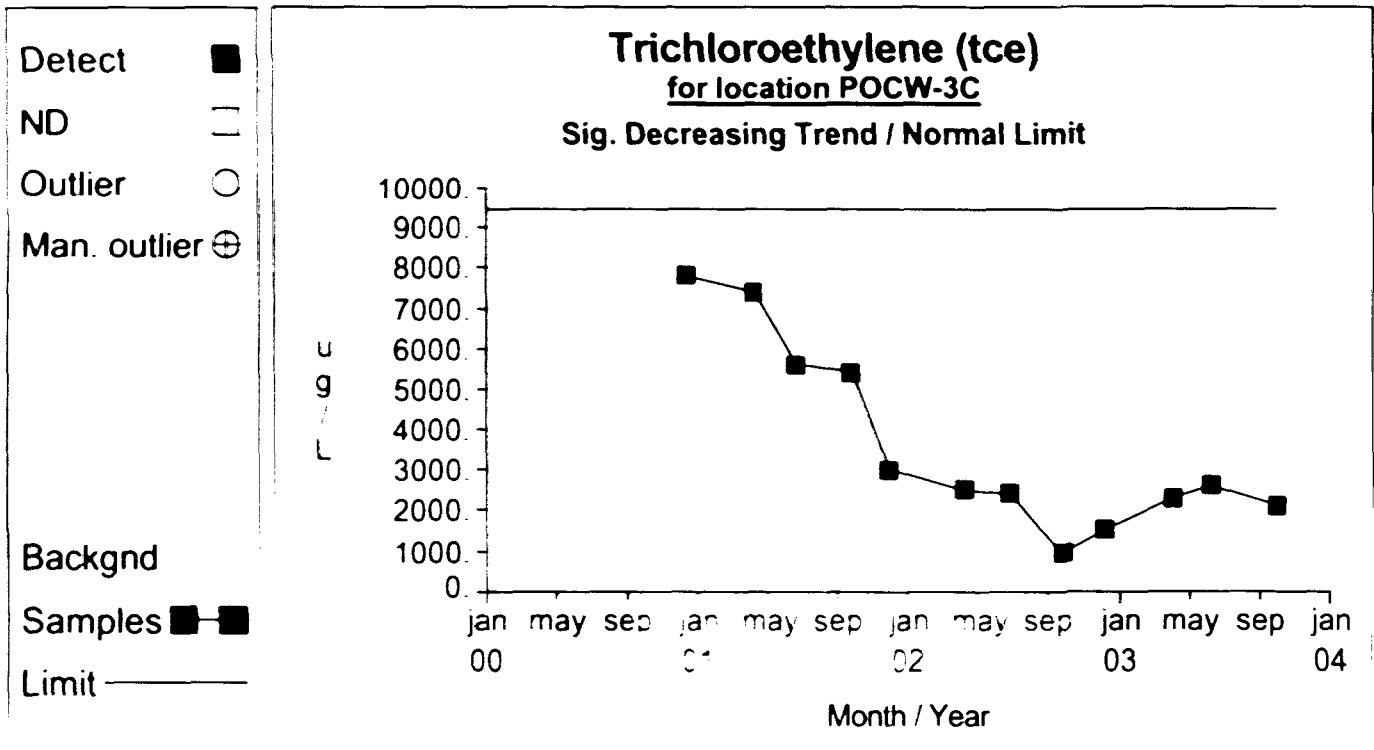


**Graph 229**

**Comparison to Baseline**

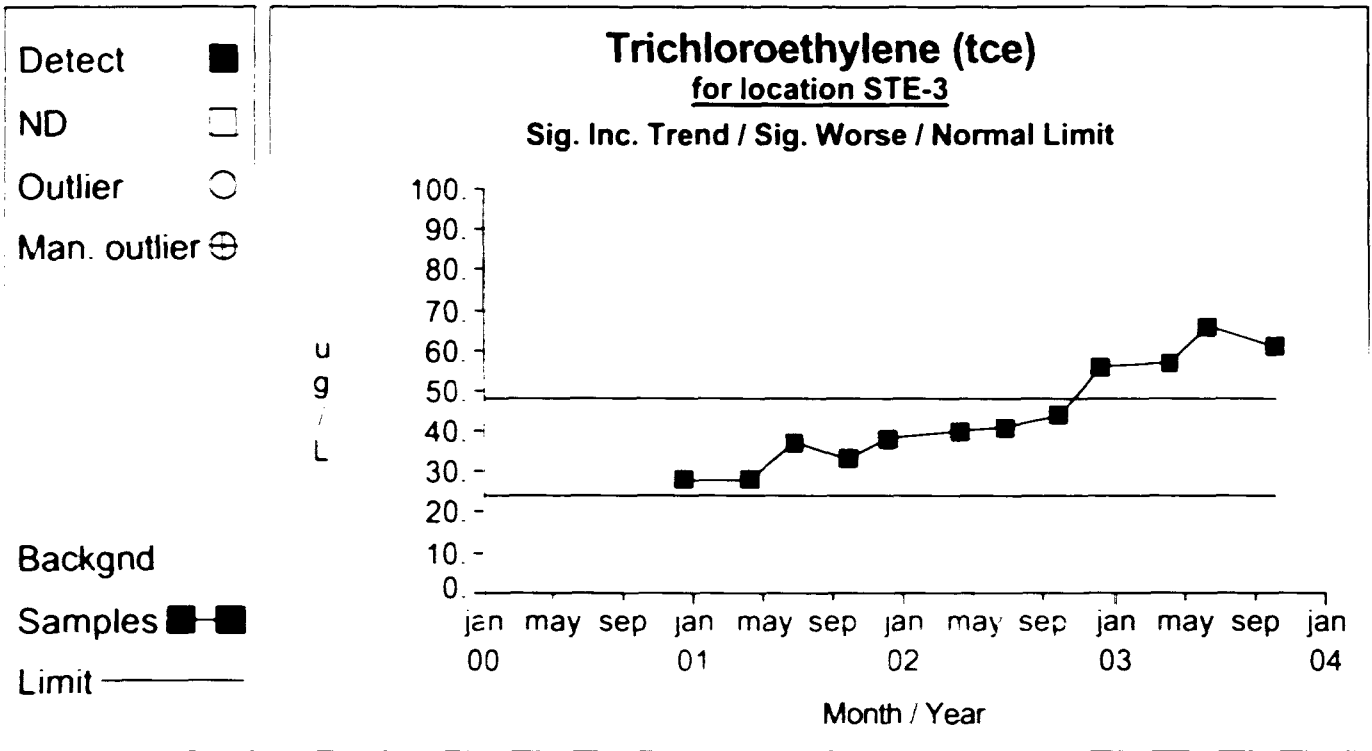


**Graph 246**



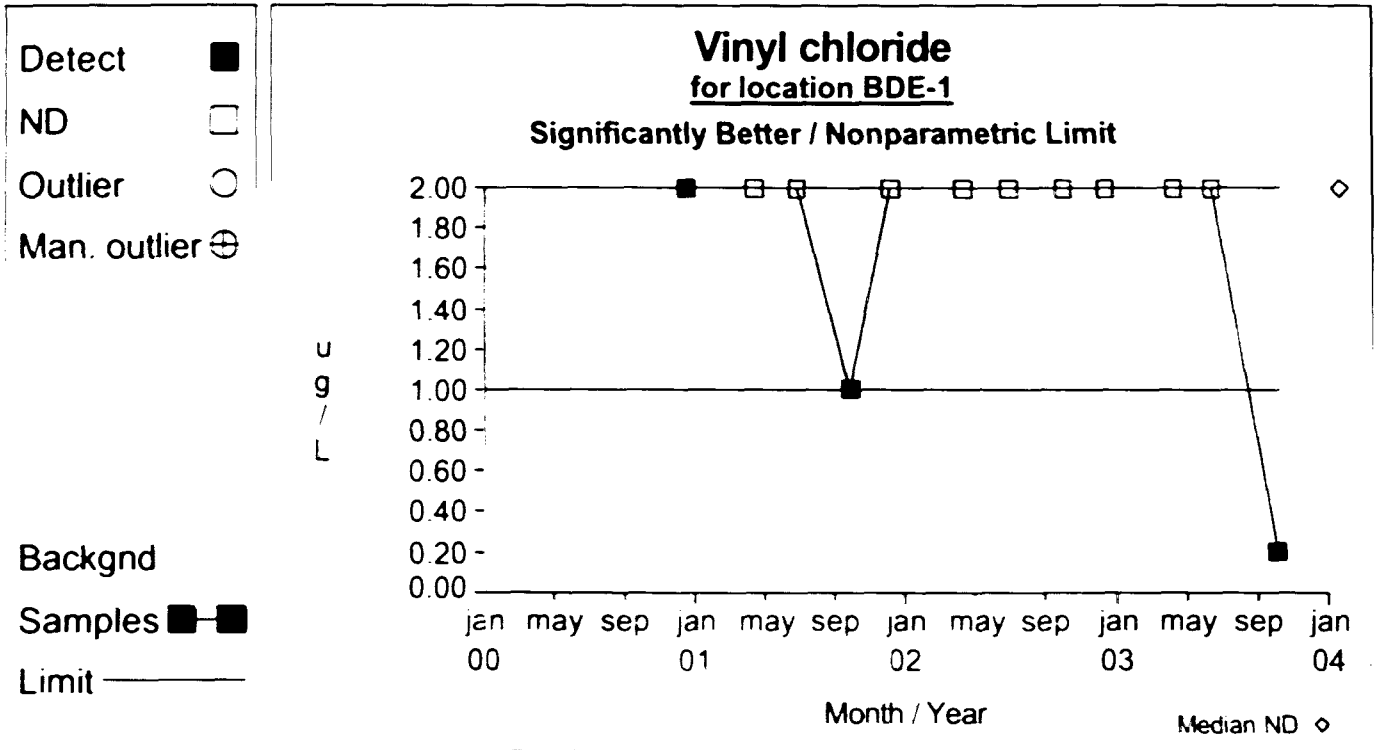
**Graph 250**

# Comparison to Baseline

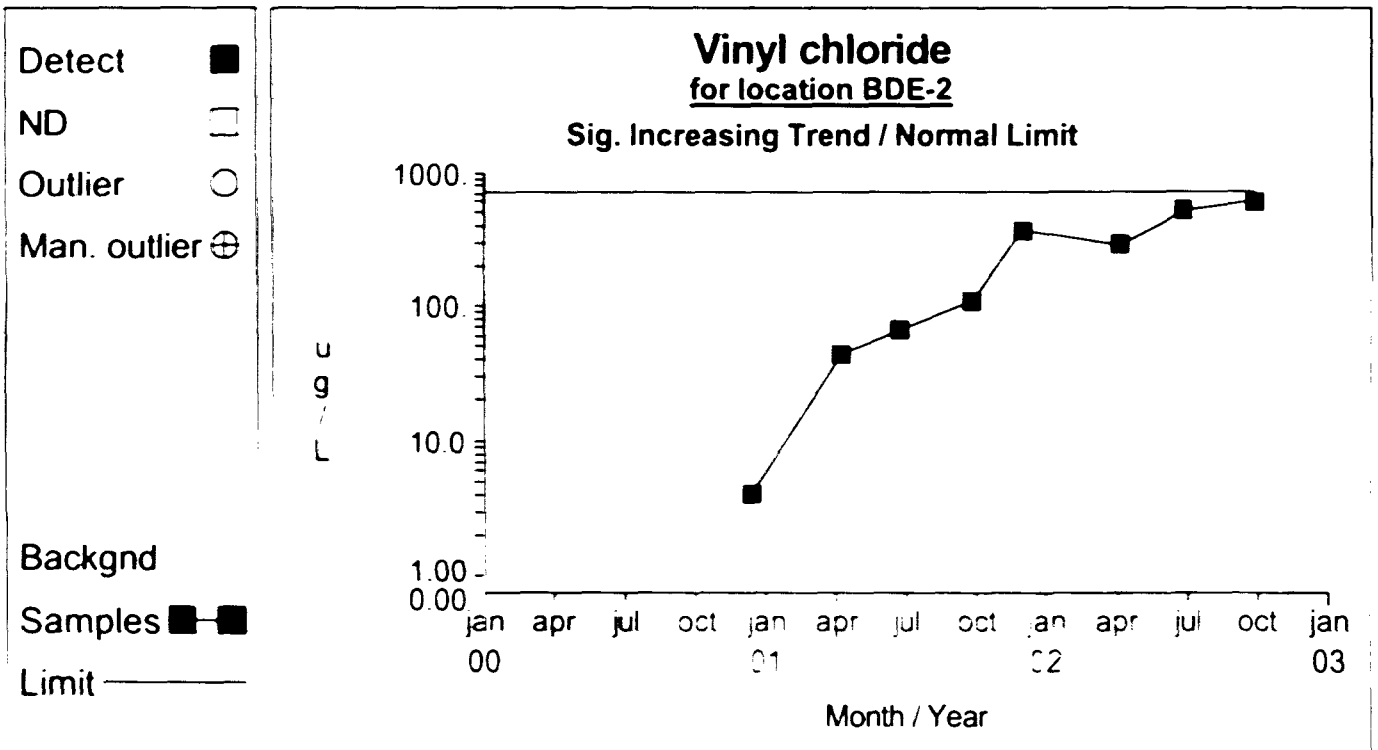


**Graph 260**

### Comparison to Baseline

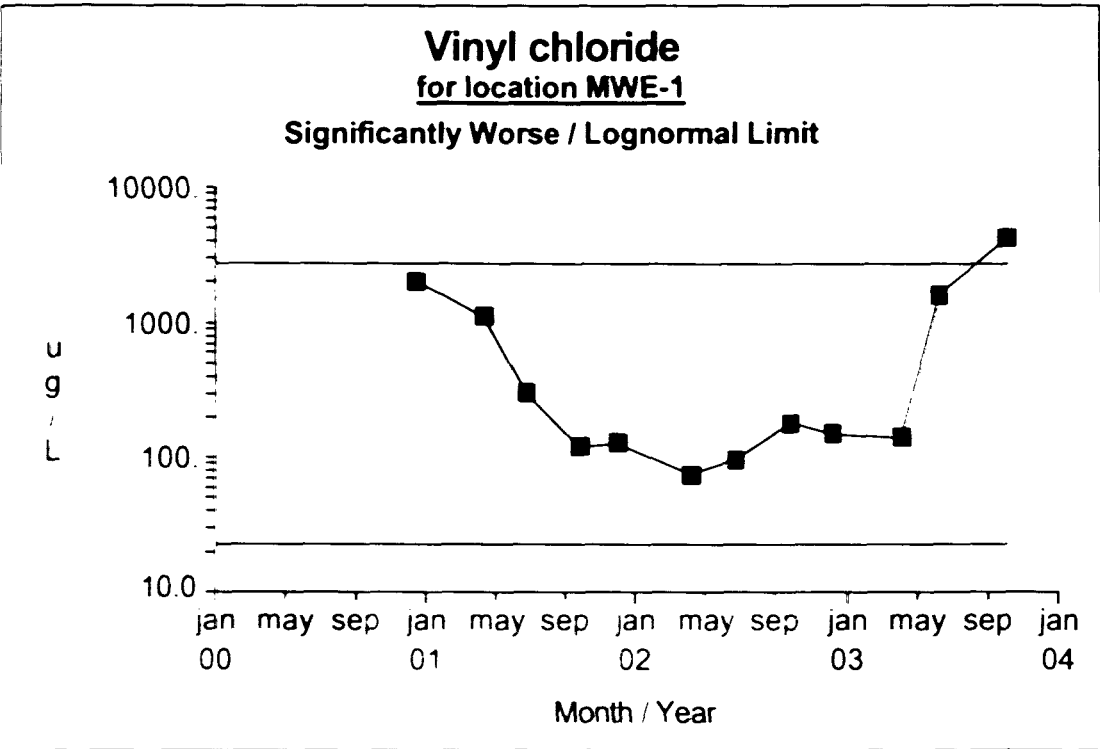
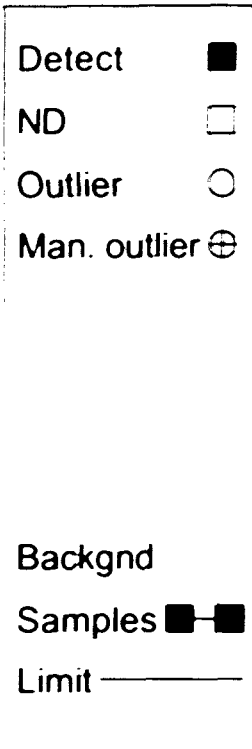


Graph 266

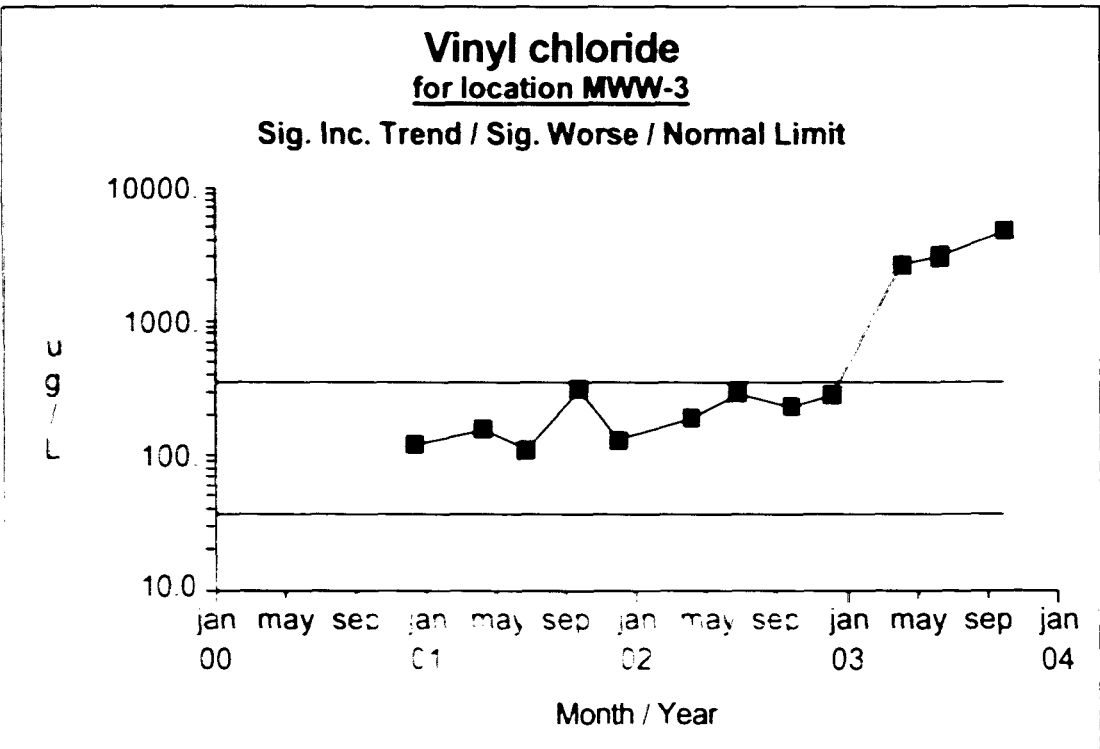
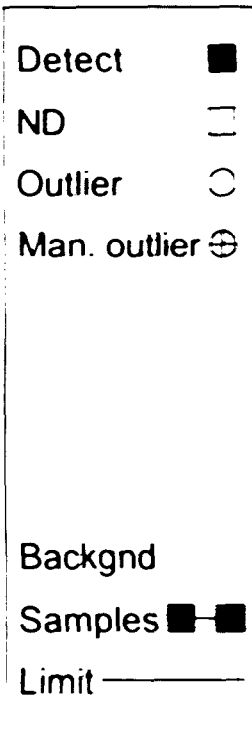


Graph 267

**Comparison to Baseline**

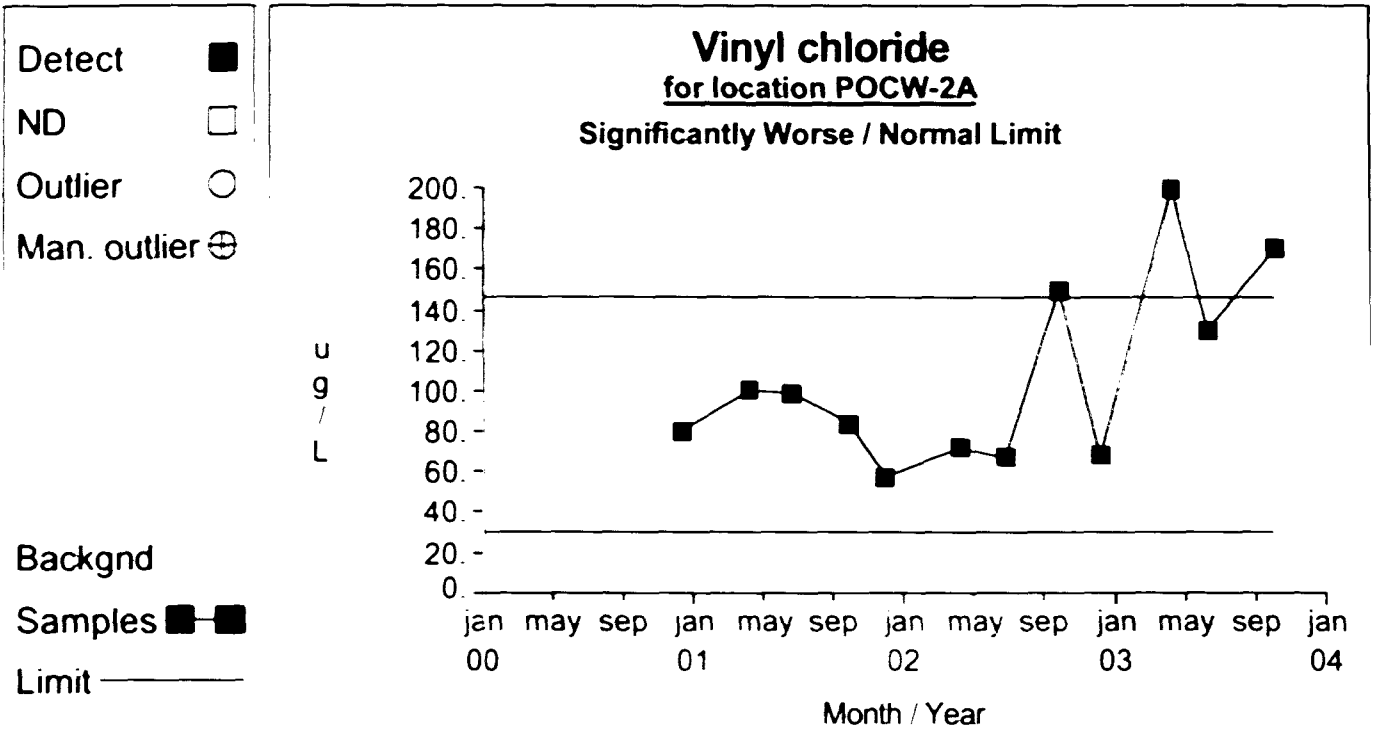


**Graph 273**

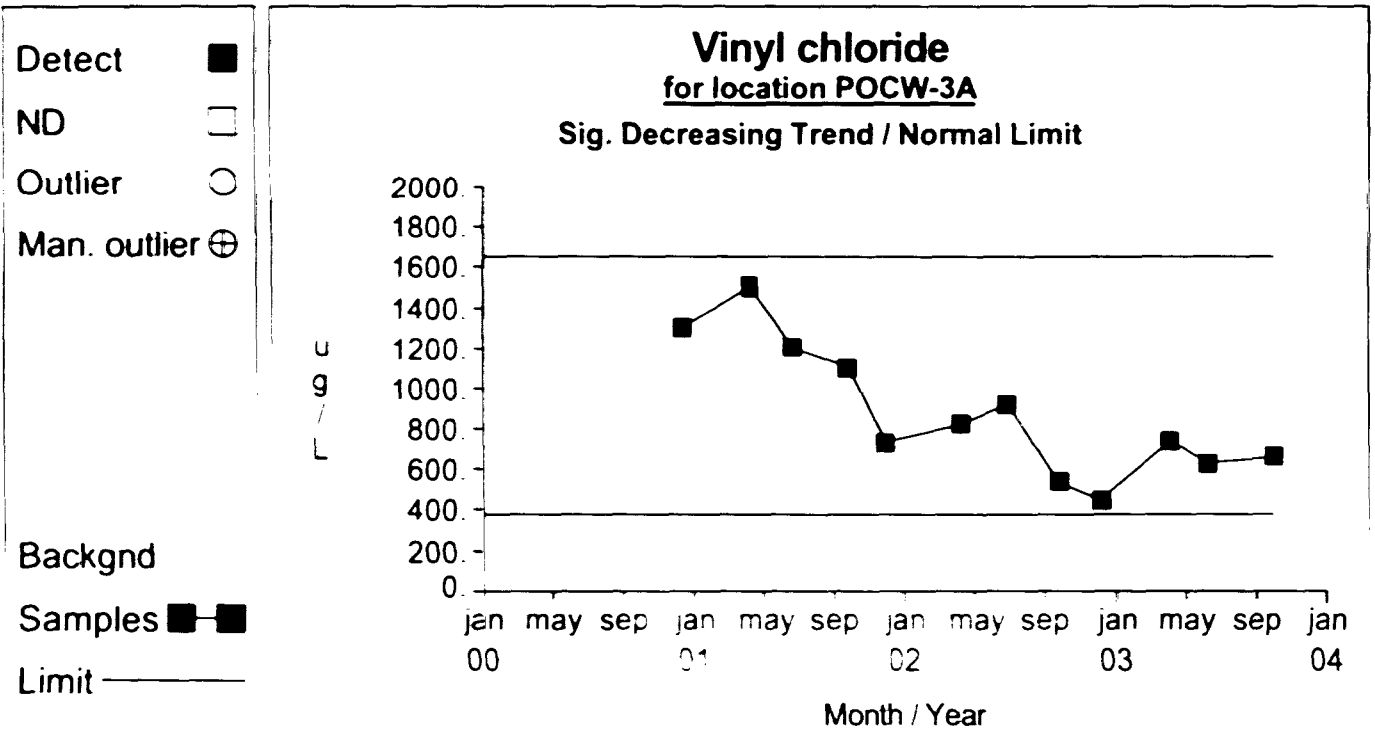


**Graph 277**

**Comparison to Baseline**



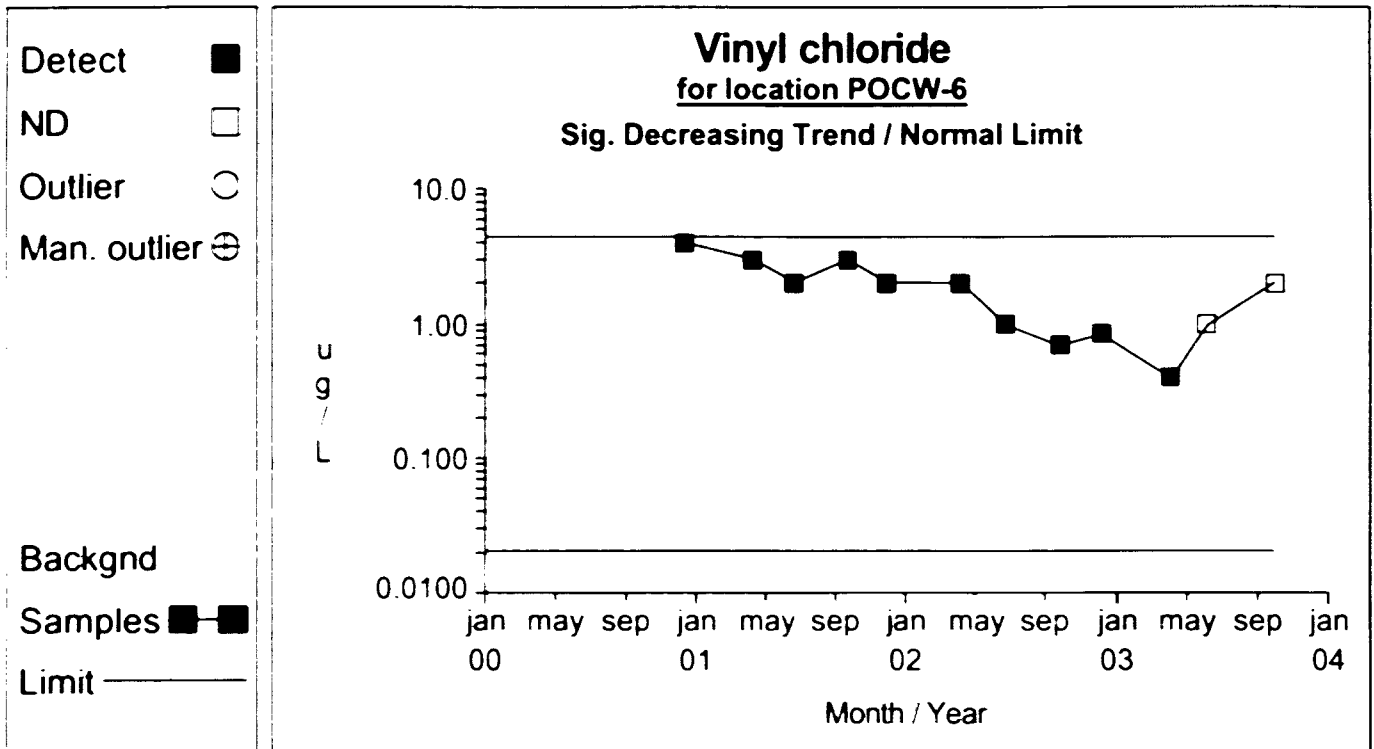
**Graph 290**



**Graph 292**

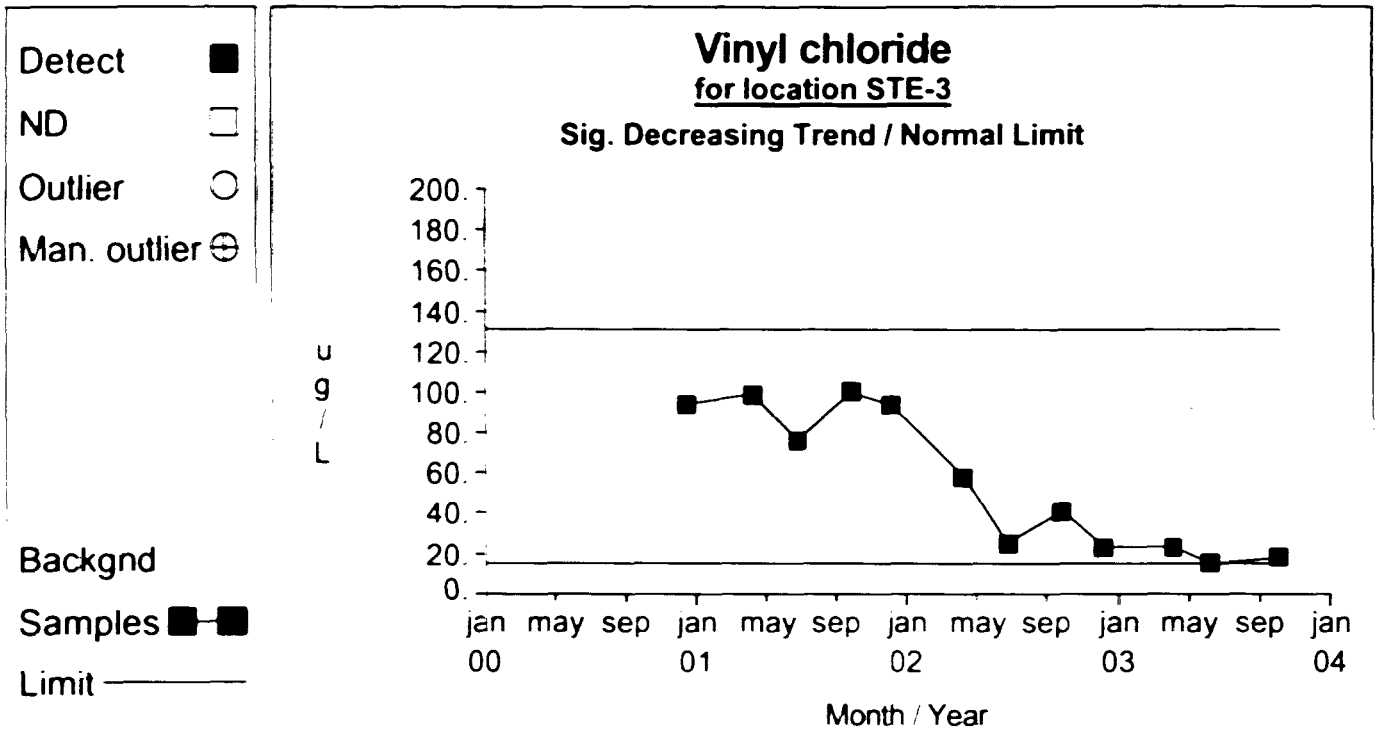


# Comparison to Baseline



**Graph 300**

### Comparison to Baseline



**Graph 304**