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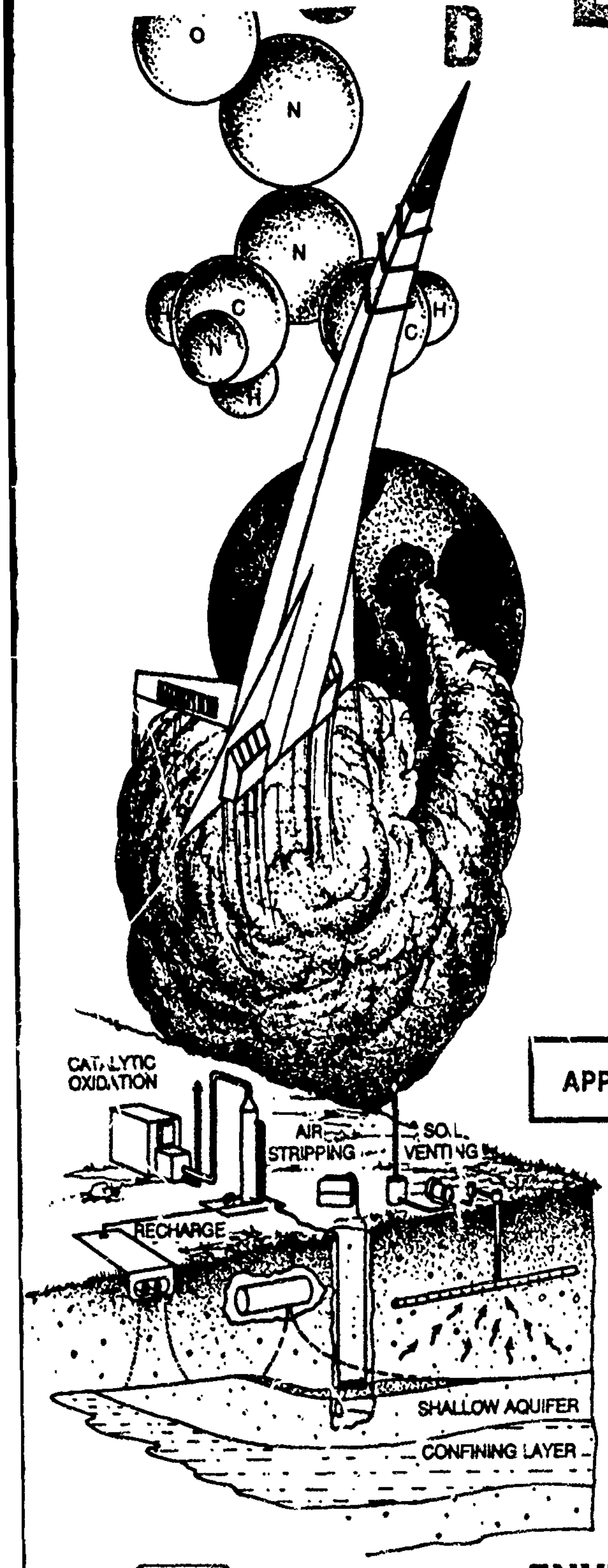
TESTING OF MONITORING DEVICES FOR JP-4 RELEASES IN THE SUBSURFACE



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The purpose of this research program was to select and test the performance of a set of external monitoring devices having the potential application for both underground storage tanks (USTs) and general subsurface monitoring. These devices may be used to detect and/or monitor jet fuel in the subsurface from leaking USTs or other sources. Seven devices considered representative of the monitoring technology available were tested for both vapor-phase and liquid-phase monitoring of JP-4 jet fuel. Cylindrical tanks 12 feet in diameter and 4 feet deep containing a uniform sand were used as test beds. The same materials and precautions were taken for constructing the monitoring wells used in this study as those that would be used in the field. A release that averaged less than 0.02 gal/hr of JP-4 was simulated at the central location of the sand test beds. Gas chromatography analysis was used to determine actual concentrations for comparison to device response. Fresh JP-4 was released into dry sand and moist sand to simulate vadose

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zone monitoring. JP-4 was also released into a test bed with a static water table to simulate a leak into the groundwater. Measurement of floating fuel thickness was determined throughout the liquid phase experiments, as well as liquid and vapor hydrocarbon concentrations. Also, aged JP-4 recovered from an actual spill site was released into moist sand to measure the response characteristics of the instruments. With the aged JP-4 still in the sand, fresh JP-4 was released to determine if the devices can distinguish a new versus old spill. Devices were tested for false positives in response to methane, carbon monoxide, carbon dioxide, hydrogen sulfide, and trichloroethylene vapors. The rapid vapor concentration rise that occurs during a leak indicates that vapor-phase monitoring is an excellent method for early warning of product release. Devices utilizing vapor phase detection for leaking JP-4 had the best overall performance. Devices monitoring for JP-4 floating product on the water table are not as quick or sensitive as the vapor phase devices at detecting a leak. The quantitative output of some devices is a relative measurement; it is not an accurate measurement of the amount of JP-4 in the subsurface. The device reading is not linear with increasing concentration and can be quite variable. Calibration procedures are necessary if the results are to be used for quantitative assessment of contamination.

EXECUTIVE SUMMARY

A. OBJECTIVE

The purpose of this research program was to select and test the performance of a set of external monitoring devices having the potential application for both underground storage tanks (USTs) and general subsurface monitoring.

B. BACKGROUND

Jet fuels are stored by the U.S. Air Force in large tanks, both above and below the surface of the ground. These tanks are associated with complex pipelines and pumping stations used for fueling and defueling aircraft. These jet fuel storage facilities at U.S. Air Force bases must comply with federal, state, and local environmental regulations which require leak detection.

External fuel-release monitoring and leak detection devices can be inserted or installed in the soil or groundwater exterior to all UST systems. These devices may be used to detect and/or monitor jet fuel in the subsurface from USTs and from other sources.

C. SCOPE/APPROACH

Seven devices were tested for both vapor-phase and liquid-phase monitoring of JP-4 jet fuel. Some devices were reportedly capable of monitoring the presence of both vapor and liquid. The tested devices include:

- Fiber optics based FiberChem (FCI) device (vapor- and liquid-phase monitoring)
- Product soluble, destructive type Total Containment, Inc., (TCI) device (vapor- and liquid-phase monitoring)
- Change in liquid conductivity detection based Leak-X system (liquid-phase monitoring)
- Product soluble, destructive type In Situ, Inc., device (vapor- and liquid-phase monitoring)
- Bulk metal oxide semiconductor technology based Arizona Instrument Corp. (AZI) device (vapor- and liquid-phase monitoring)
- Metal oxide semiconductor (MOS) technology based Universal Sensors and Device, Inc., (USD) device (vapor-phase monitoring)
- Adsistor technology based Red Jacket (RJ) device (vapor-phase monitoring)

The following tasks were conducted to evaluate the selected liquid-phase and vapor-phase devices for JP-4 leak detection and monitoring:

- Testing vapor-phase devices for fresh JP-4 leaks in dry and moist sand followed by accuracy and precision analyses of those devices

- Testing vapor-phase devices with aged JP-4 in background

- Testing vapor-phase devices for background interferences

- Testing liquid-phase devices with fresh JP-4 in sand

- Accuracy, precision, and response time determinations for liquid-phase devices

- Column testing in the laboratory to study the transport of dissolved JP-4 and JP-4 vapor in subsurface.

D. METHODOLOGY

The experiments were conducted in a 12-foot diameter and 4.5-foot deep, open-top, fiberglass tank. Monitoring wells were placed in the tank, located radially at distances of 3.0 and 5.5 feet from the tank center. The tanks were filled to a depth of 4 feet with a medium-grade silica sand. The tanks were covered with an impermeable liner to act as a vapor barrier. Devices were placed in monitoring wells as they would be in actual field application. When device design allowed for it, two probes of the same manufacturer and probes from different manufacturers were placed in the same monitoring well for statistical comparison.

Soil gas samples from the monitoring wells were collected periodically and analyzed for total organic hydrocarbon (TOHC) content using gas chromatographic methods. The instrument readings were compared with the analytical TOHC values for accuracy and precision estimates.

The effects of background interfering gases on the vapor-phase devices were tested in a closed stainless steel cylinder. The gases tested included carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), methane (CH_4), and trichloroethylene (TCE).

In the liquid-phase test tank, JP-4 was released just above the water table. Distribution of JP-4 free liquid in monitoring wells was measured using a bailer-type device. Depths required to get an alarm for each device was recorded. Also, another set of experiments were conducted using laboratory-scale columns to determine the accuracy and precision of liquid phase devices.

E. RESULTS AND DISCUSSION

1. Testing of Vapor-Phase Monitoring Devices

During the vapor-phase study, there were no false positive or negative alarms for all the devices that had audible and/or visual alarms (USD, RJ, AZI, TCI, and In Situ). The response of destructive type devices, In Situ and TCI, in detecting JP-4 vapors was rather poor. Destructive type devices (In Situ and TCI) were not effective in detecting JP-4 leaks in moist sand. The vapor-phase test results are summarized in the following sections.

a. JP-4 Leak in Dry Sand Environment

RJ devices were generally unresponsive to JP-4 vapors while USD and AZI sensors were responsive. The overall median accuracies of the sensors indicate that the USD devices are the most accurate followed by AZI sensor and then the RJ sensor.

b. JP-4 Leaks in Wet Sand Environments

When the overall median accuracies were compared, AZI was the most accurate followed by the USD sensor and then the RJ sensor. The accuracy of AZI remained essentially the same for both dry and moist conditions. The accuracy of USD sensors declined noticeably in the presence of moisture.

c. JP-4 Leaks in Contaminated Backgrounds

This test was conducted to examine the response of devices to a JP-4 leak in the presence of background contamination from past JP-4 release. Aged JP-4 was used to spike the sand 100 μg. Neither USD nor AZI responded effectively to a fresh JP-4 leak in the presence of background contamination. In this test, however, the trend of RJ device-readings followed the analytical TOHC values fairly well. Although the RJ device appears to have potential for leak monitoring in contaminated sites, its low response to JP-4 vapors indicates that further studies will be required to investigate how these sensors will compensate for the fluctuation of background hydrocarbon levels.

2. Testing of Liquid-Phase Monitoring Devices

The liquid-phase monitoring devices tested include TCI, Leak-X, In Situ, and AZI. Analysis of data indicated that 83 percent of the Leak-X detectors responded to a 0.25-inch thick layer of JP-4 and 100 percent responded to a 1.5-inch thick layer. None of the TCI devices alarmed for a free-product thickness less than 2 inches; all responded to 2-4 inch thick layers and 2-9.9 inch thick layers. In Situ probes responded rather quickly for floating JP-4. Both sensors tested in this study responded to a layer less than or equal to 0.25 inch. AZI, essentially a vapor sensor, recorded high vapor concentrations well before the appearance of free-product in the monitoring well.

The accuracy, response time, and precision for the liquid-phase devices were determined in laboratory-scale test columns. In Situ, the most responsive device, responded within 1 minute for 1/64-inch JP-4 layer. A newly designed set of TCI sensors responded to thicknesses greater than 1/32-inch, generally within 2-3 hours. Response time decreased with increasing thickness of JP-4 layer. Leak-X appeared to be 100 percent accurate for thicknesses above 15/32 inches.

3. Effects of Background Interferences on Vapor-Phase Devices

In general, the vapor-phase devices were not responsive to CO_2 and CH_4. Both USD and AZI responded to CO. CO interfered with FCI at 9,900 ppm level. Hydrogen sulfide appeared to have a very noticeable effect on USD AZI, and FCI devices. Trichloroethylene vapors were detected by the USD, AZI, and FCI sensors. RJ was not responsive to any of the tested gases or vapors.

4. Transport of Jet Fuel in Subsurface

a. JP-4 Vapor Transport in the Subsurface

The results of the sand and soil column experiments indicate that soil organic matter can result in significant retardation of all JP-4 constituents. This retardation increased from dry sand (very little retardation), to wet soil, to dry soil (very large retardation). The presence of moisture in the unsaturated zone will decrease sorption capacity and, therefore, decrease retardation compared with dry soil. The implication of this study, with respect to monitoring of JP-4 releases in the subsurface, is that small leaks may go undetected by vapor sensors for much longer in organic soil than in sand.

b. Transport of JP-4 Liquid in Porous Media

There are several models available to estimate the recoverable free liquids in pore spaces as floating product. A recently developed model, OILEQUIL, along with SOILPROP program, was tested using the experimental data obtained for the liquid-phase test. The parameter estimation procedure by van Genuchten followed by use of OILEQUIL gave a fairly accurate estimate of free liquid present in the pore spaces.

c. Transport of Dissolved JP-4 in Soil and Sand

The results of the dissolved JP-4 study indicated that benzene, toluene, xylenes, and ethylbenzene (BTX&E) were the most soluble components in water. No other components were observed in measurable quantities in the soil column effluent. No retardation of BTX&E was observed in sand columns, whereas some retardation was observed in the soil column. Retardation factors increased with molecular-weight and decreasing solubility of JP-4 components.

F. SUMMARY AND CONCLUSIONS

1. Vapor-Phase Monitoring

The USD devices: initial overprediction followed by underprediction; generally a good response at low TOHC levels (<20,000 ppm); better accuracy and precision in dry environment; nonuniform prediction makes it difficult to calibrate for a wider TOHC range; immediate response and fast recovery; not suitable for high TOHC concentrations; not applicable for contaminated sites; and interferences from moisture, H_2S, CO, and TCE.

The AZI devices: continuous underprediction; fairly uniform response; consistent accuracy and precision at both dry and moist environment;

not suitable for highly contaminated soils; and interferences from CO, H_2S, and TCE.

The RJ devices: consistent underprediction; very poor response (sometimes only above 60,000 ppm); responded to a leak when background contamination was high; apparent lag time for response; and no apparent effect from background interfering gases/vapors.

The FCI sensors: prototype unit performance was inconsistent; and responded to TCE, CO, and H_2S.

The In Situ and TCI sensors: not effective for vapor-phase monitoring; did not meet manufacturers' claims; and used only for liquid-phase monitoring.

2. Liquid-Phase Monitoring

It was found that 100 percent of In Situ devices responded to 1/64-inch thick JP-4 layer in one minute. With TCI, 100 percent responded to 1/32-inch thick JP-4 layer in three hours. With Leak-X, 83 percent responded to a 1/4-inch thick JP-4 layer.

G. RECOMMENDATIONS

The following recommendations can be made: MOS devices may be used in "clean sites" for leak monitoring; each MOS device needs to be calibrated for JP-4 vapor and quality checked prior to installation; if background is contaminated, a tracer base technology (not tested) may be used; for liquid-phase monitoring, product soluble type devices are the most effective.

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PREFACE

This report was prepared by Battelle, 505 King Avenue, Columbus, Ohio 43201-2693, under Task Order Contract F08635-85-C-0122, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RDVW), Tyndall Air Force Base, Florida 32403-6001.

Research documented in this report was performed between September 1988 and April 1990. HQ AFESC/RDVW project officers were Mr Hari Bindal and Mr Bruce Nielsen.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The purpose of this research program is to select and test the performance of the external monitoring devices having the most potential application for both underground storage tanks (USTs) and general subsurface monitoring. During Phase I of this program, the existing and emerging external monitoring and leak-detection devices were studied by reviewing technical and marketing literature. Phase II of this study involved testing a set of vapor and liquid monitoring devices selected in the Phase I study. This technical report contains the results of the Phase II study and a conceptual network design of monitoring devices for two Air Force sites.

B. BACKGROUND

Jet fuels are stored by the U.S. Air Force in large tanks, both above and below the surface of the ground. These tanks are associated with distant and complex pipelines and pumping stations used for fueling and defueling aircraft. A substantial number of these pipelines are underground. Fuel storage facilities with storage tanks and pipelines are potential sources of groundwater contamination. Such contamination may result from surface spills, as well as from leaks occurring in the subsurface, which find their way to the groundwater.

Jet fuel storage facilities at U.S. Air Force bases must comply with federal, state, and local environmental regulations. For example, the U.S. Environmental Protection Agency (EPA) developed regulations in 1988 for USTs storing either petroleum or certain hazardous chemicals. A UST is defined as any tank, including underground piping connected to it, that has at least 10 percent of its volume underground. A summary of the major points of the UST regulations is as follows:

- A UST installed after December 1988 must meet the requirements for new USTs concerning correct installation, spill and overfill prevention, corrosion protection, and leak detection.
- A UST installed before December 1988 must meet the corrosion protection, spill and overfill protection, and leak detection requirements within a certain time period established by EPA.

- Appropriate corrective action must be taken in response to a leak.
- When closing temporarily or permanently, appropriate closure requirements should be met.
- If a tank leaks, the owner of the tank is financially responsible for clearing the affected property and compensating the affected people.

Under these laws, leak detection and long-term tank monitoring is required. Detecting a small leak as it occurs can avoid or minimize large-scale groundwater contamination and the tremendous costs associated with cleanup efforts.

External fuel-release monitoring and leak detection devices can be inserted or installed in the soil or groundwater in the exterior of an underground tank or other containment systems to detect leaks by confirming the presence of the leaking jet fuel (JP-4) in the soil or groundwater. These devices may be used to detect and/or monitor JP-4 in the subsurface released from underground tanks and from other sources, including those aboveground. There is no way of relating device response to release rate of JP-4.

Devices that can measure concentration may be used to map a vapor or dissolved product plume resulting from a recent release or presence of aged JP-4. On/off-type devices, which do not measure concentrations but only activate an alarm, will also detect the presence of JP-4 when its concentration or accumulation in the subsurface exceeds a preset level.

If, for example, a drinking water well is located near a JP-4 release point(s), appropriate types of these devices may be installed at critical distances from the source to monitor the JP-4 movement and concentration increase. This may also be done by taking soil-gas or water samples and analyzing them in the laboratory. Such an approach may be more accurate, but also more labor-intensive, time-consuming, and expensive in the long run compared with *in situ* continuous monitoring.

Many of the available monitoring devices are targeted to specific subsurface fuel release applications, whereas others are mainly used for ambient air monitoring or industrial hygiene applications. Some of the known external monitoring techniques include soil gas/vapor monitoring, tracer or fuel component detection, and soil thermal and electrical conductivity measurements. Many new devices are also emerging.

One of the difficulties in selecting a device for a particular subsurface monitoring application is the lack of reliable performance data. Such data, when available, are usually found in the marketing literature to support manufacturer's claims that are sometimes unrealistic. Many of these data have not been scrutinized by the scientific and engineering community.

C. SCOPE/APPROACH

Altogether, seven devices were tested for both vapor-phase and liquid-phase JP-4 monitoring. Some devices were reportedly capable of monitoring the presence of both vapor and liquid. A list of these devices and their applications is given in Table 1. The selection of these devices was based on the technical and marketing literature. Several sensors from one manufacturer were used in some cases, not because they appeared to be technically superior to others, but because they were smaller so that several could be installed in one testing location for comparison and statistical analysis.

The following tasks were conducted to evaluate the selected liquid-phase and vapor-phase devices for JP-4 leak detection and monitoring. Some of the tasks were designed to address the effects of distance from the leak on the device response and transport of JP-4 vapor and liquid in the subsurface.

- Testing liquid-phase devices with fresh JP-4 in sand
- Accuracy, precision, and response time determinations for liquid-phase devices
- Testing vapor-phase devices for fresh JP-4 leaks in dry and moist sand followed by accuracy and precision analyses of those devices
- Testing vapor-phase devices with aged JP-4 in background
- Testing vapor-phase devices for background interferences
- Column testing in the laboratory to study the transport of dissolved JP-4 and JP-4 vapor in subsurface.

Detailed descriptions of each of these tasks are given in Section III, Materials and Methods.

TABLE 1. SELECTED DEVICES FOR MONITORING AND DETECTION OF JP-4 RELEASE IN THE SUBSURFACE.

Device ID#	Company	Product name	Fuel release occurs in	Potential application
1.	FiberChem, Inc. (FCI)	FOCS	vadose zone saturated zone	new, old sites
2.	Total Containment, Inc. (TCI)	TCI Leak Detector	vadose zone saturated zone	new, old sites, pipelines
3.	Leak-X Corporation	Leak-X System	saturated zone	new, old sites
4.	In Situ, Inc.	Petrochemical Release Monitor	vadose zone saturated zone	new, old sites
5.	Arizona Instruments Corp (AZI)	Soil Sentry 17-100L	vadose zone saturated zone	new, old sites
6.	Universal Sensors and Devices, Inc. (USD)	Leak Alert	vadose zone	new, old sites
7.	Red Jacket (RJ)	PPM 3000	vadose zone	new, old sites

SECTION II

DEVICE SELECTION AND DESCRIPTIONS

A. DEVICE SELECTION

Selection of an appropriate device for monitoring JP-4 release in the subsurface is difficult because one has to choose from a large number of devices available in the marketplace, and because of lack of reliable performance data. Generally, selection of an appropriate device depends on site-specific and device-specific characteristics. The relationship between site-specific characteristics and device selection is shown in Table 2. The selection between similar liquid or vapor-phase devices was made on the basis of device-specific characteristics. Such characteristics were related to device performance, maintenance, interferences, and ability to provide a quantitative output, as well as data. The evaluation criteria presented in Table 3 are the device-specific characteristics that were used for device selection.

The devices were evaluated in the Phase I study (Voudrias et al., 1988) by comparing the information provided by the vendors with the evaluation and selection criteria (Table 3) appropriate to the needs of the Air Force. On the basis of this evaluation, promising devices were selected and recommended for testing. These are listed in Table 1. Continuous monitoring devices from as many categories as practical were selected for testing.

Because the devices presented in Table 1 were selected based primarily on information provided by the vendors, it was necessary to test the devices before they could be used in real-world applications. This report presents the results of a series of tests conducted to study the effectiveness, advantages, and limitations of a set of devices.

All of the devices (except FiberChem) evaluated are equipped with a visual or audible alarm, which is usually activated when site concentrations of jet fuel exceed the preset alarm levels. However, activation of an alarm does not necessarily imply JP-4 release in the subsurface. Therefore, the ability of a device to activate a visual or audible alarm, although sometimes useful, may not be a critical characteristic for selection.

An important consideration was the ability of a device to measure JP-4 concentrations and store data. Such information is important in determining

TABLE 2. RELATION BETWEEN SITE-SPECIFIC CHARACTERISTICS AND DEVICE SELECTION

Site characteristic	Device selection
vadose zone	vapor-phase device
saturated zone	liquid-phase device
high background vapor concentration	vapor-phase devices may not be appropriate
old site	device may be difficult to retrofit
type of product in subsurface	device must respond to this product
highly variable water table	device with a floating detector may be unsuitable
surface spills	vapor-phase devices may not be appropriate
environmentally sensitive area	continuous monitoring device

TABLE 3. EVALUATION AND SELECTION CONSIDERATIONS FOR FUEL RELEASE MONITORING DEVICES

1. Sensitivity to JP-4 Fuel
2. Detection Limit
3. Accuracy/Precision
4. Distance Between Monitor and Sensor
5. Sensitivity to Interferences/False Negative or Positives
6. Data Collection/Alarm Capability
7. Time required for Measurement
8. Multiple Monitoring Locations
9. Site Disruption
10. Maintenance Requirements
11. Reliability
12. Life Expectancy
13. Use for Detection of Pipeline Leaks
14. Cost
15. Saturation Level

the presence or absence of JP-4. Also, some devices (Leak-X, AZI or Arizona Instruments, Universal Sensors and Devices, Fiberchem) can be interfaced with a central computer. Computer interfacing is useful not only for data storage and analysis, but also for data transmission at long distances. Computer interfacing is an important criterion when selecting devices for monitoring and managing sites located far away from a central location.

From the five diffusion sensor devices, the PPM 3000 (Red Jacket) was selected because it can measure and report concentrations in relative terms such as parts per million (ppm) total organic hydrocarbon content (TOHC) measured as isobutane. The others only register an alarm when the vapor concentration exceeds the preset level: such a mode of operation may be inadequate in detecting the presence of a release.

Leak Alert (USD) and Soil Sentry (AZI) are metal oxide semiconductor (MOS) devices and were also selected because they can measure concentrations. The former is a passive sensor (i.e., it is placed in the subsurface and responds once it comes in contact with the traveling vapor plume). The latter is an active sensor (i.e., it uses an aspirating system which, according to the manufacturer, influences the direction of transport of the vapor plume and measures its concentration).

The fiber optic-based device (FiberChem) is reported by the vendor to be capable of measuring concentrations at ppb/ppm levels of vapors in the vadose zone as well as dissolved fuel components in groundwater. The ability to measure such low concentrations is important for prompt fuel release detection, especially in the saturated zone and in clean areas. For comparison, the continuous liquid-phase Leak-X system registers an alarm only when free-floating product in the monitoring well reaches a thickness of 1/8 inch.

The Air Force needs devices for new sites, old sites, and pipelines. New sites are those in which USTs, pipelines, or other JP-4 storage is newly installed in a site with no background contamination. Old sites are locations where background contamination from past leaks or spills may exist. Of the devices listed in Table 1, the TCI Leak Detector (Total Containment, Inc.) is particularly suited to monitor JP-4 release from pipelines. Long product-permeable cables are placed along new pipelines or may be retrofitted to old pipelines. The magnitude of the change in the electrical conductivity of the permeable cable is reported by the vendor to determine the location of the leak in the pipeline.

The remainder of the devices in Table 1 can be applied to old or new sites for general subsurface monitoring of fuel releases from underground storage tanks or other sources. Devices with a low detection limit will be most appropriate to new sites, where background interference is small or negligible. Less sensitive devices will only respond when the product concentration of the clean site reaches their detection limit, but such a response may be too late in preventing a large release in the subsurface. In old contaminated sites, very sensitive vapor-phase devices may not be the most appropriate, because of potential frequent false positive alarms. Another consideration for contaminated sites is the saturation level of the device or dynamic range. For example, the saturation levels for USD and RJ reported by the manufacturers are 10,000 and 4,000 ppm, respectively. If the background contamination is above the saturation levels, a JP-4 release in the subsurface will not be detected.

B. DEVICE DESCRIPTIONS

This section provides a brief description of each of the devices listed in Table 1 and selected for testing. The following is based on the manufacturers' literature provided at the beginning of this study and may not have been tested or verified by Battelle or the Air Force. The cost estimates were those provided to Battelle at the time; actual costs may vary.

1. FiberChem, Inc. (FCI), Albuquerque, New Mexico

a. Device Description

FiberChem is developing a gasoline sensor which features a fiber optic chemical sensor (FOCS) and a reader. The FOCS consists of an inexpensive optical fiber with a chemical coating on the base fiber at the end. The reader consists of a light source, which sends the light down the fiber optic to the FOCS. There, the light transmitting characteristics are changed in response to the contaminant and returns up the same fiber to the reader for analysis. The prototype model used in this study outputs a millivolt reading which is then converted into parts per million (ppm) from a calibration curve.

FiberChem claims that FOCS can be used to detect free petroleum products, dissolved hydrocarbons, and vapors.

b. Engineering Comments

- The system has a data collection capability.
- The response to hydrocarbons is reversible, with approximately 2 to 3-second time lag.
- The system measures concentrations for both dissolved and vapor-phase hydrocarbons.
- The system is sensitive down to the ppm (possibly ppb) level Exact accuracy is currently being determined under various conditions.
- Sensor is very small, approximately the size of a pencil tip.

2. Total Containment, Inc. (TCI), Exton, Pennsylvania

a. Device Description

The TCI Leak Detector is a continuous liquid-monitoring system whose sensors are product soluble. When the probe is immersed in fuel, the insulation jacket dissolves causing the conductor wires to make contact and signal an alarm. The sensor cable reaction time for Fuel Oil #1 is 4 hours and the sensor can detect 1/100-inch layer of hydrocarbon liquids. The sensor jacket is not affected by water, therefore this device may be particularly useful in areas with saturated or variable water tables. The TCI system has been on the market since 1971 and comes with a 10-year warranty. The monitor console is approximately $1,000 and the sensors are $100 to $160 each. TCI also makes a sensor cable which may be installed in the annular spaces of piping systems.

b. Engineering Comments

- Sensors need to be replaced after exposure to hydrocarbons.
- Sensors may degrade because of background contamination, such as vapors in the vadose zone.
- The system does not have data collection capability but only activates an alarm.
- The system does not measure concentration.
- Each monitor can accommodate up to 10 sensors.
- The system can be used for fuel release from pipelines.

3. Leak-X Corporation, Englewood Cliffs, New Jersey

a. Device Description

The Leak-X System is a continuous liquid-phase detection technique. Operation of the sensors is based on the principle of electrical conductivity. Sensors monitor the fluid conductivity at the air/water interface and can detect an 1/8-inch layer of oil on water. The system has been used in the field for over 10 years and comes with a 1-year warranty. Suggested cost for the monitor and annunciator is $2,145, and $825 per sensor.

b. Engineering Comments

- The device may be subject to interferences, such as ice or biofouling or gas bubbles collected at the conductors.
- The floating mechanism may fail because of ice or physical obstacles or may not operate effectively if the well is not vertical.
- The system includes an audible and visual alarm and can be interfaced with computers, central alarms, strip chart recorders, shutdown valves, and telephone lines.
- The device does not measure concentration.
- Each monitor can accommodate 10 sensors.
- Depending on the number of sensors, the maximum distance between monitor and sensors ranges from 1,000 to 4,000 feet.
- The system has been tested by the National Bureau of Standards which reported that the operation and performance claims by the manufacturer are valid.

4. In Situ, Inc., Laramie, Wyoming

a. Device Description

The Petrochemical Release Monitor (PRM) is a continuous product-soluble device for detecting liquid hydrocarbons. The sensors can detect less than 1/10 inch of hydrocarbons at the water/air interface. An audio alarm indicates the presence of a leak, and a visual alarm identifies which sensor detected the leak. The cost of a Remote Station with four probes is approximately $1,600. The system will also respond to vapors. According to the manufacturer, activation for gasoline vapors occurs after 5 hours exposure to 5,000 ppm or 1 hour exposure to more than 25,000 ppm.

b. Engineering Comments

- Sensors need to be replaced after exposure to hydrocarbons.
- Sensors may degrade after exposure to background contamination.
- The system does not have data collection capability but only activates an alarm.
- The system does not measure concentration.
- The system can accommodate up to eight monitoring points.
- The maximum distance between sensors and monitor is greater than 1 mile.

5. Arizona Instrument (AZI) Corp. (formerly Genelco), Tempe, Arizona

a. Device Description

The newest system is the Twelve-X; Soil Sentry 17-100L was used in this study. This is a vapor-sensing system consisting of an aspirator pump for vapor collection, a bulk semiconductor (metal oxide semiconductor, MOS) vapor analyzer, a manifold assembly with solenoid valves allowing selective sampling at multiple locations, a microprocessor, an alarm system, and a printer. The monitoring probes consist of 0.5-inch inner diameter PVC pipe with 0.01-inch slots. The 1/4-inch inner diameter tubing is used to connect the module to the remote probes. The system draws air samples from the probes; the samples are analyzed in the module for their hydrocarbon content. The detection limit is reported by the manufacturer to be ~100 ppm (depending on product type). The suggested cost of the system is $4,850 plus the cost of the PVC tubes for 12 monitoring wells.

The software package available for Soil Sentry 17-100L allows someone to store and display vapor concentrations versus time on any monitoring well, as well as monitor alarm events. The software package is more flexible, although more complicated than others exhibited. The cost for the software and the IBM compatible PC is $600 in addition to the cost of the device.

b. Engineering Comments

- The system may be subject to interferences, such as methane.
- The system is suitable for sites with high vapor background.
- The saturation level of the detector is higher than 30,000 ppm.
- The system measures total vapor concentration but not specific compound concentration.
- The maximum distance between monitor and sensors is 500 feet.
- The system has data collection and computer capability, as well as audible and visual alarms.
- The system can accommodate up to 12 monitoring locations.
- Subzero-degree temperatures may cause operational problems.

6. Universal Sensors and Devices, Inc. (USD), Chatsworth, California

a. Device Description

USD manufactures the Leak Alert, a vapor-phase continuous monitoring system with both visual and audible warnings of hydrocarbon vapors generated by leaking fuels. The level at which the warning system is activated can be field adjusted for background vapor screening. The sensor is a metal oxide semiconductor (MOS) type. Components of an MOS system include a heater and a collector embedded in a solid state cell, which is composed of metal and nonmetal oxide of transition elements. Hydrocarbon vapor molecules are dissociated into charged ions or ion complexes on the surface of the sensor, resulting in a change of the electrical resistance of the junction. The vapor concentration can be determined from the proportional change in resistance. The manufacturer reports that, depending on the vapor type, the sensor has a detection limit of approximately 200 ppm. The system can be computer-interfaced for data handling. The suggested cost of the system for 16 monitoring wells is $11,200.

The Leak Alert System was able to measure JP-4 vapor concentration from a container with a slightly loosened screw-cap and activate an alarm once the alarm set level was exceeded. The total cost for 16 sensors, the monitor, the software, and the PC is $12,300. The optional site-option software costs an additional $600 plus $100 per sensor. One disadvantage is that the detector will saturate at ~10,000 ppm and, therefore, may not be appropriate for sites with high background contamination. The option available for sites with background contamination above 5,000 ppm is to use a catalytic sensor with the same Leak Alert/Software System manufactured by the same company.

b. Engineering Comments

- The system may be subject to interferences, such as methane.
- The system may not be suitable for sites with very high vapor background contamination.
- Detector may saturate at vapor concentrations above 7,500 ppm.
- The system measures total vapor concentration but not specific component concentration.
- The maximum distance between monitor and sensors is 3,000 feet.
- The system has data collection and computer interfacing capability, as well as visual and audible alarms.
- The system can accommodate up to 48 monitoring locations.

7. Red Jacket Electronics, Mission, Kansas

a. Device Description

Adsistor Technology manufactures sensors used with devices marketed by other companies for hydrocarbon vapor detection in the vadose zone. The sensor is a diffusion-type with a manufacturer's reported detection limit of less than 100 ppm and accuracy of ± 5 percent. The life expectancy in the ground is more than 10 years. Examples of companies using Adsistor sensors with their devices are Emco Wheaton, Red Jacket, and Adams Precision Instrumentation Company.

Red Jacket's model PPM 3000 is a microprocessor-based programmable control unit, equipped with eight independent diffusion sensors (Adsistor type). The claimed detection limit is 150 ppm and the sensor's active radius is 20 feet. The model PPM 3000 is priced at $1,395 per monitor plus $510 per sensor (i.e., approximately $11,000 per 16 monitoring points). The optional multiplexor is priced at $750.

b. Engineering Comments

- The model may not be suitable for sites with high vapor background.
- The saturation level of the detector is about 4,000 ppm.
- The model measures total hydrocarbon vapor concentration but not specific component concentration.
- The maximum distance between monitor and sensor is 2,000 feet.
- The model has data collection capability and can activate a visual or audible alarm.
- The model can accommodate eight monitoring locations (up to 128 with a multiplexor).

SECTION III

MATERIALS AND METHODS

The objective of this study was to test the accuracy, precision, and obtain useful information on some selected petroleum hydrocarbon vapor and liquid monitoring and leak-detecting devices for JP-4 releases. This study was conducted under several subtasks. The first two subtasks involved testing vapor-phase devices under different environmental conditions (e.g., dry and wet sand) in the presence of fresh and/or aged JP-4. The next two subtasks involved testing liquid-phase devices. In one of these subtasks, the response of the liquid-phase devices was tested in a large sand tank where a JP-4 leak was simulated. The other task involved testing accuracy, precision, and response time in controlled bench-scale studies. Further testing was conducted with vapor-phase devices to study the effects of interfering gases such as methane, carbon dioxide, etc. To determine the fate and transport of JP-4 vapors and dissolved components in the subsurface, a series of laboratory-scale column tests was conducted using sand and soil as the media. This section (Materials and Methods) presents the detailed experimental approach for each of the above subtasks.

A. ANALYTICAL METHODS

1. Gas Chromatographic Analysis of Vapor and Liquid Samples

a. Total Organic Hydrocarbon Content (TOHC) Analysis

TOHC analysis was performed on a Hewlett-Packard 5890 gas chromatograph equipped with a Hewlett-Packard 3392-A integrator. The column used was an HP-1 cross-linked methyl silicone gum, 30 meters (long) x 0.53 mm (i.d.) x 2.65 μm (film thickness), megabore capillary column (Hewlett-Packard). The GC conditions were as follows:

carrier gas : helium (10 psi)
flame : air (34 psi), hydrogen (16 psi)
detector : FID, 250°C
injector : 200°C
oven : 225°C

The sample size for all injections was controlled through the use of a 1 cc sample loop. Sample TOHC concentration was quantified through calibration against 1,000 ppm and 1 percent butane standards (Alltech Associates, Inc., Deerfield, Illinois).

b. Temperature Program Analysis

Two different temperature program analyses were used to evaluate hydrocarbon distribution in the vapor samples. Both methods employed the use of a temperature gradient to separate components of the JP-4 vapor.

One temperature program analysis, performed routinely on samples during each experiment, used the same procedure as the TOHC analysis, except that the helium flow was reduced to 6 psi and a constant temperature of 50°C for 2 minutes followed by a temperature gradient ranging from 50°C to 225°C in 15 minutes was used. This analysis was used to track the relative migration of low, medium, and heavy hydrocarbons.

A second temperature program analysis was used on selected vapor samples to identify and quantify specific compounds making up the JP-4 vapor. This procedure was also used to analyze aqueous phase samples (from the liquid-phase experiments) and neat JP-4 samples.

The samples were analyzed using a Varian Model 3700 GC equipped with a Hewlett-Packard Model 3388 integrator, a 30-meter megabore fused-silica capillary column (0.53 mm I.D.; 2.65 μm film thickness), a flame-ionization detector (FID), and a multipurpose inlet interface. The multipurpose inlet interface is shown schematically in Figure 1. This system consists of a cryogenic trap, a Nafion dryer, a heated injector, two gas inlets, a fixed-volume sample pump and two multiport switching valves. Samples of JP-4 vapor were obtained by flushing the trap (operated at room temperature) and injecting the known volume (1.01 cc-atm) of the trap. Fuel samples, typically 1 to 5 μL, were first injected into evacuated and heated 1.7 liter aluminum cylinders. The total pressure in the cylinder was then raised to approximately 15 pounds per square inch, absolute (psia), and a vapor aliquot was sampled and analyzed, as were the JP-4 vapor samples. Aqueous samples were vaporized in the heated injection port, after which they passed through the Nafion dryer. The hydrocarbon components of the aqueous samples were then collected on the cryogenic trap (T = -150°C). This procedure allowed direct injection of water samples as large as 50 μL, and multiple injections could be used for sample concentration where needed.

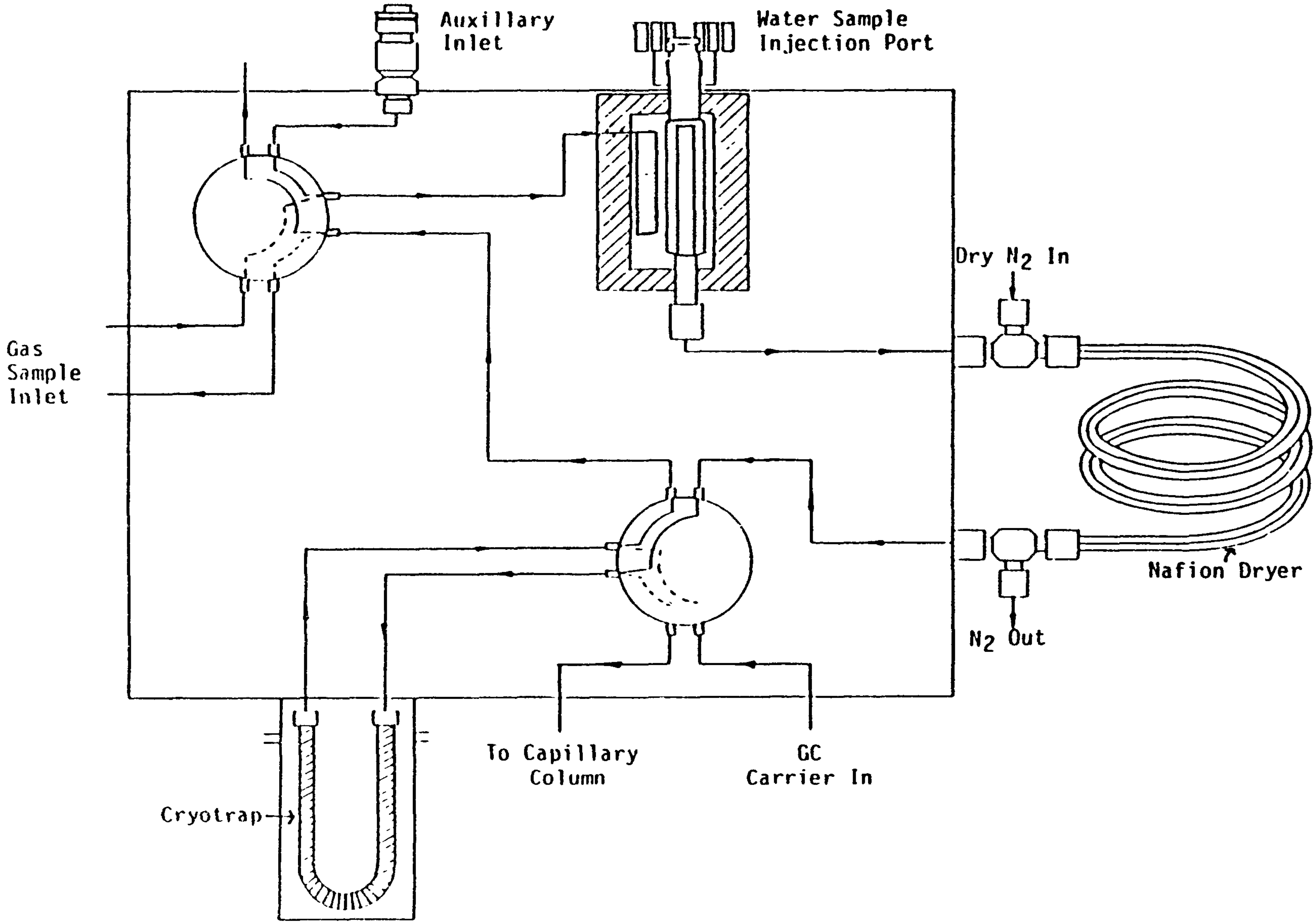


Figure 1. Multipurpose Inlet System.

Samples were routinely monitored for 29 major components of JP-4. Identification of components was based on column retention times. Integrator outputs included the mass of each component detected, weight fraction in the sample for each component, mole fraction in the sample, and evaporation rates (where applicable). Inasmuch as JP-4 consists of many minor components, as well as those being monitored directly, a procedure was developed to estimate the masses and mole fractions of the unidentified components to account for the total sample. Because the molecular weights of identified components were linearly correlated to their retention times, it was assumed that the molecular weights of unidentified components were similarly correlated. It was also assumed that the unidentified components were all saturated hydrocarbons and that their flame ionization detector (FID) response factors (weight basis) were the same as those determined for the identified saturated hydrocarbons. This procedure permitted estimation of total JP-4 fuel samples and 82 weight percent of the gas-phase samples.

2. Porous Medium Characterization

The following parameters were characterized for the #2040 medium-grade sand used in all experiments: particle size distribution, density, porosity, permeability, and total organic carbon (TOC).

a. Particle Size Distribution

The particle size distribution analysis was subcontracted to CTL Engineering, Inc., Columbus, Ohio. CTL was provided with two samples of the bagged sand (used in the JP-4 release and containment unit) and two samples of the bulk sand (used to fill the tanks) to compare particle size distribution. Each sample was passed through a series of U.S. standard sieves to see what percentage of the sample would be retained at each sieve size. The analysis showed no significant differences in sand particle size distribution between the bagged and bulk sand.

b. Density, Porosity, and Permeability

The density, porosity, and permeability measurements were subcontracted to BBC & M Engineering, Inc., Columbus, Ohio. BBC & M was provided with one 80-lb bag of the bagged sand to perform all tests. A 5-foot long, 4-inch diameter, PVC pipe was used to determine the sand density, porosity, and permeability at different depths (as would be experienced in the vapor tank). Sand was poured into the pipe in 1-foot layers, and the incremental densities were computed for each layer. The data were used to estimate the densities at various depths in the tank. A constant head permeability test was performed in a permeameter on three sand specimens at densities of 90, 93, and 96 pounds per cubic foot. The porosity was computed for the sand based on the weight of the sand, the specific gravity, the temperature-corrected unit weight of water, and the volume. All procedures used were based on Soil Testing for Engineers (Lamb, 1951).

c. Organic Carbon Content in Sand

Organic carbon content in sand was determined using an O.I. Corporation Model 524C Total Carbon System, which is a versatile instrument for the laboratory determination of carbon in discrete samples with an analytical detection limit of 0.1 ppm. The principle of the analysis is that carbon is converted to carbon dioxide gas, which is measured by nondispersive infrared analyzer equipped with a digital integrator. The integrated peak area is related to the weight of carbon in the sample by comparison with standards of known carbon content.

At least 10 grams of sand were placed in a glass ampule. Then 1 mL of 7-percent potassium persulfate and 0.5 mL of 10-percent phosphoric acid were added to the ampule and sealed. These ampules were baked at 130°C for 30 minutes and the amount of CO_2 generated was analyzed.

B. EXPERIMENTAL DESIGN FOR VAPOR-PHASE STUDIES

The vapor-phase devices were tested in a sand-filled fiberglass tank with fresh JP-4 for (1) false signal with no fuel release, (2) minimum vapor detection limit, and (3) two different vadose zone moisture contents.

1. Tank Description

In both the vapor-phase and the liquid-phase experiments, studies were conducted in 12-foot diameter and 4.5-foot deep, open-top, fiberglass tanks lined with chemically resistant Koppers 6631T resin (Bigard Inc., Newton, Illinois). Each tank was equipped with four hose hookups, located equidistant from each other at the tank bottom, to fill or drain liquids from the tanks if necessary. The tanks were filled to a depth of 4 feet with 2040 medium-grade sand (Best Sand Corp., Chardin, Ohio), after placement of the monitoring wells. A cross-sectional view of the vapor-phase test tank is given in Figure 2.

In the vapor-phase experiments, 11 monitoring wells were needed for placement of the vapor-sensing devices. The wells, labeled A through K, were placed radially from the center of the tank (see Figure 3). Wells A, B, C, D, F, G, H, I, and K had 4-inch diameter by 2-feet long, 10-slot, wrapped stainless steel screens (Cooks Screen Div., Cincinnati, Ohio) and 4-inch diameter by 3-feet long, schedule 40, PVC well casings (Aardvark Corp., Puyallup, Washington). Wells E and J had 2-inch diameter by 3-feet long, 10-slot, wrapped stainless steel screens, and 2-inch diameter by 3-feet long, stainless steel casings (Cooks Screen Div.). All wells were capped with PVC well caps (Cooks Screen Div.) fitted with vapor sampling ports. Each sampling port consisted of a septum connected to 1/16-inch (i.d.) stainless steel tubing (Small Parts Inc., Miami, Florida) extending to the depth designated for the placement of the sensors in each well. The wells were kept in place with a steel angle iron structure until the tank was filled with sand.

Before filling the tank with sand, a JP-4 vapor delivery and liquid containment unit, as shown in Figure 4, was placed in the center of the tank to contain excess liquid JP-4 and to minimize the extent of liquid JP-4 contamination in the sand bed. This system consisted of a modified 55-gallon drum (Columbus Steel Drum Co., Columbus, Ohio), with wire mesh sides (impervious to the 2040 grade sand) making up the top 34 inches and the bottom 14 inches being left as a liquid receptacle. Inside the drum, a wire mesh was installed 8 inches from the bottom, on top of which a 6-inch layer of 67 grade (1/4- to 1/2-inch size) gravel (Best Sand Corp.) was placed. A 15-inch diameter by 34-inch deep, wire mesh basket was placed on top of this layer and was filled with the 2040 grade sand. The area between the outside of the basket and the inside of the drum was then filled with gravel. A hand pump was installed so that the JP-4 receptacle could be emptied from the surface of the tank.

An Ismatec JPN-16 peristaltic pump (Cole-Parmer Instrument, Chicago, Illinois) was used to deliver JP-4 to the vapor source. In the first vapor-phase experiment Tygon® pump tubing (Cole-Parmer Instrument) was used in the Ismatec pump to meter fuel delivery. It was discovered that the Tygon® was affected by JP-4, so in subsequent experiments a more chemically inert Viton® tubing (Cole-Parmer Instrument) was used (see Vapor Test 1, Section III.C.1).

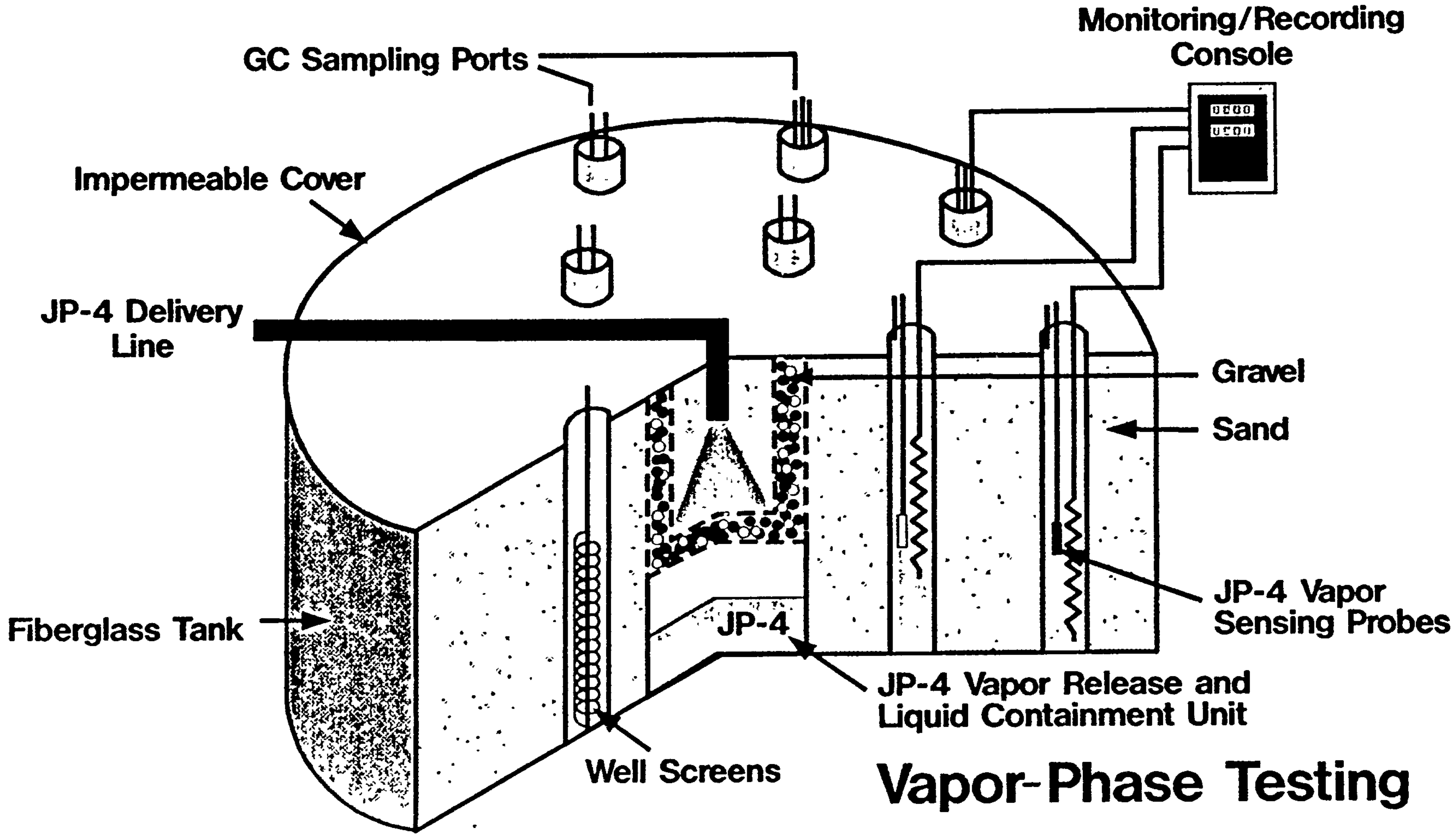
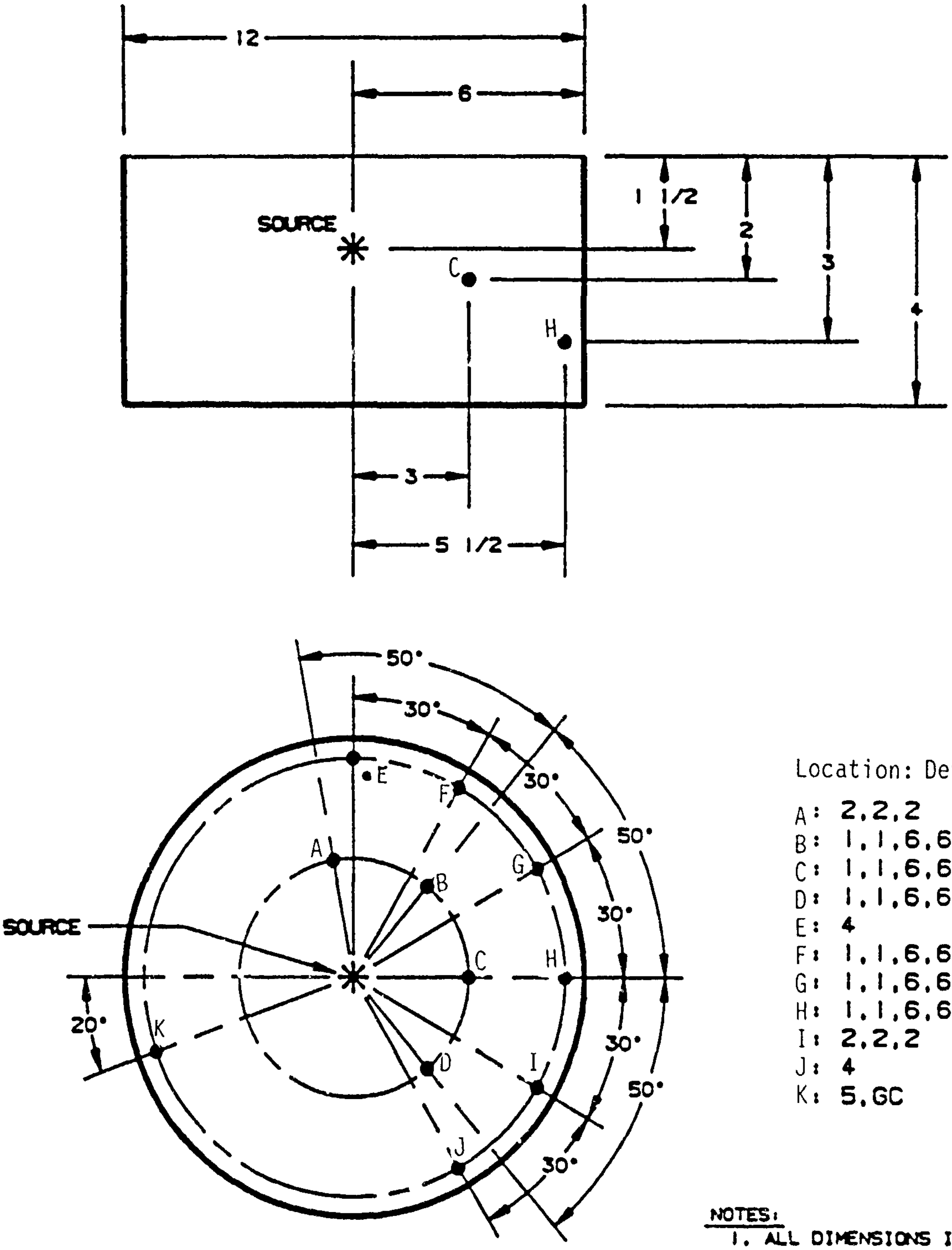


Figure 2. Vapor-Phase Testing Device for JP-4 Releases.



Location: Device (Table 1)

A: 2,2,2
B: 1,1,6,6,7,7,GC
C: 1,1,6,6,7,7,GC
D: 1,1,6,6,7,7,GC
E: 4
F: 1,1,6,6,7,7,GC
G: 1,1,6,6,7,7,GC
H: 1,1,6,6,7,7,GC
I: 2,2,2
J: 4
K: 5,GC

NOTES:
1. ALL DIMENSIONS IN FEET.
2. NOT TO SCALE.

Figure 3. Tank Configuration for Vapor-Phase Testing and Location of Sampling and Monitoring Devices.

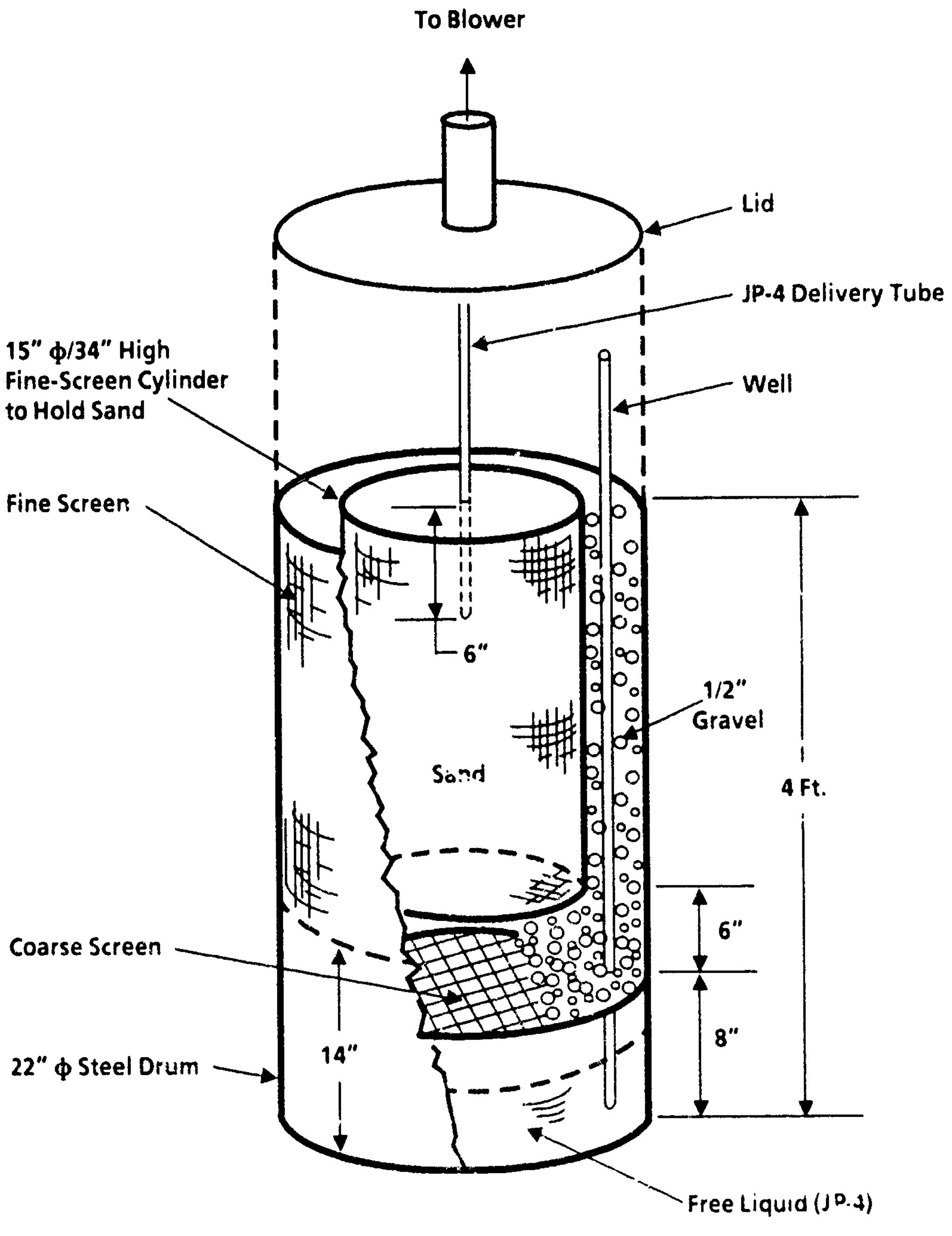


Figure 4. Schematic of Fuel Delivery and Liquid Containment System for Vapor Phase Study (not to scale).

The vapor source worked as follows: Liquid JP-4 was delivered to the center basket in the drum, the sand-filled core became wetted with liquid JP-4 and started emitting JP-4 vapor; excess liquid JP-4 migrated to the gravel surrounding the core and was drained into the liquid receptacle at the bottom of the drum. This system ensured that the vapor sensors could not come in contact with liquid JP-4.

After the vapor source and the wells were in place, the tank was filled with sand, and a liner (XR-5 Geomembrane 8130, Seaman Corporation, Wooster, Ohio) was placed on top of the tank to act as a vapor barrier. This liner was selected because of its compatibility with JP-4 As shown in Figure 5, nine sampling tubes were driven through the liner to monitor vapor concentration in the sand bed (three tubes each at radii of 2, 3.75, and 5.5 feet). These sampling tubes were made up of a septum connected to a 1/8-inch (i.d.) tube (Small Parts Inc.) tapered at the drive end. At each radius sampling tubes extended to depths of 1, 2, and 3 feet into the sand bed.

2. Vapor Sensor Installation

Technical representatives from each vapor sensor manufacturer supervised the initial installation of the vapor-sensing devices. The manufacturers' representatives were responsible for connecting the sensors to monitors and assuring that the monitors were performing according to specifications. Devices from the following companies were tested: Arizona Instrument (AZI), Tempe, Arizona; Fiber Chem, Inc. (FCI), Albuquerque, New Mexico; In Situ, Inc., Lakewood, Colorado; Red Jacket Electronics (RJ), Concord, North Carolina; Total Containment, Inc. (TCI), Exton, Pennsylvania; and Universal Sensors and Devices (USD), Chatsworth, California. A detailed description of these devices is given in Section II.

In both Wells A and I, a total of six TCI sensors (three per well) were placed at a depth of 2 feet below the surface of the sand bed. (The TCI probes are actually 3 feet long so the sensors were centered at the 2-foot depth and the sampling tubes in these wells extended to 2 feet.) In Wells B, C, D, F, G, and H, two probes each, from FCI, RJ, and USD, were placed next to each other to allow the three devices to be statistically compared. Sensors in Wells B, C, and D were 2 feet deep and sensors in F, G, H were at 3-foot depths. Wells E and J each had one In Situ, Inc., sensor. The In Situ, Inc., probe consists of

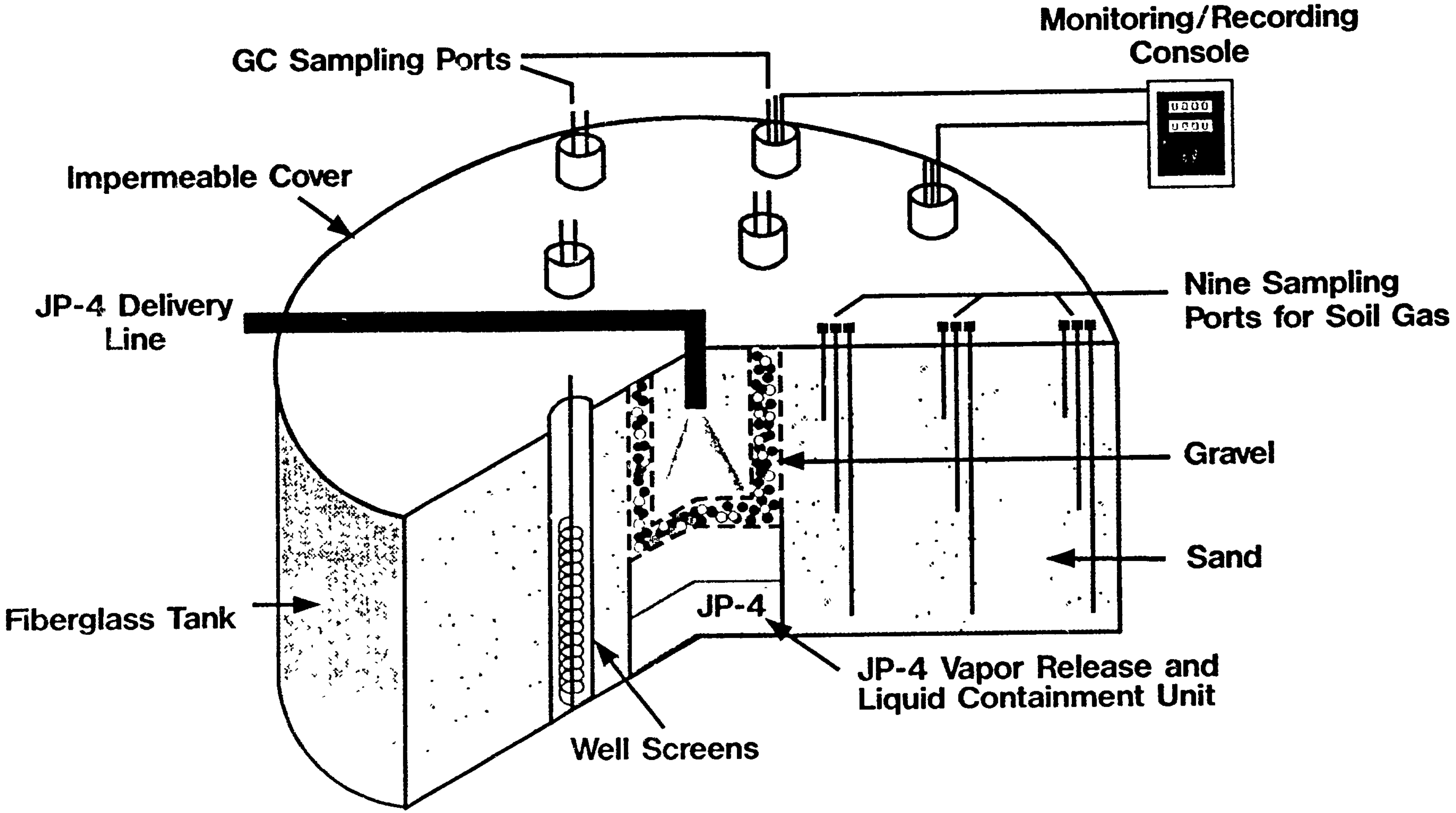


Figure 5. Distribution of Nine Vapor Sampling Ports in the Vapor-Phase Test Tank.

a chemically reactive filament which extends through most of the length of the monitoring well; for consistency, the well was sampled at 3 feet in depth. The AZI probe, unlike the other instruments tested, is not a passive detector. The AZI instrument pumps air from the monitoring well to a vapor detector located in the instruments control panel. To reduce the effect this pumping action could have on the vapor concentration in the other wells, the AZI probe was placed in Well K, as far from the other wells as possible (see Figure 3). The sampling port in Well K extended to a depth of 3 feet.

3. Sampling Procedure

The vapor concentration was measured by drawing air samples from the sampling ports in the wells, and from the nine-point sampling tubes. Airtight glass syringes measuring 20 cc and fitted with 22-gauge stainless steel needles (Becton, Dickinson and Co., Rutherford, New Jersey), were used to draw all vapor samples. The sampling tubes were purged with 20 cc of tank air/vapor mixture before drawing the sample. All the samples were sealed in the syringes immediately after being drawn by placing a septum on the needle tip. Samples were analyzed for total organic hydrocarbon (TOHC) and for hydrocarbon distribution by gas chromatography (GC) methods.

4. Vapor Test Design

For all vapor tests, the general experimental design was the same. After the vapor-sensing probes were in place, background concentrations of TOHC were taken for all the wells, and initial readings were recorded for all the instruments that give numerical outputs. (AZI, RJ, and USD give direct ppm readings while FCI gives only a voltage reading which can later be converted mathematically to ppm.) The alarm thresholds for AZI and RJ were set at 500 ppm for the start of each experiment. Any sensor that alarmed at 500 ppm was raised to a 1,000 ppm threshold for the remainder of the test. Ten of the 12 USD sensors were also set at 500-ppm and 1,000-ppm alarm thresholds. The other two USD sensors had initial readings very near 500 ppm, so they were started at 1,000-ppm and then raised to 1,500-ppm alarm thresholds. Calibration curves for the FCI probes were not provided before the start of the experiments, and the prototype units provided for the present study did not have alarms, so no alarm threshold could be set.

Before starting JP-4 delivery to the tank, devices were monitored for at least 24 hours to check for false alarms. After the 24-hour equilibration period, TIME-0 samples were taken from all wells and were analyzed for both TOHC and hydrocarbon distribution by GC. TIME-0 instrument readouts were taken to correlate with the GC samples. Liquid JP-4 delivery was then started using the peristaltic pump at a starting flow rate of 3.1 mL/min (0.05 gal/h). Periodic samples, and the correspond-ing instrument readouts, were taken from designated wells for the duration of the test, tracking instrument response to measured TOHC concentration (see Table 4 for generalized sampling schedule). Also, TOHC samples were taken to correspond to any alarming vapor sensor.

TABLE 4. VAPOR-PHASE EXPERIMENTS SCHEDULE
FOR SAMPLING WELLS

Time (hours)	Wells Sampled
0.00	All wells
8.00	B, C, D, F, G, H, K
16.00	B, C, D, F, G, H, K
24.00	B, C, D, F, G, H, K
36.00	B, C, D, F, G, H, K
48.00	All wells
60.00	B, C, D, F, G, H, K
72.00	B, C, D, F, G, H, K
96.00	All wells
120.00	B, D, D, F, G, H, K
144.00	All wells
168.00	B, C, D, F, G, H, K
192.00	All wells
216.00	B, C, D, F, G, H, K
240.00	All wells
264.00	B, C, D, F, G, H, K
288.00	All wells
312.00	B, C, D, F, G, H, K
366.00	All wells

The nine-point sampling tubes were sampled periodically to track vapor migration, both horizontally and vertically, from the vapor source (see Table 5 for the nine-point sampling schedule). These samples were analyzed for both TOHC and hydrocarbon distribution to try to identify any stratification of the JP-4 vapor.

The room temperatures and sand bed temperatures were monitored throughout each experiment. To monitor any microbial activity in the tank, carbon dioxide and oxygen percentages were taken during each experiment using Fyrite CO_2 indicator, Model CND and Fyrite O_2 indicator, Model CPD, (Bacharach Instrument Co., Pittsburg, PA), respectively.

TABLE 5. VAPOR-PHASE EXPERIMENTS NINE-POINT SAMPLING SCHEDULE

Sampling Time (hours)
0.00
4.00
16.00
28.00
40.00
52.00
72.00
96.00
120.00
144.00
168.00
192.00
216.00
240.00
264.00
288.00
312.00
336.00
360.00

5. Tank Cleanup

After each vapor-phase test the tank had to be cleaned to reduce the background hydrocarbon concentration to an acceptable level. First the vapor-sensing devices were removed from the wells. The liquid JP-4 collected in the receptacle at the bottom of the vapor source was then pumped out using the hand pump. The liquid JP-4 fuel was restricted to the vapor release and liquid containment unit (see Figures 2 and 4), so only the sand and gravel in the barrel had to be changed between tests. After removing the contaminated sand and gravel, the inside of the barrel was cleansed of residual JP-4 with a methanol wipe. The barrel was then hooked up to an exhaust fan and the tank was purged with room air for several days. After air purging, the tank was flushed with tap water until the background TOHC concentration was lowered to an acceptable level (100 ppm or less). Fresh sand and gravel were then placed back in the barrel, and the vapor sensors were placed back in the proper wells.

C. TESTING OF VAPOR-PHASE DEVICES WITH FRESH JP-4 IN SAND

1. Dry Sand Tests

The first vapor-phase test was conducted using a dry sand bed and fresh JP-4 jet fuel. (Sixty gallons of fresh JP-4 were obtained from Rickenbacker Air Force Base for use in all vapor-phase and liquid-phase experiments.) The fuel delivery system was set up using 0.1009-inch (i.d.) Tygon® pump tubing (Cole-Parmer Instrument) in the Ismatec peristaltic pump. The Tygon® tubing at the inlet side of the pump was connected to a 1/8-inch diameter stainless steel tubing which extended to the 5-gallon JP-4 container. Tygon® tubing at the outlet side of the pump was also connected to a stainless steel tubing which extended to the vapor delivery system at the center of the test tank.

The peristaltic pump was started at a delivery rate of 3.14 ml/min (0.05 gal/h) at the beginning of the test. It was discovered at T = 96 hours that the Tygon® tubing had collapsed and JP-4 was no longer being delivered to the vapor source. The volume of JP-4 delivered to this point was calculated, based on the influent container dimensions, to be 5.3 liters. It had been noted at T = 48 hours that approximately the same volume of JP-4 had been used as was discovered at 96 hours; it was therefore assumed that 5.3 liters of JP-4 was delivered in the first 48 hours, with no JP-4 being delivered in the next

48 hours. New Tygon® pump tubing was installed at 96 hours and the pump was restarted. The pump tubing was replaced on a daily basis for the duration of the study.

The experiment continued to T = 264.5 hours, when it was decided that no other devices would alarm. The volume of JP-4 used from 96 hours to 264.5 hours was 12.6 liters, making the total used for the first vapor test 17.9 liters. It was decided that fuel delivery in future vapor tests would be run to simulate the fuel delivery in vapor-phase test 1. For the remainder of the vapor-phase experiments the fuel delivery schedule would be as follows: TIME-0 to TIME-48 - 1.85 mL/min (0.03 gal/h); TIME-48 to TIME-96 - no fuel delivery; TIME-96 to END of TEST - 1.22 mL/min (0.02 gal/h).

At the end of the experiment, the tank was cleaned as described earlier.

2. Wet Sand Tests

The purpose of the second vapor test was to see what effect a high moisture content in the sand bed would have on the JP-4 leak detection and monitoring devices and transport of the JP-4 vapors. The moisture content in the sand was set by filling the tank with tap water, and then allowing the tank to gravity drain. A coring device was used to take sand samples periodically during the experiments. This procedure allowed sampling sand at different depths. Wet weights were taken for the sand samples; the samples were then oven dried and reweighed, and the wet-weight to dry-weight ratios were used to determine the sand moisture content.

The Tygon® pump tubing used in the first vapor test was replaced with a more chemically resistant Viton® tubing (0.1-inch i.d.; Cole-Parmer Instrument). The JP-4 delivery rate was set as outlined in the first vapor-phase test (i.e., T = 0 to 24 hours, 0.03 gal/h; T = 24 to 48 hours, no flow; T > 48 hours, 0.02 gal/h), and was checked periodically to ensure a consistent flow rate. The problems encountered with the Tygon® pump tubing did not recur with the Viton® tubing. Because the moist sand slowed JP-4 vapor migration, the second vapor test was not stopped until T = 336 hours.

At the end of the experiment, the tank was cleaned by purging with air as described earlier.

D. TESTING OF VAPOR-PHASE DEVICES WITH AGED JP-4 IN SAND

The third vapor-phase test was designed to see if the vapor sensor devices could distinguish between an existing aged JP-4 background and a fresh JP-4 release. The moisture content of the sand was set as outlined for vapor-phase Test 2. Aged JP-4 was obtained from Eglin Air Force Base, and came from a site where the JP-4 had been recovered from the water table as part of a site remediation program. Aged JP-4 was then added to the tank at 25 grid points (see Figure 6) marked off radially from the tank center. At each grid point, 130 mL of aged JP-4 were poured through a polyethylene funnel extending to a depth of 4 inches in the tank bed. This corresponds to an average soil concentration of approximately 100 µg/g. The tank was allowed to equilibrate for 7 days before starting the experiment. GC samples were periodically taken from the wells to track aged JP-4 concentration in the soil gas.

The vapor sensor devices were placed back in the tank 24 hours prior to starting delivery of the fresh JP-4. To make certain that the devices had equilibrated to the aged background, the instrument readouts were monitored during the 24-hour period. The fresh JP-4 was delivered on the same schedule as for vapor-phase Tests 1 and 2, but, unlike the first two vapor tests, no nine-point samples were taken. The moisture content of the sand bed was monitored as outlined for vapor-phase Test 2. The vapor concentration in the tank was relatively high, so most of the instruments reached their saturation point very quickly; for this reason vapor-phase Test 3 ran for only 168 hours. At the completion of vapor-phase Test 3, the vapor sensors were removed from the wells and the tank was cleaned as outlined earlier.

E. TESTING OF LIQUID-PHASE DEVICES WITH FRESH JP-4 IN SAND

The liquid-phase devices were tested with fresh JP-4 for (1) false signal with no fuel present, (2) the minimum detection limit of 1/8 inch required by the EPA, and (3) response to incremental increases of JP-4 thickness. Devices measuring concentration were compared with chromatographic measurements. Both laboratory and tank-scale experiments were used for this study.

1. Tank Description

The tank used for the liquid-phase experiment was identical to the tank used for the vapor-phase experiments (see Section III.B.1), except that two of

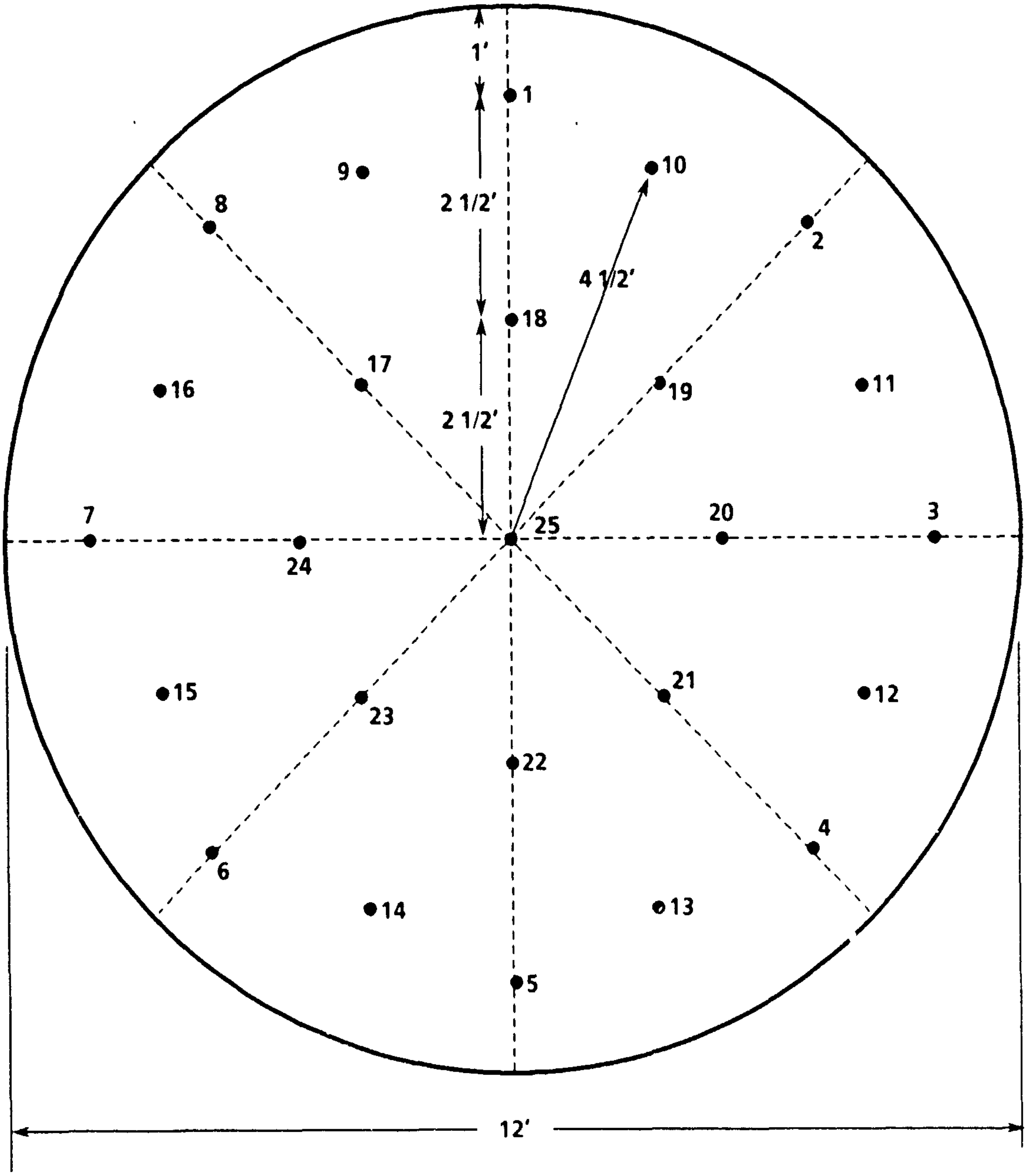


Figure 6. Aged JP-4 Injection Points for Aged Fuel Study. 125 mL Aged JP-4 Added to Each Point at 4 Inches Depth.

the drains were equipped with clear PVC view tubes (United States Plastic Corp., Lima, Ohio) for monitoring the water table.

In the liquid-phase experiment, 17 monitoring wells were needed for the placement of the JP-4 sensing devices. The wells, labeled A through Q, were placed radially from the center of the tank as shown in Figures 7 and 8. Wells P and L had 2-inch diameter stainless steel screens and casings for the placement of the In Situ, Inc., probes (see Section III.B.1 for screen and casing descriptions). Wells A, B, C, E, G, H, I, J, N, and O all had 4-inch (diameter) stainless steel screens with 4-inch, schedule 40, PVC casings. Wells D, F, K, M, and Q had 4-inch diameter stainless steel casings and screens. The well caps for Wells D, F, K, and M were fitted with sampling ports, as outlined for the vapor-phase experiments, which extended to 3.5 feet below the top of the sand bed for aqueous phase sampling. Well Q was equipped for vapor-phase sampling at 2 feet in depth.

The tank was set up as outlined for the vapor-phase tank, except that the JP-4 vapor delivery system was not installed (see Section III.B.1). After the liner/top was in place, the tank was filled with tap water to a depth of 3 feet and was then drained to 1.75 feet (2.25 feet from top) to establish the water table. The fuel delivery system (see Section III.B.1) was put in place using an Ismatec JPN-16 peristaltic pump and Viton® pump tubing. The stainless steel fuel-delivery tube was positioned to deliver fuel in the center of the tank at the depth of the water table.

2. Liquid Sensor Installation

Technical representatives from each liquid sensor manufacturer supervised the initial installation of the liquid-phase sensing devices. The manufacturers' representatives were responsible for connecting the sensors to the monitors, and ensuring that the monitors were performing to manufacturers' specifications. Devices from the following companies were tested in the liquid-phase tank test: Arizona Instrument (AZI), Tempe, Arizona; FiberChem, Inc. (FCI), Albuquerque, New Mexico; In Situ, Inc., Lakewood, Colorado; Leak-X Corp., Englewood Cliffs, New Jersey; and Total Containment, Inc. (TCI), Exton, Pennsylvania.

Wells B, E, J, and O each contained two TCI sensors. These wells were covered with aluminum foil to allow for easy sampling access. Wells A, C, G,

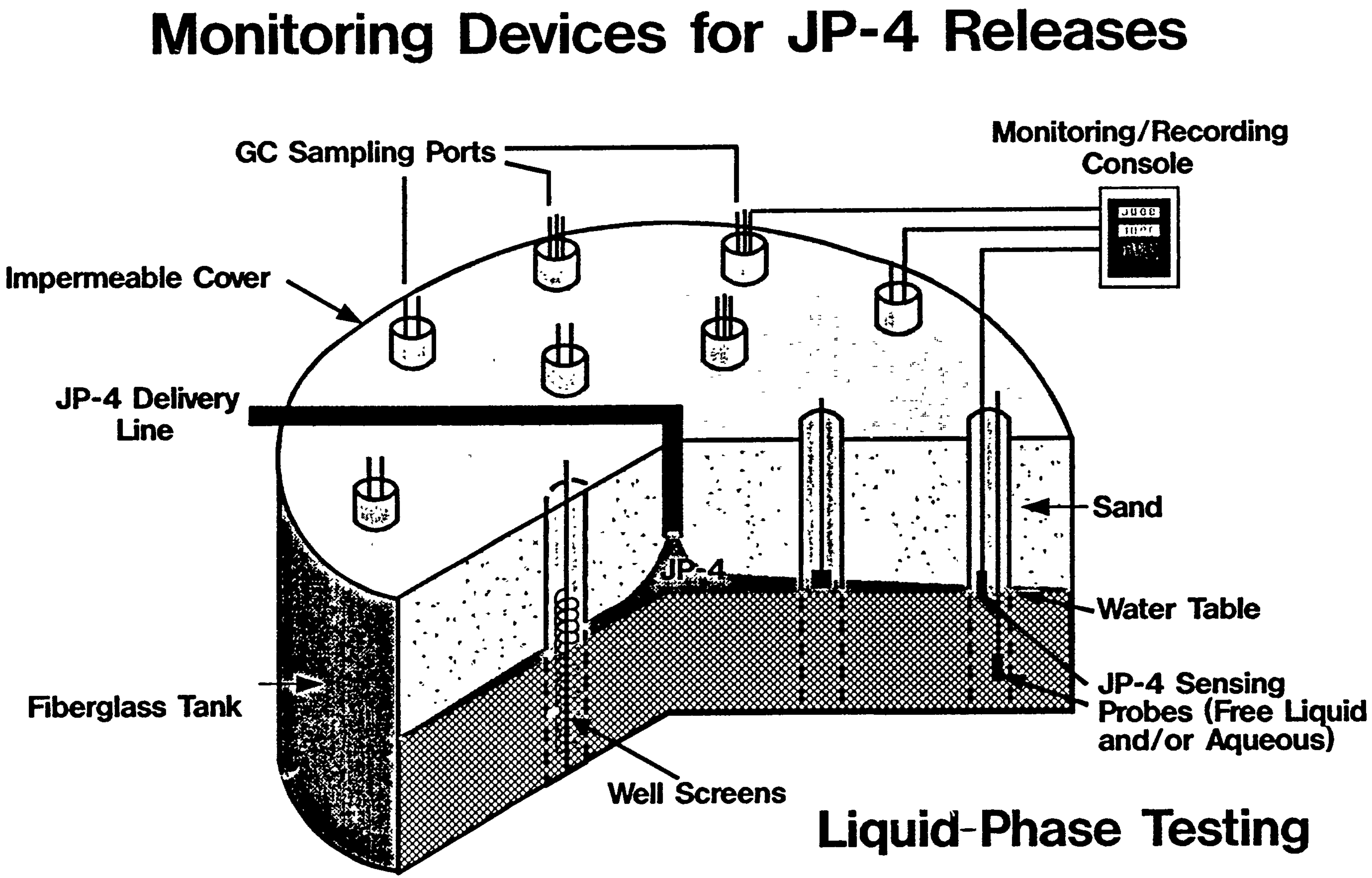
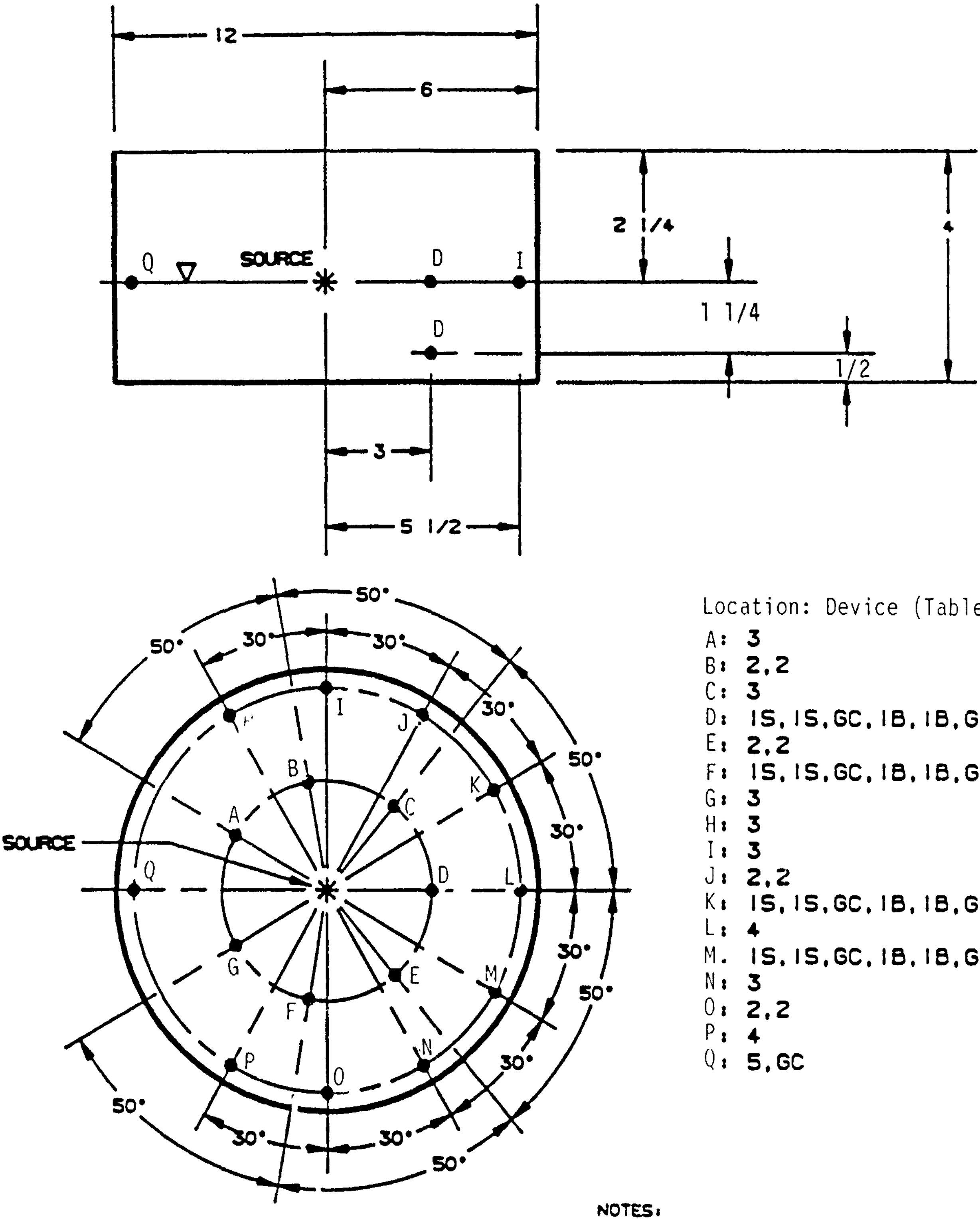


Figure 7. Liquid-Phase Testing Device for JP-4 Releases.



Location: Device (Table 1)

A: 3
B: 2,2
C: 3
D: 1S,1S,GC,1B,1B,GC
E: 2,2
F: 1S,1S,GC,1B,1B,GC
G: 3
H: 3
I: 3
J: 2,2
K: 1S,1S,GC,1B,1B,GC
L: 4
M. 1S,1S,GC,1B,1B,GC
N: 3
O: 2,2
P: 4
Q: 5,GC

NOTES:
1. ALL DIMENSIONS IN FEET.
2. NOT TO SCALE.

Figure 8. Tank Configuration for Testing the Liquid-Phase Devices in Sand with Fresh JP-4 at Fixed Water Table.

H, I, and N each contained one Leak-X sensor each. The Leak-X sensor consisted of a well cap assembly, with a cable connected to a probe floating on the liquid interface in the well. Well Q contained an AZI probe which was set up identically to the AZI unit used in the vapor-phase experiments (see Section III.B). Wells D, F, K, and M each contained four FCI sensors, two positioned at the liquid interface and two positioned in the aqueous zone (at 3.5 feet in depth). The probes placed at the liquid interface were to detect a floating liquid JP-4 layer. The FCI probes positioned in the aqueous zone were to detect dissolved JP-4. The FCI sensor registers a drastically different reading when completely immersed in water than it does when only partially immersed, or when only exposed in the air. The sensing portion of the FCI probe is approximately 1-inch long, so small changes in the relative position of the sensor at the liquid interface could affect readings. The FCI sensors were not equipped with a float to adjust to the water table depth, so the sensors were strapped to a stainless steel rod fixed in the well.

3. Sampling Procedures

The following samples were required for the liquid-phase study; JP-4 product thickness in all wells; aqueous samples to measure dissolved JP-4 concentration in Wells D, F, K, and M; and, JP-4 vapor samples in Well Q.

a. Product Thickness Measurement

To track the movement of liquid JP-4 in the tank, it was necessary to measure the thickness of the JP-4 layer in each well. A sampling device was designed to remove an undisturbed liquid sample from the well; the free product thickness was directly measured from the liquid column. The sampling device consisted of 6 feet of 1-inch diameter, clear, PVC tubing with 7 feet of 1/8-inch diameter stainless steel rod with a Teflon® plug attached to its bottom (see Figure 9.) The steel rod extended up through the PVC tubing with the Teflon® plug positioned at the bottom of the tube. To check product thickness the sampling device was slowly lowered into the well, with the Teflon® plug held 8 to 10 inches below the tubing bottom. When the plug reached the bottom of the well, the PVC tubing was slowly lowered until it made a seal with the Teflon® plug. The sampler was then retrieved, using the steel rod to hold the plug in

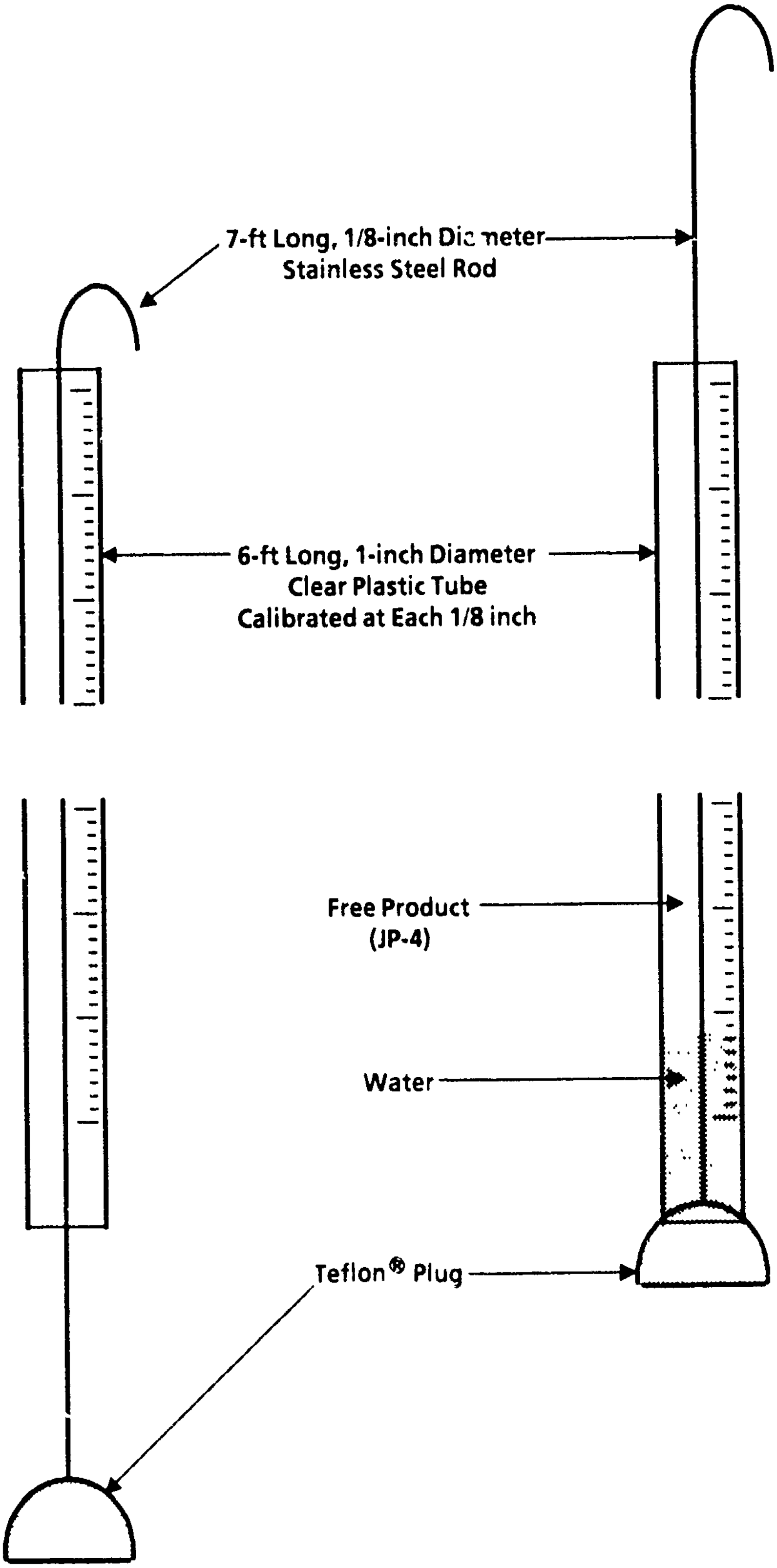


Figure 9. Sampling Device for Liquids in Monitoring Wells.

place, and the JP-4 and underlying water layers were measured. The sample was then returned to the well.

b. Aqueous Phase Sampling

The FCI probes were stated to have the capability of measuring dissolved JP-4 in the aqueous phase. To check the sensors' response to dissolved JP-4, aqueous samples had to be taken from Wells D, F, K, and M. These wells had stainless steel instead of PVC casings, to ensure that PVC would not contaminate the samples. The 10-mL aqueous samples were drawn from the sampling ports in the well cap of each FCI well. The samples were taken using 20 cc glass syringes as described for vapor sampling in Section III.B.3. Samples were immediately transferred to 10 cc glass vials with Teflon® cap liners, and were refrigerated until analysis.

c. Vapor Sampling

Well Q contained the AZI vapor sampling probe. This well had vapor samples drawn as described in Section III.B.3 for the vapor-phase experiments.

4. Sample Analysis

See Section III.A for analytical procedures.

5. Liquid-Phase Test Design

After the liquid-phase devices were installed, initial samples were drawn from Wells D, F, K, M (aqueous), and Q (vapor). Initial readings were taken from the FCI devices and from AZI. The Leak-X, In Situ, Inc., and TCI probes give only a qualitative response to the presence of JP-4, so no initial samples or readings were required. The devices were allowed to equilibrate to the test system for 24 hours, before the start of the test, to monitor for false alarms. The fuel delivery system was calibrated to deliver liquid JP-4 at 3.14 mL/min (0.05 gal/h). TIME-0 samples and readings were taken from Wells D, F, K, M, and Q, and the peristaltic pump was started. For the first several days of the experiment samples and readings were taken every 12 hours from Wells D, F, K, M, and Q, and then were taken daily for several weeks. The product thickness was measured in all wells every 12 hours for the first 10 days, and then daily until the test was completed. The instrument readings and JP-4 layer thickness measurements were also taken in response to any alarming probe. The

AZI probe was set to alarm at 500 ppm initially and, when the alarm was activated it was moved up to 1,000 ppm; when the alarm was activated at 1,000 ppm it was set at 3,500 ppm for the duration of the test. The FCI probes had not been calibrated for ppm response, so no alarm threshold could be set.

The FCI probes were giving unstable readings throughout the test. FiberChem Inc., decided to have its probes removed, from the experiment to investigate the problem. After the FCI probes were removed, no further aqueous samples were taken.

F. ACCURACY AND RESPONSE TIME DETERMINATION FOR LIQUID-PHASE DEVICES

A procedure was designed to determine the minimum thickness detection limit of the In Situ, Inc., Leak-X, and TCI devices. This was a bench-scale experiment, based on the procedure developed by the Radian Corporation under a contract from the U.S. Environmental Protection Agency (US EPA, 1988).

1. Test Vessel Description

a. In Situ, Inc., and TCI

Each test vessel consisted of a 24-inch long and 4-inch diameter (o.d.) glass tube sealed at the bottom with a rubber stopper. Silicone adhesive was used to attach a calibrated thermometer to the inside of the test vessel. A 5-inch section of 4-inch diameter PVC well casing was attached to the top of the glass tube to allow for normal installation of the liquid-phase probe.

b. Leak-X

The Leak-X sensor consists of a sensor contained in a large float approximately 4 inches in diameter. The float had a tendency to adhere to the glass walls of the test vessel (described above), which could affect the sensor's response to a JP-4 layer. To avoid this problem, a 5-gallon glass, wide-mouth jar was used in place of the glass tubing as the test vessel. The larger surface area inside the jar reduced any interference caused by the vessel walls. As with the In Situ, Inc., and TCI test vessels, each glass jar was fitted with a thermometer and a 5-inch PVC well casing extension.

2. Calibration Procedure

a. In Situ, Inc., and TCI Calibration

Each test vessel had to be calibrated for the volume of JP-4 needed to form the desired product layer thickness for each experiment. The easiest way to perform this calibration is to calculate the height of the column of JP-4 formed by a given volume of fuel, based on the cross-sectional area of the test vessel. Because of the surface irregularities, the calibration could not be based on the assumption that the glass vessels had uniform cross-sectional areas. The vessels had to be calibrated directly by adding a known volume of liquid, and then directly measuring the change in the height of fluid in the column. The calibration measurements were made using a "Flower" caliper modified with a 11.5-inch long, 1/8-inch diameter stainless steel rod as an extension. The level of fluid inside the test vessel could be measured accurately to 0.025 inch with this device.

The calibration was performed for each test vessel as follows: Water was added to the test vessel to a height of approximately 18 inches. The device to be tested in the vessel was installed as it would be during the test, ensuring that the volume of liquid displaced by the device would be factored into the calibration. The top of the liquid layer was marked with the caliper. A known volume of water was then added to the test vessel, and the change in the height of the water column was measured with the caliper. A total of seven data points were taken, and a statistical regression was performed relating height increase to volume of water added. The volume of JP-4 needed to form a layer of a given thickness could then be estimated from this data.

b. Leak-X Calibration

The cross-sectional area of the Leak-X float varies with depth. The amount of liquids displaced by the float in multilayers of fluids (JP-4 and water) is not the same as the amount of liquid replaced by either JP-4 or water. Therefore, rather than performing a calibration similar to that used for the In Situ, Inc., and TCI devices, direct measurements were used to set the product thickness for each test. At the start of each experiment the Leak-X device was set up in the test vessel with a water layer of approximately 8 inches. The caliper was set at the water surface and was then extended to the height of the product layer desired. Liquid JP-4 was then added to the test vessel until the fuel layer just touched the caliper tip.

3. Test Procedure

For each type of device (In Situ, Inc., Leak-X, TCI), five tests were run simultaneously at each thickness tested. The devices were set up in the appropriate test container and liquid JP-4 was added to form the desired product thickness. The devices were then monitored for 24 hours for any alarms. The ambient and test vessel temperatures were monitored throughout the test. The time required for each device to alarm was recorded. Any device that did not alarm within 24 hours to a particular product thickness was considered unresponsive.

4. Data Analysis

The accuracy of each device for a given JP-4 layer thickness was estimated by using the percentage of sensors responded. Since these devices did not give any quantitative output, precision could not be estimated on the basis of a concentration or fuel thickness. Consequently, precision was determined in terms of response time as given in the following equation.

Precision = (standard deviation of response time to a given thickness)
x 100/(Average response time for that thickness).

The above precision analysis was used to interpret data from TCI and In Situ, Inc. For Leak-X, precision was determined based on the lowest JP-4 thickness required by each sensor to activate the alarm.

G. TESTING OF VAPOR-PHASE DEVICES FOR BACKGROUND INTERFERENCES

This task was originally designed to test the devices for false signals in the field. More precisely, the purpose was to determine what interferences the vapor sensors might experience from natural background concentrations of methane, hydrogen sulfide, carbon monoxide, and carbon dioxide found in the field. Also, it was essential to examine the effect of solvents such as trichloroethylene, which can be found at some Air Force sites. Gases such as CH_4, CO_2, and H_2S, and vapors of TCE are potential interference gases in subsurface environments. Carbon monoxide, on the other hand, is likely to be found only aboveground and may affect any sensor used as a control or background probe (e.g., AZI). Because of the difficulty in locating a site with suitable concentrations of possible interfering compounds, and the regional variability of such compounds, it was decided to conduct the experiment in the laboratory under controlled conditions.

This study was conducted using a 20-inch diameter (i.d.) and 48-inch high stainless steel container. Each vapor-sensing device was placed inside the chamber to see if it responded to any of the following gases or vapors: CH_4, CO_2, CO, H_2S, and TCE.

1. Experimental Design

The 20-inch by 48-inch chamber was connected to a vacuum pump (Acurex Corp. Model #1022,V103,G272X) capable of drawing 25 inches of mercury vacuum on the chamber. Vapor-sensing probes from Arizona Instrument (AZI), FiberChem, Inc. (FCI), In Situ, Inc. (In Situ), Red Jacket Electronics (RJ), Total Containment, Inc. (TCI), and Universal Sensors and Devices, Inc., (USD) were placed in the chamber. There was a makeup air line equipped with an on/off valve and a septum to introduce the test compounds (gases or vapors). Test concentrations were confirmed by drawing samples from a septum on the chamber body for GC analysis (CH_4), and from a sampling line at the top of the chamber for Draeger Tube analysis (CO_2, CO, H_2S, and TCE). Three different concentration levels were planned for each gas or vapor.

a. CH_4, CO_2, CO, and H_2S Experiments

Each gas was used individually with a starting concentration of 500 ppm. Other concentrations were based on the results of the 500-ppm experiments (i.e., whether to use concentrations above or below 500 ppm). The following procedure was used for each gas.

Background readings were taken for all probes that give concentration readouts before introducing the test gas. Analysis of the chamber background air was performed to check for prior contamination. The chamber was evacuated to approximately 5 inches of mercury with the vacuum pump; the makeup air line was then opened and an appropriate volume of test gas (CH_4 -- 99.0 percent, Matheson Co.; CO_2 -- 99.8 percent, CO -- 99.3 percent, H_2S -- 99.5 percent, all Scott Specialty Gases) was injected with the makeup air to achieve the desired concentration. The tank was then allowed to equilibrate to atmospheric pressure and the gas concentration was measured by the appropriate analytical method (see the following section on Gas Analysis). The probes were allowed to equilibrate to the test gas for at least 2 hours and responses were recorded. The chamber was cleaned between experiments by purging the chamber several times with room air.

b. TCE Experiments

The TCE experiments were run in the same manner as the other test compounds except that the TCE vapor concentration was set using vaporized liquid TCE. The injection port in the makeup air line was heated to 50°C with a heater tape. As the chamber pressure was being brought back to atmospheric pressure, an appropriate volume of liquid TCE (99 percent) was injected into the injection port where it vaporized before entering the chamber.

c. Gas Analytical Methods

Methane analysis was run on the GC. Draeger gas analysis tubes, of the appropriate concentration range, were used to analyze the concentrations of CO_2, CO, H_2S, and TCE in the chamber.

H. COLUMN TESTING IN THE LABORATORY

1. Jet Fuel Vapor Experiments

Glass columns measuring 4.1 inches (10.5 cm) i.d. and 39.4 inches (100 cm) long were used for the sand and soil experiments. Each column was equipped with six sampling ports located along the column axis at distances of 0, 3.4, 7.2, 15.2, 23.0, and 30.8 inches, respectively (Figure 10). The first sampling port was located at beginning of the soil column (0 cm). Each sampling port included a cylindrical glass septum holder, measuring 5 mm i.d. and 10 mm high. A septum was placed into each septum holder. Then, a perforated 10-cm long, 18-gauge stainless steel needle was inserted through the septum of each sampling port. A cleaning wire was kept inside the needle to prevent soil from entering during the insertion step. The Luer hub of each needle was plugged with a two-way Teflon® (Mininert®) valve which, when opened, allowed the needle of a gas-tight syringe to be inserted for vapor sampling. The whole sampling port system was tested for tightness to ensure a perfect seal. Two layers of an 80-mesh stainless steel screen supported on a 1.2-cm thick and 1-cm wide, circular aluminum ring were used on each end of the glass column to support the soil.

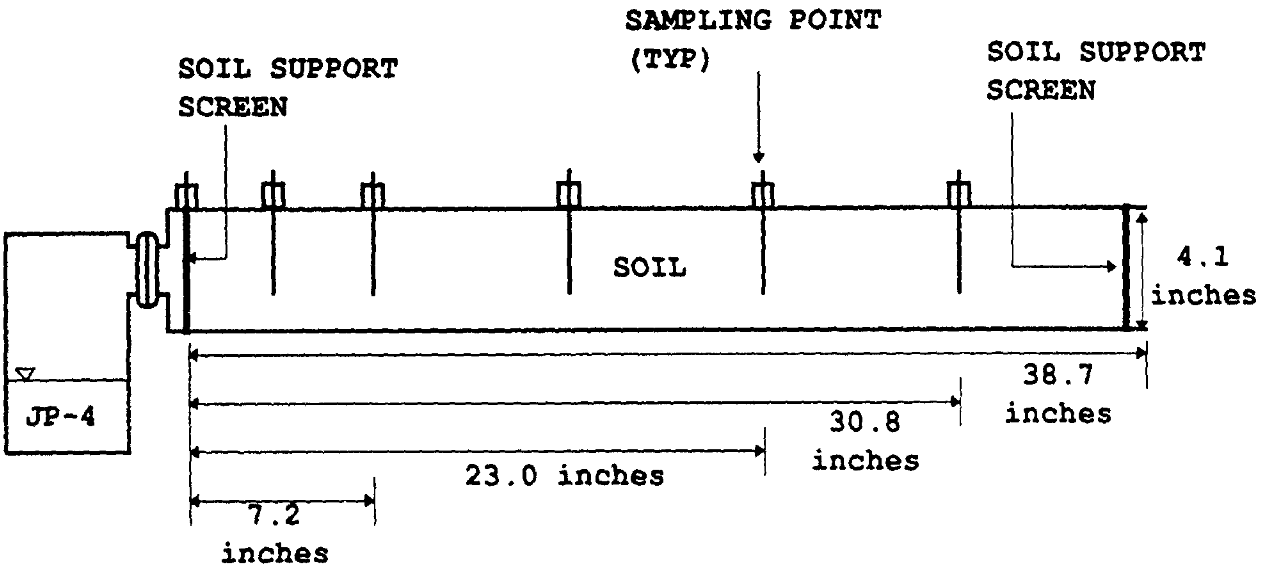


Figure 10. Experimental Column Setup for JP-4 Vapor Experiments.

The outlet of each column filled with sand or soil was left exposed to the atmosphere in an attempt to provide a modelable boundary condition (i.e., concentration of the contaminant approaching zero).

The inlet of each column was connected to a reservoir containing approximately 500 mL of JP-4. Preliminary experiments showed that this volume of JP-4 would result in a constant JP-4 component concentration at the beginning of the soil column (Sampling Port 1) for more than 300 hours. Prior to starting each vapor experiment, the JP-4 reservoir was connected to a similar sand or soil column to establish a steady-state vapor concentration (i.e., constant source strength at Sampling Port 1). Then, the reservoir was connected to the actual soil column and the measurement of time was started. All experiments were conducted in a 20°C constant temperature room.

All columns were filled with 0.265-0.268 ft^3 (7,500-7,600 cm^3) of soil or sand. Soil was added in portions of 6.1 cubic inches (100 cm^3) at the surface of previously added soil, using a scoop attached to the end of a 100-cm aluminum rod. After each soil addition, the column was compacted by hand in a uniform fashion using a 3-cm diameter and 120-cm long wooden rod. This procedure minimized the column stratification that occurs when pouring soil into the column. A water-filled micromanometer was used in an attempt to measure pressure gradients within the soil column. No measurable pressure gradients were measured, however.

Before packing, sand used for the dry sand column was dried at 80°C for 12 hours. Soil used for the dry soil column was taken out of the 7°C room, spread on large plastic sheets, and air-dried at room temperature. Then the soil was passed through a 0.85-mm sieve (U.S. Standard 20) to remove large debris. The sieved soil was further dried at 80°C for 12 hours and used to pack the column. Soil used for the wet soil column was only partially air-dried at room temperature and sieved through a 0.85-mm sieve (U.S. Standard 20). Representative aliquots of the soil used to pack the columns were analyzed for particle size distribution, particle density, and organic carbon content.

To establish whether biological activity occurred during the long (> 200-hour) JP-4 diffusion experiments, gas samples from the column void space were analyzed for oxygen, carbon dioxide, and nitrogen using a Fisher Model 25V Gas Partitioner. No measurable reduction of oxygen or increase of carbon dioxide was detected, however, indicating that JP-4 vapor biodegradation was not significant. The total volume of gas withdrawn for GC analysis was less then 1 percent of total void space of the soil column.

2. Dissolved JP-4 Experiments

Glass columns measuring 1.97 inches (5 cm) i.d. and 23.6 inches (60 cm) long (Scientific Spectrum, Los Angeles, CA) were used for all dissolved jet fuel experiments. Each column was equipped with an adjustable length plunger and end-fittings made of Teflon®. The inlet and outlet of each column was equipped with a three-way Teflon® valve for JP-4 application and effluent sampling. Each column was specially designed to minimize the dead volume and prevent apparatus-induced dispersion.

The inlet of each column was connected to a reservoir of deionized water through an FMI metering pump, capable of delivering flow rates up to 180 mL/h. Approximately 1.5 mg/L of $AgNO_3$ was added to the reservoir to prevent biological growths.

All columns were dry-packed with approximately 36.6 cubic inches (600 cm^3) of soil or sand to a length of 11.8 inches (30 cm). Soil or sand was added in portions of 3.05 cubic inches (50 cm^3) at the surface of previously added soil. After each addition the column was compacted by and in a uniform fashion using a 1.18-inch (3-cm) diameter wooden rod. Sand was used without any pretreatment. Soil was taken out of the 7°C room and was air-dried at room temperature. The, it was passed through a 0.85-mm sieve (U.S. Standard 20) to remove large debris and was used to pack the column. Representative aliquots of the soil used to pack the columns were analyzed for particle size distribution, organic carbon content, and particle densitv.

Following packing, each column was purged with carbon dioxide to expel trapped air and flooded with deionized water in the upflow mode. Because of its high water solubility, carbon dioxide is less likely to form bubbles during flooding of the column. Column flooding was continued overnight.

Prior to applying jet fuel, a tracer study was conducted to establish whether the column was properly packed. In addition, the breakthrough curves of the tracer were compared with those of jet fuel components to determine retardation factors. Chloride was used as a conservative tracer and was applied as a broad pulse of NaCl to each column at a concentration of 200 mg/L. After all Cl^- was washed our of the column, the flow of deionized water was stopped and

2 mL of JP-4 were injected slowly at the inlet of the column using a 2-mL gastight glass syringe. Then the flow of deionized water was restarted at a rate of approximately 110 mL/h.

Soluble JP-4 components moved through the column and their concentration was measured in the effluent. Column effluent was sampled periodically from the outlet valve, using a gastight syringe. Effluent samples were analyzed for dissolved jet fuel components by "purge-and-trap," according to EPA Method 624 (EPA, 1982).

I. STATISTICAL METHODS FOR VAPOR-PHASE DATA ANALYSIS

Analysis of the data for all three phases of the study--dry sand, wet sand, and sand with aged JP-4--were done to evaluate the accuracy and precision of the sensors. Data bases for each of the three phases were created, using Lotus 1-2-3 software. TOHC values from GC analyses were available for many of the times where concentrations were recorded from the sensors. For sensor readings without associated TOHC concentrations from the GC analyses, linear interpolation was used to estimate the TOHC concentrations. "Delta" values were also calculated in Lotus 1-2-3 by subtracting the concentrations recorded by the sensor from those recorded from the GC analyses. The Lotus files were then electronically transferred to an IBM mainframe computer where the data were analyzed, using the Statistical Analysis System (SAS). Concentrations recorded from the sensors were compared with those from the GC measurements. Ideally, the slope for the regression for a 100-percent accurate sensor would have been 1.0. The slopes generated from the regressions were then tested against a slope of 1.0 to see whether the slopes deviated significantly from 1.0. The Type I error rate used was 0.05. That is, if the Type I error rate was less than 0.05, the hypothesis that the slope was significantly different from 1.0 would be rejected and the sensor would not be statistically similar to a 100-percent accurate sensor.

An additional analysis was conducted to examine the response of the sensors at 3 and 5.5 feet. A multiple-regression model, Proc GLM, was used to examine the relation at the two distances between the GC concentrations and those recorded by a specific type of sensor. The model had the following form:

$$\text{conc} = b0 + b1\,(\text{dist}) + b2\,(\text{GC conc}) + b3\,(\text{dist} * \text{GC conc}) + E$$

where:

conc = concentration recorded from the sensor (ppm)
dist = distance (3 or 5.5 feet)
GC conc = TOHC concentration recorded from GC analyses
dist * GC conc = interaction between the two parameters
E = error term.

The b3 term would indicate if the slopes were statistically similar for the two distances and the b1 term would indicate if the y-intercepts for the two distances were statistically similar. The same model was used to evaluate the response of the sensors under wet and dry sand experimental conditions.

A similar analysis was conducted to examine how individual sensors functioned under dry and wet experimental conditions. A multiple-regression model (Proc GLM) was used to examine the response of the individual sensors in relation to each other. This analysis was conducted for each of the two distances from the JP-4 source and for each moisture condition (wet and dry). The model had the following form:

conc = b0 + b1 (rep) + b2 (GC conc) + b3 (rep * GC conc) + E

where:

conc = concentration recorded from the sensor (ppm)
rep = replicate number
GC conc = TOHC concentration recorded from GC analyses
rep * GC conc = interaction between the two parameters
E = error term.

The b3 term would indicate if the slopes were statistically similar for the replicates and the b1 term would indicate if the y-intercepts for the replicates were statistically similar.

An overall average measure of percent error or inaccuracy for the three devices was defined as (|GC conc - conc|/GC conc) * 100. The sensors with the least accuracy would be those with the highest values.

To examine the relation between precision and average concentrations, the deviations between replicate sensors normalized to the average concentrations for the two sensors were plotted against the average concentrations. Simple linear regressions were then run on the same set of data to determine if precision was affected by the concentrations recorded in the wells.

As an overall measure of precision, the deviations calculated for each replicate pair of sensors were divided by the average concentration and then averaged.

SECTION IV

RESULTS AND DISCUSSION

A. CHARACTERIZATION OF FRESH AND AGED JP-4

Fresh and aged JP-4 were characterized by two methods. In the first method 1/μL of jet fuel (either fresh or aged) was injected into a clean 1.5-liter aluminum cylinder which was under vacuum, then the cylinder was pressurized to 15 psi with pure air and kept at a temperature of 50°C. For analysis, 1.0 cc of this vapor-air mixture was directly injected into the gas chromatograph. In the second method, jet fuel was dissolved in carbon disulfide (1:1000 volume/volume ratio) and 1 μL of the mixture was directly injected into the gas chromatograph.

The chromatograms for vapor injection (Figure A-1) and liquid injection (Figure A-2) for fresh JP-4 are given in Appendix A. The respective chromatograms for aged JP-4 are given in Figures A-3 and A-4. Analytical data given in Appendix A, Table A-1 show the distribution of major hydrocarbons present in JP-4. Data for fresh JP-4 indicate that direct injection of vaporized JP-4 yields slightly higher concentrations of low molecular-weight hydrocarbons such as butane and pentanes. However, the vaporization technique either showed lower concentrations or failed to detect some hydrocarbons that were detected by the carbon disulfide (CS_2) method. Compounds such as the C_6 to C_{10} hydrocarbons appeared in lower concentrations in the vaporization method. Some compounds, such as naphthalene and decanes, were detected only when JP-4 was dissolved in CS_2.

The aged JP-4 for the present study was collected from recovery wells located on Eglin Air Force Base. The exact age and sources of these fuels are unknown. Analytical data for aged JP-4 are also included in Table A-1. Aged JP-4 appeared to contain relatively small quantities of low molecular-weight hydrocarbons. These compounds would probably have volatilized while heavier molecular-weight hydrocarbons were retained in the subsurface. Benzene and toluene, which have been found in relatively high levels in fresh JP-4, were either absent or found in very low levels in aged JP-4. The lower concentrations for all the compounds in aged JP-4 can be attributed to volatilization as well as other removal mechanisms such as biodegradation, dissolution, and adsorption.

Data reported in Table A-1 also include the analysis of JP-4 obtained from the reservoir of the JP-4 vapor distribution and liquid containment unit at the end of the fresh JP-4--dry sand study. In this test, fresh JP-4 was released into the sand bed, traveled in the sand, and drained into the reservoir. Therefore, most of the volatile hydrocarbons tend to volatilize from jet fuel. Analytical data indicate that the concentration level of volatile compounds was lower than in fresh JP-4. The proportion of heavy molecular-weight compounds has increased. The concentration of chemical compounds was between those of fresh and aged JP-4.

B. SAND AND SOIL CHARACTERIZATION

1. Sand Characterization

a. Particle Size Distribution

Sieve analyses were performed on four different sand samples to determine the grain-size distribution. Table B-1 in Appendix B summarizes the data and Figure B-1 in Appendix B presents a typical grain-size accumulation curve. Medium sand having fairly uniform particle size distribution was used in this study. The uniformity coefficient for sand (d_{60}/d_{10}) is less than 1.5.

b. Density, Porosity, and Permeability

The purpose of this testing was to determine the density, porosity, and permeability of the sand at various depths in the tank. To estimate its density, sand was poured into a 4-inch diameter PVC pipe. At known sand column heights, the weight of the sand was determined. Based on the heights and weights, densities were computed. The incremental densities ranged from 90.6 pounds per cubic foot (pcf) to 94.5 pcf, but no defined trend with depth was noted. The average density of the sand column, which had a total height of above 5 feet, was 93.0 pcf. After vibrating the pipe, the average density increased to 99.8 pcf.

It is believed that the rate at which sand is added and the vertical distance the sand is dropped are more important in determining the density of the sand than the depth. Although the results of previous measurements did not reveal a consistent trend in the variation in density of the sand with depth, it is estimated that the density near the top of the tank was nearly 90 pcf, and density near the base was around 96 pcf.

A constant-head permeability test was performed in a permeameter on three specimens of the sand. The specimens were placed at densities of 90, 93, and 96 pcf. The specific gravity of the sand was determined to be 2.64. The porosity was computed, based on the weight of the soil, the specific gravity, the temperature-corrected unit weight of water, and the volume. The results are summarized as follows:

Density (pcf)	Porosity (percent)	Coefficient of permeability (cm/sec)
90	45.3	0.22
93	43.4	0.24
96	41.6	0.25

c. Organic Carbon Content in Sand

Organic carbon analysis was performed on six sand samples. The results were 73.8, 67.8, 43.5, 66.3, 96.4, and 69.7 μg/g, respectively. The average organic carbon content was determined to be 69.6 μg/g or 0.007 percent.

2. Soil Characterization

The soil used in the column experiments was from a wooded depression in south Georgia, part of a very shallow aquifer, identified by Mr. Allen Rigdon, a scientist from the Soil Conservation Service. The soil was collected from a depth of 8 to 20 inches and was black, indicative of high organic content. Mr. Rigdon classified the soil as Surrency Loamy Sand. The soil was stored in black plastic bags at 7°C to maintair its integrity. Soil used in vapor-phase wet soil and dissolved jet fuel experiments was partially air-dried and sieved through a 0.85-mm (0.033-inch) sieve (U.S. Standard 20) to remove large debris. Soil used in dry soil experiments was further air-dried and then dried at 80°C for 12 hours. Representative aliquots of soil used to pack the columns were used to determine moisture content, particle density, particle size distribution, and organic carbon content. Soil characterization was conducted at Georgia Institute of Technology.

a. Moisture Content

Moisture content was determined according to Gardner (1986), by heating a soil sample of known size at 103°C until constant weight was achieved. The percent moisture content reported was on a dry-weight basis and is an average of five replicates. The moisture contents of the dry sand, dry soil, and wet soil used in the vapor-phase experiments were 0.005 ± 0.0001 percent, 0.07 ± 0.001 percent, and 26.0 ± 0.1 percent, respectively.

b. Particle Density

The particle density of each soil used was determined according to Blake and Hartge (1986), by measuring the mass and the volume of the sample. The mass was determined by weighing and the volume was determined by calculation from the mass and density of water displaced by the sample at that temperature. The particle specific gravities for the dry sand, dry soil, and wet soil used in the vapor-phase experiments were 2.50 ± 0.05, 2.43 ± 0.005, and 2.38 ± 0.02, respectively. The particle specific gravity of the soil used in the dissolved jet fuel experiments was 2.50 ± 0.025.

c. Particle Size Distribution

Particle size distribution was determined following a standard ASTM procedure. According to this procedure, approximately 100 grams of oven-dried soil were passed through a series of sieves and the amount of soil retained by each sieve was expressed as weight percent. The particle size distribution of soil used in vapor-phase and dissolved jet fuel experiments showed that the soil used was predominantly sand. The results of the particle size distribution analysis are summarized in Table B-2.

d. Organic Carbon Content

Organic carbon of the soil was determined from the difference of total carbon and inorganic carbon content, using a Coulometrics, Inc., Total Carbon Apparatus, Model 5020 (Coulometrics, Inc., 1986). The carbon dioxide produced from combustion of a soil sample in an oxygen atmosphere was determined using a microcoulometer and was converted into percent total carbon. Inorganic carbon was determined by acidifying the sample in a heated vessel, purging, and measuring the carbon dioxide of inorganic origin. The organic carbon contents of the dry sand, dry soil, and wet soil used in the vapor-phase experiments expressed on a dry-weight basis were 0.008 ± 0.001 percent, 2.09 ± 0.1 percent, and 4.15 ± 0.1 percent, respectively. The organic carbon content of soil used in the dissolved jet fuel experiments expressed on a dry-weight basis was 1.323 ± 0.008 percent.

C. TESTING OF VAPOR-PHASE DEVICES WITH FRESH JP-4 IN SAND

1. Dry Sand Tests

The distribution and location of wells and monitoring devices for this study are given in Section III.B.1. All the devices were allowed to stay in the wells for more than 24 hours before JP-4 release. There were no false positive alarms with any of the devices. Fresh JP-4 was then released at a rate of 0.03 gal/h (1.85 mL/minute) for the first 48 hours of this study. During the 48- to 96-hour time period, there was no fuel release. After 96 hours fuel was released at a rate of 0.02 gal/h (1.22 mL/minute) for the rest of the period. This experiment lasted 265 hours. As shown in Table C-1 (Appendix C), temperature in the test tank remained at 20-21°C.

All of the alarms were set to 500 ppm in the wells where the background readings were significantly below 500 ppm. When the reading exceeded 500 ppm, an alarm was reset to 1,000 ppm. All the devices alarmed only if they reached the preset concentration levels. In this study, only USD, AZI, and In Situ devices alarmed. USD was responsive and alarmed as soon as it reached the threshold level. For the AZI device, samples were automatically drawn only once every 8 hours. Sometimes the alarm sounded the first time it reached the threshold level, whereas in other cases it alarmed only if the observed readings were higher than the threshold levels for three consecutive times. The alarm activated immediately only if the background concentrations were significantly higher than the threshold level. If the AZI reading is just above the threshold level, the alarm was activated only after the second or third consecutive time it exceeded the threshold level. During the course of the study only one In Situ, Inc., device responded and its alarm was activated. For the other destructive-type device, TCI, none of the alarms was activated. In the case of the FCI device, a prototype unit, a millivolt reading was registered, which was converted to a ppm value using an equation provided by the manufacturer. There were no provisions to set an alarm.

The responses of the nondestructive-type devices were monitored regularly. The USD device can continuously monitor and store the data on a floppy disk. The digital display continuously showed the latest sensor readings and a printout of readings at a given time can be obtained. The AZI unit recorded the concentration values every 8 hours. However, a printout can be obtained at any time, if needed. The RJ device has a display which shows the alarm status and concentration levels.

During this study vapor samples collected from Wells B, C, D, F, G, H, and K were regularly analyzed using GC methods. Samples were also taken for analysis when the alarms were activated. The analytical data are presented as total organic hydrocarbon (TOHC) levels in parts per million (ppm). Since JP-4 contains a large number of aliphatic and aromatic hydrocarbons, it is difficult to analyze a large number of samples for all these individual compounds. The practice is to present the total hydrocarbon concentration in a gas sample. In this report TOHC level refers to the mole fractions of carbon (in hydrocarbon vapors) in air. For example, 3 ppm of TOHC means 3 micromoles of carbon (from a mixture of hydrocarbon) in 1 mole of air. Also, 1 ppm of butane is equal to 4 ppm of TOHC; or, 1 ppm of benzene is equivalent to 6 ppm of TOHC. The responses of nondestructive devices to JP-4 vapors are given in Figures C-1 through C-15 in Appendix C. The data are for device readings in ppm versus TOHC level in ppm. For very sensitive devices, such as USD units, the readings versus TOHC values are presented in two separate figures, one to cover the whole time span (Figure C-1) and the other to show the initial time period when the sensor readings were more representative (see Figure C-2).

Some USD sensors were positively biased at the initial time period (e.g., Sensor 1 in Well B; see Figures C-1 and C-2), whereas other sensors (e.g., Sensor 2 in Well B) were continuously negatively biased. The AZI unit was also negatively biased but appeared to follow the general trend (Figure C-15). All of the RJ sensors were negatively biased and, in some cases, failed to respond to relatively high TOHC levels such as 60,000 ppm (e.g., Sensors 3 and 4 in Well C [Figure C-6] and Sensors 1 and 2 in Well D [Figure C-8]). The following section provides a more detailed statistical analysis on USD, AZI, and RJ sensors. No statistical analysis was performed on the other devices because either they did not respond adequately (e.g., destructive devices such as TCI and In Situ, Inc.) and/or the manufacturer failed to provide adequate information in time to estimate the sensor reading in ppm values (e.g., FCI sensors).

a. Accuracy Estimates for Nondestructive Sensors

Figures C-16 through C-18 illustrate the average delta values for each sensor located 3 feet from the JP-4 source for time periods 0 to 10 hours (0 to 3,500 ppm TOHC), 10 to 40 hours (3,500 to 26,000 ppm TOHC), and 40 to 220 hours (26,000 to 342,000 ppm TOHC). In general, the USD sensor overpredicts for the first 5 hours and then progressively underpredicts to a greater degree over time until it reaches its maximum value of 9,999 (approximately 10,500 ppm TOHC). The RJ sensor consistently underpredicts, recording 0 values until approximately 100 hours (69,700 ppm TOHC) after initiation of the experiment. At 5.5 feet (Figures C-19 through C-21) a similar pattern occurs where the USD sensor overpredicts initially, and then underpredicts TOHC concentrations. The RJ sensor consistently underpredicted TOHC concentrations, recording 0 values till approximately 120 hours (42,800 ppm TOHC) after initiation of the experiment. The AZI sensor also consistently underpredicted TOHC concentrations although concentrations greater than 0 were recorded within 5 hours after initiation of the experiment (200 ppm TOHC).

Plots of the relations between the concentrations from the probes and those from the GC analyses indicate that some probes were very accurate while others were not (Figures C-22 and C-23). The simple linear regression relating the USD sensor readings (<9999) with the GC data produced the following equations (Figures C-24 and C-25):

$$\text{at 3 feet, conc} = 382.02 + 0.5635\ (\text{GC conc}) \quad (R^2 = 0.52,\ n = 71,\ PR > T = 0.0001) \tag{1}$$

$$\text{at 5.5 feet, conc} = 326.92 + 0.2049\ (\text{GC conc}) \quad (R^2 = 0.51,\ n = 130,\ PR > T = 0.0001) \tag{2}$$

where:

conc = concentration recorded from the sensor (ppm)

GC conc = TOHC concentration recorded from GC analyses; GC concentrations ranged from 0 to 7,375 ppm TOHC for the 3-foot distance and 0 to 8,602 ppm TOHC for the 5.5-foot distance

R^2 = coefficient of multiple determination

n = sample size

PR > T = the significance of the slope coefficient relative to a hypothetical 100 percent accurate sensor as shown in Figures C-24 and C-25 (i.e., if PR > T is less than 0.05, then the slope coefficient is significantly different from 1).

For the AZI sensor, the equation was as follows (Figure C-26):

$$\text{conc} = 1156.23 + 0.0402\ (\text{GC conc}) \qquad (3)$$
$$(R^2 = 0.72,\ n = 41,\ PR > T = 0.0001)$$

where:

GC conc ranged from 0 to 105,000 ppm TOHC.

The slopes were significant for both the USD and AZI sensors, indicating that as the concentrations of TOHC increased, the concentrations recorded from the sensor also increased. This was not the case for the RJ units where the data indicated that most of the sensors did not respond until the TOHC levels were very high (> 60,000 ppm). The slopes for the data when the sensors were responding still did not deviate significantly from 0. The plots of the regressions for the USD, AZI, and RJ sensors as compared with a sensor that would have responded with 100 percent accuracy are plotted in Figures C-27 and C-28. The figures illustrate that the RJ sensor shows little response over the measured TOHC concentrations while the USD and AZI sensors show a linear response, even though the response is less than the actual concentrations of TOHC.

An additional analysis was conducted to examine the response of the USD sensors at 3 and 5.5 feet. The multiple regression indicated that the relations between GC concentrations and those recorded by the sensor were significantly different (PR > F = 0.0001). The slopes of the regression indicated that the USD sensors at 3 feet were more accurate than those at 5.5 feet.

Medians of the percent error or inaccuracy calculated for each sensor provided an overall measure for each of the three devices. This overall measure of inaccuracy indicates that the larger the percentage, the less accurate the device (i.e., the sensors with the least accuracy are those with the highest values):

(1) USD, 3 feet - 64.7 percent
(2) USD, 5.5 feet - 83.6 percent
(3) RJ, 3 feet - 100.0 percent

(4) RJ, 5.5 feet - 100.0 percent
(5) AZI, 5.5 feet - 92.7 percent

In summary, the accuracy of some sensors is dependent upon the concentration of TOHC in the sand. RJ devices were unresponsive to TOHC in the sand while AZI and USD sensors were responsive. The AZI sensor consistently underpredicted TOHC concentrations, while the USD sensor overpredicted TOHC concentrations early in the experiment and then underpredicted TOHC concentrations. The overall median inaccuracies of the sensors indicates that the USD devices are the most accurate (64.7 to 83.7 percent) followed by the AZI sensor (92.7 percent) and then the RJ sensor (100 percent).

b. Precision Estimates for Nondestructive Sensors

The precision of the sensors was evaluated by examining the deviations of replicated sensors in each of the wells. Analysis of the deviations over time indicated that the deviations were generally in the range of 100 to 300 ppm. The RJ sensors recorded 0 concentrations until approximately 100 hours (69,740 ppm TOHC) into the experiment and consequently the precision recorded up to this point was 0. After approximately 100 hours, the RJ sensors recorded low concentrations of TOHC, generally less than 1,000 ppm, and the deviations were small relative to the USD deviations.

To examine the relation between precision and TOHC concentration, the deviations between replicate sensors normalized to the average concentrations for the two sensors were plotted against GC TOHC concentrations. The slope coefficient for the linear regressions fit to the data indicated that precision remained the same for the RJ sensor since the slope coefficient was not significant ($P > 0.1$). For the USD device, there was an increase in the deviations with increased concentrations of TOHC (i.e., decreased precision). The equations for the USD sensor at distances of 3 and 5.5 feet are as follows (Figures C-29 and C-30):

$$\text{at 3 feet, dev} = 0.31 + 4.65 \times 10^{-5} \text{ (x conc)} \quad (R^2 = 0.26,\ n = 58,\ PR > T = 0.0001) \tag{4}$$

$$\text{at 5.5 feet, dev} = 0.14 + 0.0001 \text{ (x conc)} \quad (R^2 = 0.29,\ n = 128,\ PR > T = 0.0001) \tag{5}$$

where:

dev = absolute value of the concentration recorded from a replicate sensor (ppm) minus the average of the replicates divided by the average of the replicates
x conc = average concentration recorded by the replicate sensors
R^2 = coefficient of multiple determination
n = sample size
PR > T = the significance of the slope coefficient (i.e., if PR > T is less than 0.005, then the slope coefficient is significantly different from 0).

As an overall measure of precision, a median value was calculated for the deviations calculated for each replicate pair of sensors. As with the overall measure of accuracy, the larger the percentage, the less precise the device.

(1) USD, 3 feet - 33.6 percent
(2) USD, 5.5 feet - 16.6 percent
(3) RJ, 3 feet - 42.0 percent
(4) RJ, 5.5 feet - 92.2 percent

2. Wet Sand Tests

During the wet sand study, the tank was filled with water and drained so that only a small amount of free liquid remained at the bottom of the tank. The moisture content distribution in sand is given in Table C-1 (see Appendix C). The devices were installed in the tank as in Section III.C.2 and allowed to equilibrate for 24 hours. There were no false positive alarms from any of the devices. Then fresh JP-4 was released at a rate of 0.03 gal/h for 48 hours. There was no fuel release for 48 to 96 hours; the release was restarted at 96 hours at a rate of 0.02 gal/h. This test was continued for a total of 336 hours. The temperature in the tanks varied from 28 to 20°C (see Table C-2).

The alarms were set to 500 and 1,000 ppm values. There were no false positive alarms for USD, RJ, or AZI devices, and no false negative alarms with USD, AZI and RJ devices. However, the AZI device is designed to alarm after exceeding the threshold level for the first time (only if background hydrocarbon levels were significantly higher than the threshold value); in other cases, AZI units alarmed only after exceeding the threshold level for three consecutive times.

None of the destructive devices (In Situ, Inc., and TCI) responded to JP-4 vapors even after exposing them to more than 50,000 ppm for longer than 200 hours. The TOHC values and device readings for USD, RJ, and AZI are given in Figures C-31 through C-43. It appeared that USD sensors had a lag time in negative bias and generally did not respond to JP-4 at concentrations below 40,000 ppm of TOHC. The moisture effects appeared to be minimized when using AZI devices. The effects of moisture will be discussed in a later section. The following section presents the accuracy and precision analyses of USD, AZI, and RJ devices.

a. Accuracy Estimates for Nondestructive Sensors

Figures C-44 and C-45 illustrate the average delta values for each sensor over time at 3 and 5.5 feet, respectively (0 to approximately 100,000 ppm TOHC). In general, all of the sensors underpredicted the TOHC concentrations except for the USD sensors which overpredicted the TOHC concentrations during the first 2 hours of the experiment (less than approximately 100 ppm TOHC). As time progressed the extent of underprediction by the sensors increased. Some USD sensors registered the maximum value (9,999 ppm) at approximately 68,000 ppm of TOHC at 3 and at 5.5 feet, whereas the others never reached the maximum value (9,999 ppm) even after exposure to TOHC concentrations ranging from 70,000 to 120,000 ppm. The RJ sensors recorded 0 values until approximately 160 hours at 3 feet and at 5.5 feet. The AZI sensor also consistently underpredicted TOHC concentrations though concentrations greater than zero were recorded within 21 hours after initiation of the experiment (3,042 ppm TOHC).

Plots of the relation between the concentrations from the USD sensors and those from the GC analyses indicated that most of the USD sensors located at 3 feet responded after TOHC values were greater than 40,000 ppm (Figure C-46). Following this "threshold" concentration, the sensors responded to increasing concentrations of TOHC with varying degrees of accuracy. At 5.5 feet, the "threshold" TOHC concentration was approximately 30,000 ppm (Figure C-47). After this concentration was reached, the sensors again responded to increasing TOHC concentrations with varying degrees of accuracy. The simple linear regression relating the USD sensor readings with the GC data produced the following equations (Figures C-48 and C-49):

$$\text{at 3 feet; conc} = -1324.01 + 0.0648\ (\text{GC conc}) \qquad (R^2 = 0.30,\ n = 241, \text{PR} > T = 0.0001 \tag{6}$$

$$\text{at 5 feet; conc} = -793.22 + 0.0714\ (\text{GC conc}) \qquad (R^2 = 0.53,\ n = 294,\ \text{PR} > T = 0.0001) \tag{7}$$

where:

where:

conc = concentration recorded from the sensor (ppm)
GC conc = TOHC concentration recorded from GC analyses; GC concentrations ranged from 0 to 70,000 ppm TOHC for the 3-foot distance and 0 to 80,000 ppm TOHC for the 5.5-foot distance
R^2 = coefficient of multiple determination
n = sample size
$PR > T$ = the significance of the slope coefficient relative to a hypothetical 100-percent accurate sensor as shown in Figures 9 and 10 (i.e., if $PR > T$ is less than 0.05, then the slope coefficient is significantly different from one)

According to these equations, a USD sensor located 3 feet from the leak would record a value above 0 only after the TOHC value reaching about 20,000 ppm. Similarly, a USD sensor located 5.5 feet from the leak would require an appropriate TOHC level of 11,000 ppm to begin registering a reading in the monitor.

For the AZI sensor, the linear regression relating the sensor reading and GC data is as follows (Figure C-50):

$$\text{conc} = 476.99 + 0.0649\ (\text{GC conc}) \qquad (8)$$
$$(R^2 = 0.35,\ n = 68,\ PR > T = 0.0001)$$

where:

GC conc ranged from 0 to 80,000 ppm TOHC.

The slopes were significant for both the USD and AZI sensors, indicating that as the concentrations of TOHC increased, the concentrations recorded from the sensor also increased. The USD sensors at 3 feet showed basically two clusters of responses. One set of sensors responded to increasing concentrations of TOHC while another set did not respond as much (Figure C-48). The dichotomy of responses was less evident at the 5 feet distance, although the variability of the sensors' responses increased as the TOHC concentrations increased. The RJ sensor did not respond until near the end of the experiment. The slopes for the data when the sensors were responding did not deviate significantly from 0.

The plots of the regressions for the USD, AZI, and RJ sensors as compared with a sensor that would have responded with 100 percent accuracy are plotted in Figures C-51 and C-52. These figures illustrate that the RJ sensor

AZI sensors show a linear response, even though the response is less than the actual concentrations of TOHC.

An additional analysis was conducted to examine the response of the USD sensors at 3 and 5.5 feet. The multiple regression indicated that the relationships between GC concentrations and those recorded by the sensor were significantly different (PR > T = 0.0001). The slopes of the regression indicated that the USD sensors at 5.5 feet were slightly more accurate than those at 3 feet.

Medians of the percent inaccuracy calculated for each sensor provided an overall measure for each of the three devices. This overall measure of inaccuracy indicates that the larger the percentage, the less accurate is the device.

(1) USD, 3 feet - 98.1 percent
(2) USD, 5.5 feet - 97.9 percent
(3) RJ, 3 feet - 100.0 percent
(4) RJ, 5.5 feet - 100.0 percent
(5) AZI, 5.5 feet - 93.2 percent

In summary, the AZI and USD sensors were responsive to changes in concentration of TOHC in the wet sand while the RJ sensor was unresponsive. The AZI sensor consistently underpredicted TOHC concentrations while the USD sensor overpredicted TOHC concentrations very early in the experiment and then underpredicted TOHC concentrations. The overall median inaccuracy estimates of the sensors indicated the AZI sensor (93.2 percent) was the most accurate followed by the USD sensor (97.9 to 98.1 percent) and then the RJ sensor (100 percent).

b. Precision Estimates for Nondestructive Sensors

The precision of the sensors was evaluated by examining the deviations of replicated sensors in each of the wells. For USD sensors, which responded to increasing concentrations of TOHC, the relations among precision and TOHC concentrations were examined by plotting the deviations between replicate sensors normalized to the average concentrations for the two sensors against GC TOHC concentrations. There was an initial increase in the deviations with increased concentrations of TOHC (i.e., decreased precision) followed by a zone (greater than 40,000 ppm TOHC) where the precision was stable. The equations for the USD sensor at 3 and 5.5 feet are as follows (Figures C-53 to C-54):

$$\text{at 3 feet, dev} = 0.31 + 0.00016\ (\text{x conc}) - 1.29 \times 10^{-8}\ (\text{x conc}^2) \quad (R^2 = 0.72,\ n = 182,\ PR > T = 0.0001) \tag{9}$$

$$\text{at 5.5 feet, dev} = 0.13 + 0.00016\ (\text{x conc}) - 2.10 \times 10^{-8}\ (\text{x conc}^2) \quad (R^2 = 0.28,\ n = 298,\ PR > T = 0.0001) \tag{10}$$

where:

dev = absolute value of the concentration recorded from a replicate sensor (ppm) minus the average of the replicates divided by the average of the replicates
conc = average concentration recorded by the replicate sensors
R^2 = coefficient of multiple determination
n = sample size
$PR > T$ = the significance of the slope coefficient (i.e., if $PR > T$ is less than 0.005, then the slope coefficient is significantly different from zero)

As an overall measure of precision, a median value was calculated for the deviations calculated for each replicate pair of sensors. As with the overall measure of accuracy, the larger the percentage, the less precise the device.

(1) USD, 3 feet - 45.6 percent
(2) USD, 5.5 feet - 27.0 percent
(3) RJ, 3 feet - 100.0 percent
(4) RJ, 5.5 feet - 100.0 percent

In summary, precision of the USD sensor decreased with increasing concentration of TOHC until about 40,000 ppm TOHC when the precision stabilized. The overall precision calculated for the USD and RJ sensors indicated the USD sensor was more precise than the RJ sensor with median precision values being 27.0 to 45.6 percent for the USD sensor and 100 percent for the RJ sensor.

3. Comparison of Results from Dry and Wet Sand Studies

The evaluation of the replicate USD sensors 3 feet from the JP-4 source during the dry sand experiment indicated that all of the sensors differed significantly with respect to accuracy (Table C-3). The most accurate USD sensor was Replicate Sensor 1 in Well B. The degree of accuracy declined from Replicate Sensor 1 to 5, and then 5 to 4, followed by Replicate Sensors 3, 2, and 6 (Figure C-55). For the wet sand experiment, three distinct groups of sensors were evident with Replicate 5 comprising Group 1 which was the most accurate sensor (Table C-3). Group 2 included Sensor Replicates 1 and 4 which were the second most accurate group of sensors, followed by Sensors 2, 3, and 6 in Group 3 (Figure C-56).

For the USD sensors located 5.5 feet from the JP-4 source, generally three distinct sensor groups were noted. In the dry sand experiment, Replicate Sensors 9, 8, and 11 were generally similar and comprised the two most accurate groups (Figure C-57). The third group consisted of Replicate Sensors 7, 10 and 12. For the wet sand experiment, the first and most accurate group consisted of Replicate Sensor 9. The second group contained Replicate Sensors 8 and 11, and the least accurate group contained Replicate Sensors 7, 10, and 12 (Figure C-58).

In general, for USD sensors located 3 feet from the JP-4 source, Replicates 1, 4, and 5 were the most accurate sensors both in the dry and wet sand experiments while Replicates 2, 3, and 6 were less accurate. For sensors located 5.5 feet from the source, Replicate Sensors 8, 9, and 11 were the most accurate in both the dry and wet sand experiments while Replicate Sensors 7, 10, and 12 were less accurate.

The multiple-regression analysis comparing the results from sensors in dry versus wet sand indicated that in all cases the slopes of the lines were significantly different ($P < 0.05$). For the USD sensor, the sensors were more accurate in dry versus wet sand while the reverse was true for the AZI sensor (Figures C-59, C-60, and C-61). The RJ sensor essentially did not respond in either wet or dry sand, though its response was slightly better in dry versus wet sand (Figures C-62 and C-63).

4. Response of FCI Devices to JP-4 Vapors

The fiber optics system available for the present study consisted of prototype units. The monitor readout was in millivolts and concentration values had to be estimated from appropriate calibration curves. The calibration data were not available from FiberChem, Inc. for dry sand test at the time of the data analysis, which was over 8 months into the study. Consequently, the test results for FCI sensors are presented below as a separate section and are not subjected to statistical analysis.

a. FCI Response to Fresh JP-4 Vapors in Dry Sand

Response of FCI sensors to fresh JP-4 in dry sand is given in Figures C-64 through C-69. The estimated hydrocarbon concentrations were at least one order of magnitude lower than TOHC values. Even when the TOHC values were above 40,000 ppm, some sensors (12, 23, 14, 25) were recording either very low concentrations or negative values. Some sensors recorded significant fluctuation of readings. For example, when the TOHC value was gradually increasing from 2,000 to 5,000 ppm, Sensor 12 readings dropped from 139 to -1082 ppm. In a similar concentration range, Sensor 24 readings increased from a nearly zero value to 3292 ppm and then dropped to negative values. Sensors 1 and 9 in Well H appeared to be responding to JP-4 vapors with some consistency, but there were some drastic fluctuations of sensor readings intermittently.

b. FCI Response to Fresh JP-4 Vapors in Wet Sand

The manufacturer of FCI sensors decided to remove the multiplexor monitoring console unit assuming that the discrepancy was associated with the unit but not the sensors. Subsequently, two of the single probe readout monitoring consoles were provided to be used in the wet sand study. To compare the two sensors (2 and 12), both were installed at the same location in Well H. The results are presented in Figure C-70. Sensor 2 consistently recorded a very low reading whereas Sensor 12 recorded a continuously increasing reading. None of the devices appeared to follow the trend of the JP-4 vapor concentration determined by the GC method.

c. FCI Response to Fresh JP-4 Vapor in Aged JP-4 Background

The results of this test are given in Figure C-71. Both FCI sensors were underpredicting the vapor concentration in the monitoring well. Sensor 12 was more responsive than Sensor 2, but the variation of sensor readings did not consistently follow the changes in vapor concentration.

D. TESTING VAPOR-PHASE DEVICES WITH AGED JP-4 IN SAND

The sample of aged JP-4 used in this study was obtained from recovery wells located on Eglin Air Force Base. Aged JP-4 was analyzed for its constituents and the results are given in Table A-1 (Appendix A). These data indicate that the aged fuels contained relatively small quantities of low molecular weight and volatile hydrocarbons such as benzene and toluene.

During this task, about 3.25 liters of aged JP-4 was added to wet sand at 25 different points resulting in an average concentration of approximately 100 µg aged JP-4 per gram of sand. The system was allowed to equilibrate for 7 days to achieve relatively uniform hydrocarbon distribution in the sand bed. The TOHC levels varied from 22,000 to 35,000 ppm in all the wells except for Well K where the TOHC levels were about 10,000 ppm. The low levels in Well K may be attributed to intermittent pumping of soil gas by AZI device where dilution might have occurred from the air pumped from outside. Since it appeared that the system can take a very long time to reach uniform hydrocarbon levels in all the wells, experiments were initiated after 7 days from aged JP-4 injection. Temperature readings are given in Table D-1 (Appendix D).

The experimental results are given in Figures D-1 through D-13 in Appendix D. The responses of USD sensors were inconsistent. For example, prior to starting the fresh JP-4 release, Sensors 1 (Well B), 3 and 4 (Well C), 5 (Well D), 8 (Well F), and 9 (Well G) were saturated and the devices were reading 9,999 ppm, the maximum response. However, the other sensors were reading values ranging from 2,000 to 8,000 ppm. The sensors that recorded maximum readings in this test (Sensors 1, 3, 4, 5, 8, and 9) also responded rather quickly during the previous tests with fresh JP-4 (dry and wet sand). The sensors that recorded lower readings in the previous tests (see Sections IV.C.1 and IV.C.2) were showing consistently lower values in this test. However, continuous exposure of USD sensors to high JP-4 vapor concentrations resulted in significant fluctuation of device readings. In most cases USD readings declined gradually and fluctuated, but never reached the maximum reading of 9,999 ppm again. When the manufacturer was consulted regarding this behavior of the devices, we were informed that the response of metal oxide semiconductor (MOS) type devices are unpredictable, for some unknown reason, at very high hydrocarbon vapor concentrations.

Response of RJ devices was significantly different from what was observed in the previous tests where RJ devices did not respond adequately for fresh JP-4 vapors in the absence of background aged JP-4 contaminations (see Sections IV.C.1 and IV.C.2). In the present test, however, RJ was much more responsive. One major problem occurred during the present test since one of the RJ monitoring consoles was not properly connected to the main power supply. Therefore, the sensors in Wells D, F, G, and H continuously recorded 4,000 ppm, the maximum reading of the device. (This is an important safety feature with the RJ devices.) In this test, since there were high background hydrocarbon levels at the initiation of the experiments, the instrument was assumed to be responding to aged JP-4 vapors. The RJ device did not indicate or display any malfunctioning or other defects. Therefore, this problem remained undetected throughout this experimentation.

Four RJ sensors which generated useful information, were connected to a different monitoring console. These were Sensors 1 and 2 in Well B and Sensors 3 and 4 in Well C. Sensor 3 in Well C reached the maximum reading within the first 20 hours of the experiment, whereas the Sensor 4 response was generally low (Figure D-4). However, the data generated by Sensors 1 and 2 in Well B are important. As shown in Figure D-2, although the RJ readings were over two orders of magnitude lower than the TOHC values, the trend of instrument response was very much similar to the variation of TOHC levels. These data indicate that some RJ sensors that adequately respond to fresh JP-4 release in the presence of background JP-4 contaminations.

The response of Soil Sentry (AZI) is given in Figure D-13. Data indicate that AZI did not follow the trend of TOHC levels very closely. Since the AZI device is also an MOS type, it is uncertain whether the response is not very accurate at high hydrocarbon concentration as observed with USD sensors.

E. TESTING OF LIQUID-PHASE DEVICES WITH FRESH JP-4 IN SAND

The devices tested during this task included Leak-X, TCI, and In Situ, Inc. At the very early stages of this test, FCI sensors were removed by the manufacturer due to equipment problems. There were 17 monitoring wells and the monitoring devices were distributed as described in Section III.E. The water table in the tank was 1.75 feet (static) and fresh JP-4 was released at the center of the tank, just above the water table, at a rate of 0.05 gal/h. Jet fuel was added continuously for 573 hours as shown in Figure E-1 (Appendix E). The test was continued for 816 hours until there was free product in all the wells.

The distribution of JP-4 (free product) in the wells located at 3-foot radial distances from the source is given in Figure E-2. Free product was observed in Well C as early as 27.5 hours whereas it took over 330 hours to get to Well G. Figure E-3 presents the distribution of JP-4 in wells located at 5.5 feet radial distances from the release point. The free product appeared in

Well J at 120 hours, but it was observed in Well Q after 500 hours. Although fairly uniform sand was used to pack the tanks, transport of JP-4 in sand did not appear to be uniform in all horizontal directions.

Table E-1 (Appendix E) summarizes the test results for different devices. Leak-X generally responded well for JP-4 thickness of 0.25 inch. However, in Well I, Leak-X was not alarming for a free-product thickness of 1.5 inches. In Well C, the Leak-X device activated the alarm for a thickness of 0.25 inch. However, when the device was removed and put back, it did not alarm immediately. Overall analysis of data indicates that about 83 percent of Leak-X devices responded to a 0.25-inch thick free-product layer and 100 percent responded to a 1.5-inch thick layer.

Eight TCI devices were tested in four wells. None of the devices alarmed for a free-product thickness less than 2 inches. Based on the tank test data, the following accuracy determinations were made for TCI:

JP-4 layer thickness (inches)	Accuracy (percent)
< 2.25	0
2.25	25
4.0	50
7.5	75
9.875	100

The In Situ probes appeared to respond rather quickly for floating JP-4. Both sensors tested in this study responded to a layer less than or equal to 0.25 inch. One sensor was observed to respond to a thickness < 0.06 inch.

Based on these data, In-Situ followed by Leak-X responded to a thickness of 0.25 inch. TCI was the least sensitive with a minimum response thickness of 2.25 inches.

During the liquid-phase test, tank temperature was essentially 19 to 20°C (Table E-2).

F. ACCURACY AND RESPONSE TIME DETERMINATION FOR LIQUID-PHASE DEVICES

1. Test Results

This laboratory test was performed to determine the accuracy, response time, and precision of liquid-phase devices under controlled environmental conditions. Each test was conducted in five replicates to generate statistically valid results. The test procedures listed in US EPA (1988) were used with some modifications as discussed in Section III.

a. Test Container

In the present study, glass tubes were used instead of the stainless steel pipes that EPA/Radian used as test containers. The reasons for using glass tubes are (1) glass was relatively inexpensive, (2) the test unit was easy to assemble, and (3) the inside of the setup is visible. The glass tubes were 4 inches diameter and 24 inches long. The bottom was closed with a rubber stopper. A glass-mercury thermometer was attached inside the test container.

b. Volume/Depth Relation

Some of the concerns associated with using glass test units were that the glass tubes were not exactly circular and the cross section was not necessarily uniform throughout the length. Therefore, the test containers were calibrated using a vernier caliper. The moving (central) arm of the vernier caliper had an extended pointer to facilitate locating the surface of the liquid layer. The test containers were calibrated with the detector and probe in place. The advantage of having the probe is that we did not have to calculate or measure the liquid volume displaced by the probe. The accuracy of such measurement or calculations is questionable for some of the probes that have irregular cross sections (e.g., TCI, Leak-X).

The tube was calibrated at locations (depths) where the monitoring devices were tested using floating jet fuel. For the calibration purposes, known volumes of water were added to the container, and the corresponding changes in depth were measured using the vernier caliper. The calibration data and calculated depth/volume relation are given in Table F-1 for one test container (Appendix F).

The depth of water column and volume dispersed was linearly related with a high correlation coefficient (0.999868). This linear relation was used to estimate the amount of liquid required to obtain the depths (e.g., 0.125, 0.25, 1.0 inch) that need to be tested for liquid-phase devices. The results of statistical analyses and estimated volumes for one test vessel are listed in the last three lines of Table F-1.

c. Test Results for In Situ, TCI, and Leak-X Devices

Tables F-2, F-3, and F-4 (Appendix F) present the JP-4 layer thickness, response time, and average temperature of the system for In Situ, TCI, and

Leak-X, respectively. Since In Situ and TCI responded to 1/4 inch rather quickly, additional tests were conducted to determine the response time at lower depths such as 1/8, 1/16, and 1/32 inch. Since the In Situ device responded to a JP-4 layer of 1/32 inch within 1 minute, an additional test was conducted at the depth of 1/64 inch.

2. Analysis of Test Results

The accuracy of the devices was estimated by the following equation:

$$\text{Percent Accuracy} = \frac{\text{No. of positive responses at a given thickness}}{5} \times 100$$

These results are summarized in Table F-5. Both In Situ and TCI appeared to be 100 percent accurate for all the depths tested. Leak-X, however, recorded zero accuracy for thicknesses of 1/4 and 1/8 inch. Therefore, the thickness of the JP-4 layer was increased gradually in all the Leak-X test containers until the alarm was activated. Leak-X appeared to be 100 percent accurate for thicknesses above 0.46 inch.

The laboratory test data deviated from some of the large-scale tank test results. Direct comparison of data, however, is not possible since the present system is static where as the liquid-phase tank test was dynamic. Data obtained from the laboratory study appeared to be more useful in statistical analysis since the system was monitored continuously.

Results of both liquid-phase tests indicate that the In Situ devices responded very quickly to very thin free-product layers. TCI responded a little later but appeared to be more precise than In Situ. Since both of these devices have certain response times, precision was estimated as follows:

$$\text{Precision} = \frac{T_{SD}}{T_{AV}} \times 100$$

where,

T_{SD} = Standard deviation of response time

T_{AV} = Average response time.

The precision estimates are listed in Table F-6. The lower the percent precision value, the more precise the sensor. Average response time for In Situ and TCI were 0.86 and 163 minutes, respectively.

Based on the thickness values, precision can be estimated for Leak-X.

$$\text{Precision} = \frac{D_{SD}}{D_{AV}} \times 100$$

where,

D_{SD} = Standard deviation of JP-4 layer thicknesses responded

D_{AV} = Average of the responded JP-4 layer thicknesses.

For Leak-X, D_{SD} = 0.0495 inch and D_{AV} = 0.373 inch with a precision of 13.3 percent.

G. TESTING OF VAPOR-PHASE DEVICES FOR BACKGROUND INTERFERENCES

The effects of background interfering gases on the vapor-phases were tested in a closed stainless steel cylinder. The gases tested included CO_2, CO, H_2S, CH_4, and TCE. The test results are shown in Tables G-1 through G-5. Each device was exposed to each of the gas concentrations for at least 3 hours. Carbon dioxide did not affect any of the devices except FCI. Both USD and AZI responded to CO. FCI responded to CO at 9,900 ppm level. Hydrogen sulfide appeared to have a very noticeable effect on USD, AZI, and FCI devices. One USD sensor recorded 9,999 ppm, its maximum possible reading for a H_2S concentration of 450 ppm. The effects of methane on all the devices appeared to be insignificant. Trichloroethylene was detected by the USD, AZI, and FCI sensors. AZI device recorded at least three times the TCE level at concentrations exceeding 600 ppm. The FCI unit had a significant response when the TCE level was 1,500 ppm.

The results of the present study indicate that USD, AZI, and FCI devices will be subjected to interfering effects from TCE vapors and gases such as H_2S, and CO. However, even at very high concentrations, none of the tested gases or vapors interfered with or were detected by RJ sensors and the two destructive-type sensors (TCI and In Situ).

H. DISTRIBUTION OF JP-4 VAPOR AND LIQUIDS IN SAND

1. JP-4 Vapor Distribution in Sand

During this study, transport of different chemical components of JP-4 in dry and wet sand was studied. Figure H-1 (Appendix H) presents the distribution of benzene in two sampling wells located at a distance of 3 and 5.5 feet from the JP-4 release point. As expected, concentrations in the closer well were always higher. It was also observed that the presence of moisture retarded the rate of migration of all the hydrocarbons. The degree of retardation was significant for more water-soluble hydrocarbons such as benzene. The chemical components with low solubility (e.g., high molecular-weight alkanes such as nonane and decane) showed very little retardation as a result of moisture.

The chemical analysis indicated that relatively high levels of light hydrocarbons such as butane and pentane appeared within 24 hours in the monitoring wells located 3 feet from the leak. The heavier hydrocarbons including octane, nonane, and decane appeared in relatively high concentrations only after 48 hours. The early appearance of low molecular-weight hydrocarbons may be attributed to rapid volatilization and high diffusion rates of these compounds. No significant retardation from adsorption is expected because of the very low organic-carbon content (<0.01 percent) in sand.

Distribution of organic vapors in sand is given in Figures H-2 and H-3. In these contour plots, the vertical axis is the centerline of the test tank and the horizontal axis is the base of the tank. The scales are depth and radial distances, respectively, in feet. The concentrations are reported as total organic carbon as parts per million (ppm) by volume/volume basis. Figure H-2 presents the distribution of organic vapor in dry sand at different time periods. Figure H-3 is for organic vapor distribution in wet sand. At the early stages of fuel release where the organic vapor concentrations are low, no stratification was observed. That is, the concentration isopleths are nearly vertical at low concentrations. As the organic vapor concentration increased with time, the stratification became more apparent. These data indicate that the vapor transport is diffusion-driven at low concentrations. As the concentration increases, vapor transport appears to be by both diffusion and density-driven advective flow.

The concentration isopleths shown in Figures H-2 and H-3 indicate that the presence of moisture resulted in a noticeable retardation of vapor transport at the initial stages. With time, however, the retardation of vapor in wet sand was not significantly different from that of dry sand. Apparently, the retardation resulting from dissolution of hydrocarbon vapors gradually decreased as moisture became saturated with those compounds.

Data analysis was continued to see whether the stratification is limited to heavier molecular-weight hydrocarbons. JP-4 vapor was categorized into low, medium, and high molecular-weight hydrocarbon vapors. Low molecular-weight vapors consist of those in the molecular-weight range of propane, butane, and pentane. The medium molecular-weight includes hydrocarbons having molecular-weight in the range of benzene, heptane, and toluene. The high molecular-weight category is represented by organic vapors heavier than C_7 hydrocarbons. For JP-4, ethylbenzene, octane, xylene, nonane, and decane are the major compounds that fall into the high molecular-weight category. The different molecular-weight hydrocarbon distributions in dry sand are given in Figure H-4. These plots show that the density-driven transport was associated with low molecular-weight hydrocarbons as well as medium and high molecular-weight hydrocarbons. Similar observations were also made for distribution of JP-4 vapors in wet sand.

The distribution of different organic vapor fractions are shown in Figure H-5. At shallow depths (e.g., 1 to 2 feet), more than 50 percent of the total hydrocarbon observed during the first 10 hours consisted of low molecular-weight compounds. The medium molecular-weight hydrocarbons fraction, which was generally at about 70 percent when it is at equilibrium stage, ranged from less than 10 to 50 percent during the same initial time period at shallow depths. These data indicate that, at early stages of a leak where the hydrocarbon concentrations are low, the shallow depths are likely to contain the majority of the light hydrocarbons. The medium to high molecular-weight compounds tend to accumulate at the lower depths.

2. JP-4 Jet Fuel (Liquid) Distribution in Sand

One of the subtasks in the present study involved testing liquid-phase monitoring devices. In this test, JP-4 was released at the water surface of the sand tank at an approximate rate of 0.05 gal/h. Detail description of the test is given in Sections III.E and IV.E. The variations of JP-4 layer in the wells with time are given in Figures H-6 and H-7. Wells A through G are located at 3 feet radius and the depth of JP-4 in these wells are given in Figure H-6. Figure H-7 shows the JP-4 distribution in the outer most wells (H through Q) which are located at 5.5 feet radius. As shown in these figures, jet fuel distribution was not uniform over a given radius. Although fairly uniform sand was used, nonuniformity in the degree of compaction and groundwater capillary zone may have influenced the transport of JP-4 from the release point to different locations in sand. Figure H-8 is a contour plot for JP-4 distribution which indicates two regions of fuel accumulation in the early stages of the study.

Some Air Force sites are contaminated with fuel either by spills or leaking underground tanks and pipes. The quantity of fuel leaked or spilled is not always available. If site cleanup is necessary, the most common approach is to recover the free-floating nonaqueous phase liquid (NAPL). Prior knowledge on the amount of free NAPL remaining in soil pores is useful in the design and costing of cleanup efforts. Several techniques are used to estimate the recoverable NAPL from the subsurface. The purpose of the effort described in this section of the report was to test those techniques using the data generated in the present study.

Previous studies have shown that the product thickness of NAPL in the aquifer (within the porous media) is smaller than that observed in the wells (Vam Dam, 1967; Hampton and Miller, 1988). One of the models developed by Zilliox and Muntzer (1975) was based on the density and capillary pressure relation for both water and NAPL. De Pastrovich et al. (1979) modified this equation where true hydrocarbon thickness can be obtained by dividing the observed well thickness by a factor of 4. This factor is known as the "Concave Factor." The average JP-4 layer thickness at the equilibrium conditions (i.e., after 900 hours into the test where JP-4 release was stopped 573 hours) was 9.14 inches. Based on the above approach, the amount of JP-4 in the soil pores is estimated to be about 70 gallons. However, during this experimentation, only 28.3 gallons of JP-4 was released and the quantity of JP-4 retained within the porous media is only about 20.6 gallons; about 7.7 gallons were in the monitoring wells as free liquid. Therefore, the "Concave Method Factor" appeared to overestimate the quantity of JP-4 in sand by over 3 times.

Studies by Pastrovich et al. (1979) and Hall et al. (1984) gave the hydrocarbon thickness rather than the NAPL specific volume. Since the NAPL saturation varies over the depth, the above calculations based on hydrocarbon thickness tend to overestimate the quantity of NAPL present in the pore spaces. Parker et al. (1987) developed a model after considering the saturation capillary pressure relations and their variation with the depth. A computer model named OILEQUIL was developed based on this approach. OILEQUIL was used to estimate the specific volume of JP-4 in sand during the present study.

Some of the input data needs for OILEQUIL have to be generated by another program called SOILPROP. The SOILPROP program calculates soil drainage and retention properties using the grain size distribution and the physical properties of soil. These parameters can be estimated either using Brooks-Corey (1966) or van Genuchten (1979) methods employed in SOILPROP.

The OILEQUIL program uses the SOILPROP output along with air-oil and oil-water scaling factors, depth to water table, and apparent NAPL thickness. The scaling factors for air-oil and oil-water interfaces can be determined from interfacial tension data. OILEQUIL calculates the air-water, air-oil, and oil-water saturation properties and integrates under the air-oil curve to find the specific volume of NAPL in the vertical soil profile. Specific volumes can be calculated by either using Brooks-Corey or van Genuchten parameters. The results are presented in Figure H-9. It appears that both methods tend to overestimate the specific volume of JP-4 in sand. The difference is significant in the range where the JP-4 layer has not reached the equilibrium stage (up to 800 hours). However, when the JP-4 remaining in the subsurface reached the equilibrium stage, van Genuchten method was able to estimate the specific volume of JP-4 in sand fairly accurately.

I. JET FUEL VAPOR TRANSPORT IN THE SUBSURFACE

1. Column Test with Sand

Two preliminary column experiments using dry sand were conducted to establish operating conditions for JP-4 diffusion experiments in sand. The third experiment was also conducted with dry sand and JP-4 and the experimental conditions are summarized in Table I-1.

Vapor samples were taken from Sampling Ports 1, 3, 5, and 6 and analyzed using a gas chromatograph. Runs with standard vapor mixtures containing ten JP-4 components demonstrated a linear relation between vapor concentration (mg/L) and detector response (peak area) well beyond the highest vapor concentrations used in all experiments. Because of the linear detector response, the area, A, of each JP-4 component in each sampling port, divided by the respective average component area, A_0, for the same day in Sampling Port 1, was equal to respective vapor concentration ratio G/G_0. These ratios were plotted for 15 JP-4 components for Sampling Ports 3, 5, and 6 as a function of time and the results are shown in Figures I-1 through I-13. Included in these figures are also the computed lines using the diffusion equation adjusted for porous medium (see Section I.3).

As the distance from the source (Port 1) increased, vapor concentration ratios at steady state decreased (Figures I-1 through I-13). At the outlet of the soil column, vapor concentration for each component was equal to zero, because of direct exposure and dilution into the atmosphere. This is in agreement with Fick's laws of diffusion.

JP-4 components volatilized from the fuel reservoir and moved towards the sand column by diffusion. After entering the sand, fuel components diffused in the porous medium and were adsorbed. The extent of adsorption determines the degree of contaminant retardation by dry sand. Retardation is quantified by a retardation factor which, in the solute transport literature, is defined as the ratio of average groundwater velocity by the average velocity of advance solute (Freeze and Cherry, 1979). For linear adsorption isotherms, this ratio can be approximated by the ratio of time required for 50 percent breakthrough of the solute by the respective time of a conservative (nonsorbing and nonreacting) tracer (Reynolds et al., 1982). The conservative tracer simulates the groundwater flow. In case of a mixture (e.g., JP-4), retardation factors are determined for individual components and not for the mixture as a whole.

To assess the degree of retardation for the JP-4 diffusion experiments, relative retardation ratios were computed using the times required to reach 50 percent of steady-state vapor concentration for 15 JP-4 components and n-butane. Butane is a gaseous constituent of JP-4 with the lowest molecular weight, the lowest adsorbability, the highest mobility, and, therefore, the lowest retardation. Butane was used in this case as a conservative tracer, but there is no ideal conservative tracer and some degree of retardation is always expected.

Approximate times corresponding to 50 percent of steady-state vapor concentration for each position were determined graphically using the experimental data in Figures I-1 through I-13. Prior to this step, approximate steady-state concentrations were also graphically determined. The 50-percent breakthrough times and the computed relative retardation ratios for 15 JP-4 components are shown in Table I-2. Data for ethylbenzene and m-xylene, p-xylene were not available because of significant analytical error caused by the gas chromatographic analysis.

Sorption of fuel components may occur because of partitioning onto sand organic fraction, as well as sorption by sand mineral phase (Curtis et al., 1986). Because the organic fraction of dry sand used was small, it was expected that most of sorption occurred directly onto the mineral phase. With the exception of C-8 components, normal and branched alkanes and cycloalkanes showed very little retardation relative to butane, as indicated by relative retardation ratios of less than 2. C-8 alkanes had retardation ratios, for the most part, larger than 2.

From the aromatic components, benzene was not retarded by dry sand, whereas toluene showed retardation ratios larger than 2 for all sampling ports. Ethylbenzene and xylene showed even more retardation but, because of analytical error, it was difficult to compute relative retardation ratios.

2. Column Test with Soil

Three preliminary column experiments using wet and dry soil were conducted to establish operating conditions for JP-4 diffusion experiments in soil. The experimental conditions for the fourth and fifth experiments are discussed below and are summarized in Table I-3. Although all soil samples were collected from the same general area, there was a significant difference in percent organic carbon content (Table I-3). Unfortunately, it was not possible to obtain more of the 4.15-percent organic carbon soil, therefore, a lower percent organic carbon soil was used for the dry soil experiment. The conclusions of the study are not altered, however.

Vapor concentration ratios for the dry soil column were plotted against time and the results are shown in Figures I-14 through I-26. Also included in these figures are the computed lines using the diffusion equation adjusted for the porous medium (see Section IV.I.3). Unlike sand, several vapor components did not reach steady state because of significant retardation by the dry soil.

In fact, some components were not even detected at Sampling Port 6, 700 hours after starting the experiment. Because of analytical difficulties, cyclohexane and 2-methyl-hexane could not be separated by GC and their diffusion patterns exhibited erratic behavior. Therefore, no figures were included for cyclohexane and 2-methylhexane.

To assess the degree of retardation of JP-4 components by dry soil, relative retardation ratios were computed using the same approach described in the dry sand column study. Retardation data for the dry soil are shown in Table I-4. The larger than symbol (">") used in Table I-4 indicates that the particular JP-4 component has not reached steady-state yet. For components not detected at particular sampling ports, retardation ratios could not be computed (NA, not available).

Table I-4 indicates a strong retardation of virtually every fuel component compared with butane. Retardation ratios ranging from 3 to larger than 30 were observed at 18.4 cm from the source. As expected, retardation increased with molecular weight, indicating that larger, less water-soluble molecules were adsorbed to a greater extent.

Experimental and computed vapor concentration ratios for the wet soil column were plotted against time and the results are shown in Figures I-27 through I-41. Retardation data are shown in Table I-5. As was also observed in the dry soil column (Table I-4), retardation increased with molecular weight for all alkane, cycloalkane, and aromatic components of JP-4. Pentane, with a retardation ratio less than 2, was retarded the least, whereas all other constituents had a retardation ratio larger than 2 for all sampling ports of the column.

3. Modeling of Jet Fuel Vapor Transport

When JP-4 is released in the vadose zone in limited amounts, the immiscible with water JP-4 plume will be immobilized before reaching the water table. This will occur because, within the plume, capillary forces will be equal to gravitation forces. For a more extensive JP-4 release, equilibrium of these forces is not achieved within the plume and the fuel will penetrate downward after the residual saturation of the vadose zone is satisfied. As soon as the fuel reaches the top of the capillary fringe, it will spread out over the water table and will form a lens of free-floating product.

Although JP-4 and water are immiscible, some of the fuel components have limited solubility and will dissolve in the water of both saturated and vadose zones. In addition, because of their high volatility, some fuel components in the vadose zone will volatilize.

Significant portions of the fuel will be immobilized in the vadose zone at residual saturation by capillary forces. Hoag and Marley (1986) experimentally determined residual saturation of gasoline to be 26 and 44 g/kg for medium and fine sand, respectively, at field moisture conditions. Vapors originating from such residual saturations of JP-4 will diffuse in the vadose zone and may be detected by external monitoring devices positioned in appropriately spaced monitoring wells.

A liquid reservoir of jet fuel located at the inlet of a horizontal soil column of finite length will be a continuous source of jet fuel vapors. If density-driven flow is neglected in a horizontal soil column, vapor diffusion may be described by the following one-dimensional diffusion equation (Baehr, 1987):

$$\frac{\partial G}{\partial t} = D \frac{\partial^2 G}{\partial x^2} \tag{1}$$

where: G = vapor concentration for a specific component, g/cm^3

t = elapsed time, sec

x = distance from the source, cm

D = apparent diffusion coefficient for a specific component, cm^2/sec.

D can be calculated from the following equations:

$$D = \frac{D_w H + D_a}{\epsilon_a R} \tag{2}$$

$$R = (H/\epsilon_a)\ (\epsilon_w + K_d\ \rho_b) + 1 \tag{3}$$

$$D_w = D_{wb}\ \epsilon_w\ \tau_w \tag{4}$$

$$D_a = D_{ab}\ \epsilon_a\ \tau_a \tag{5}$$

$$\tau_a = \frac{\epsilon_a^{7/3}}{\epsilon^2} \tag{6}$$

where: R = retardation factor

D_w = effective diffusion coefficient in water in porous medium, cm^2/sec

D_a = effective diffusion coefficient in air in porous medium, cm^2/sec

D_{wb} = bulk water diffusivity, cm^2/sec

D_{ab} = bulk air diffusivity, cm^2/sec

ϵ_a = air-filled porosity

ϵ_w = water-filled porosity

ϵ = total porosity

τ_a = tortuosity for air phase in vadose zone

τ_w = tortuosity for water phase in vadose zone

H = water/air partition coefficient

K_d = linear soil/water partition coefficient, mL/g

ρ_b = bulk density of dry porous medium, g/cm^3

The initial and boundary conditions are as follows:

$$\text{I.C.} \quad G = 0, \quad t = 0, \quad x > 0 \tag{7}$$

$$\text{B.C.s} \quad G = G_o, \quad t > 0, \quad x = 0 \tag{8}$$

$$G = 0, \quad t > 0, \quad x = L \tag{9}$$

The solution to the differential equation (Equation 1) for the above initial and boundary conditions is given by Equation 10, which was derived by modifying an equation given by Crank (1975).

$$\frac{G}{G_0} = 1 - \frac{x}{L} - \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi x}{L}\right) \exp\left(\frac{-D\, n^2 \pi^2 t}{L}\right) \tag{10}$$

where: G_o = vapor concentration for a specific component at the inlet of the column (Sampling Port 1), g/cm^3

L = length of column, cm.

Fitting of the diffusion model (Equation 10) to the experimental data was a trial and error procedure during which the retardation factor was varied until the fitting parameter FMIN was minimized. FMIN is related to the sum of squares of deviations measured from predicted G/G_o ratios according to Equation 11 (Thacker et al., 1981):

$$\text{FMIN} = \left[\frac{1}{N} \sum_{i=1}^{N} [(\frac{G}{G_o})_m - (\frac{G}{G_o})_c]^2 \right]^{1/2} \tag{11}$$

where: N = number of data points
$(\frac{G}{G_o})_m$ = experimentally measured concentration ratio.

$(\frac{G}{G_o})_c$ = model computed concentration ratio.

For each new retardation factor, corresponding new values of D, $(G/G_o)_c$, and FMIN were computed using Equations 2, 10, and 11, respectively. Then, values of $(G/C_o)_c$ corresponding to the lowest FMIN value were plotted against $(G/G_o)_m$ as shown in Figures I-1 through I-41.

The boundary condition $G = G_o$ at $x = 0$ (Equation 8) must be satisfied in order to fit the solution to the diffusion equation (Equation 10) to the column experimental data. Vapor concentrations at Sampling Port 1 were plotted for each JP-4 component versus time and these plots indicated that G_o was constant within experimental error for the dry sand and wet soil experiments. A change of G_o with time, however, was observed for the dry soil experiments.

According to Raoult's Law, the concentration of a vapor component in contact with a multicomponent liquid mixture is proportional to the mole fraction of the component in the liquid mixture (Baehr, 1987). As a result, G_o of the most volatile components will increase with time, until a pseudosteady state is established.

The difference in G_o versus time patterns was attributed to different volatilization rates of jet fuel components, caused by different compositions of liquid JP-4. The liquid JP-4 used in the dry soil experiment was taken from a completely filled, brand-new container, whereas the liquid JP-4 used for the dry sand and wet soil experiments was taken from an older container with significant headspace. The presence of headspace in the latter container resulted in loss of most volatile fuel components prior to initiation of the column experiments. After initiation of the column experiments, a steady-state volatilization process had been already established which resulted in approximately constant G_0 versus time profiles.

Since Equation 8 was not completely satisfied for the dry soil column, G_0 was measured daily and G/G_0 for each component was computed using the average G_0 of that particular day. With this adjustment, model-predicted G/G_0 fitted experimental G/G_0 ratios very well, as shown in Figures I-14 through I-26. Best fit retardation factors for dry sand, dry soil, and wet soil are listed in Table I-6.

4. Comparison of Sand and Soil Experiments

Previous studies (Karickhoff, 1984) demonstrated that the extent of adsorption onto soils and sediments of organic compounds dissolved in water increased with increasing organic carbon fraction of soil or sediment. In fact, a linear relation between sorption coefficient (K_d) and percent organic carbon was established (Karickhoff, 1984). Soil organic matter affects adsorption of organic vapors in a similar manner as that of dissolved organic compounds. Therefore, a higher degree of retardation for JP-4 components is expected in soil containing organic matter than in sand.

To assess the effect of soil organic matter on retardation, diffusion times required to reach 50-percent breakthrough at Sampling Port 5 and model best-fit retardation factors were compared for sand and soil in Table I-6. The data of Table I-6 indicate that retardation of every fuel component, including butane, increased from dry sand to wet soil to dry soil. Retardation caused by dry soil was so large that several high molecular-weight components were not even detected at Sampling Port 5 within 700 hours after the beginning of the experiment and, therefore, a 50-percent breakthrough time could not be determined (NA, not available).

Retardation caused by the dry soil would be expected to be lower than that caused by the wet soil, because the organic fraction of the former (2.09 percent) was lower than the organic fraction of the latter (4.15 percent). Higher retardation, however, was observed for every fuel component (Table I-6) for dry than for wet soil. This behavior was attributed to a decrease of sorption capacity because of stronger competition with water for sorption sites (Chiou and Shoup, 1985). Thus, the effect of lower organic carbon in the dry soil was compensated for by the absence of moisture.

Retardation of water-soluble constituents, such as benzene and toluene, would be expected to be higher in wet than in dry soil, because the constituents would partition in the soil moisture and, therefore, would be retarded more (Baehr, 1987). Apparently, the combination of moisture and organic carbon contents of wet soil resulted in lower combined retardation compared with that caused by the dry soil.

The results of the sand and soil experiments indicated that soil organic matter can significantly retard all JP-4 constituents. This retardation increased from dry sand (very little retardation), to wet soil, to dry soil (very large retardation). The presence of moisture in the unsaturated zone will decrease sorption capacity and, therefore, decrease retardation compared with dry soil.

Retardation factors for a particular site can be determined experimentally using soil column experiments, as shown by this study. Then, these retardation factors may be used as input parameters to a two- or three-dimensional model to compute the rate of fuel vapor transport as a function of time and spatial coordinates.

The implication of this study, with respect to monitoring of JP-4 releases in the subsurface, is that small leaks may go undetected by vapor sensors for much longer in organic soil than in sand. Therefore, use of sand instead of native soil as backfill material for underground storage tanks and placement of vapor sensors in or very close to the backfill area is recommended as the most effective JP-4 release detection approach.

J. DISSOLVED JET FUEL TRANSPORT

One sand and one soil column experiment were conducted and the experimental conditions are summarized in Table J-1. Effluent samples were analyzed for chloride (Cl^-) and soluble JP-4 components. Gas chromatographic analysis indicated that benzene, toluene, xylenes, and ethylbenzene were the main soluble components of JP-4. Aqueous concentrations of these compounds were measured and concentration ratios C/C_{max} versus pore volumes were plotted in Figures J-1 through J-10. C_{max} was the highest concentration of each soluble component observed in the column effluent. C_{max} instead of C_0 (soluble concentration at column inlet) was used because C_0 for JP-4 soluble components was unknown. C_0 for chloride was equal to its highest effluent concentration when 100 percent breakthrough was achieved.

Soluble JP-4 components were dissolved from the nonaqueous JP-4 phase at the column inlet and moved through the column by advection and dispersion. Adsorption onto the porous medium retarded the movement of some of these components. Retardation is quantified by a retardation factor defined as the ratio of average groundwater velocity by the average velocity of advance of solute (Freeze and Cherry, 1979). For linear isotherms, this ratio can be approximated by the ratio of time required for a 50-percent breakthrough of the solute by the respective time of a conservative tracer (e.g., chloride [Reynolds et al., 1982]). The conservative tracer simulates groundwater flow.

Retardation factors for benzene, toluene, xylenes, and ethylbenzene were determined graphically using the data of Figures J-1 through J-10. Retardation factors for the above compounds for sand and soil columns are presented in Table J-2. No retardation was observed for any of the soluble JP-4 components in the sand column, as indicated by the retardation factor equal to 1. This behavior was consistent with very low adsorption caused by extremely low organic carbon content of sand (0.008 percent).

Retardation factors ranging from 1.0 to 3.8 were determined for the soil column and followed an increasing trend with molecular size: benzene < toluene < xylenes. This trend was consistent with increasing sorption and with increasing molecular size or decreasing solubility. The observed higher retardation factors for soil were caused by the higher organic carbon content of soil compared with that of sand (Table J-1). Higher organic carbon content resulted in higher sorption coefficient (Kd), which resulted in higher retardation factor values (Curtis et al., 1986).

In conclusion, the results of the dissolved JP-4 study indicated that benzene, toluene, xylenes, and ethylbenzene (BTX&E) were the most soluble components in water. No other components were observed in measurable quantities in the column effluent. No retardation of BTX&E was observed in sand columns, whereas some retardation was observed in the soil column. Retardation factors increased with molecular weight and decreasing solubility of JP-4 components.

K. QUALITY ASSURANCE/QUALITY CONTROL

1. Sampling and Analysis Quality Assurance

The sampling and analytical procedures, used for the collection and analysis of JP-4 contaminated samples, were designed to assure sample integrity and analytical precision.

a. Sampling Quality Assurance

(1) Vapor-Phase Experiments:

In the vapor-phase studies gas samples were drawn from all of the monitoring wells and from the nine-point sampling tubes. The sampling ports were constructed of stainless steel tubing with brass or stainless fittings (Small Parts, Inc., Miami, Florida). All gas samples were drawn using 20-cc glass syringes with 22-gauge stainless steel needles (Becton, Dickinson and Co., Rutherford, New Jersey). Prior to each use the syringes and needles were rinsed with reagent grade methanol (99 percent) and baked at 80°C for 30 minutes. The sampling procedure for all vapor samples was as follows:

(a) Purge the sampling tube with at least 20 cc of sample vapor (approximately 5 line volumes) prior to drawing sample.

(b) Leak test a clean syringe and needle by placing a septum on the needle tip and then pull the syringe plunger back to draw a vacuum.

(c) Draw a 20-cc vapor sample from the purged sampling port and immediately seal the syringe by placing the septum back on the needle tip.

(d) Store the sample no longer than 24 hours prior to analysis.

(2) Liquid-Phase Experiments:

There were two experiments used to evaluate the liquid-phase devices. One experiment, set up similarly to the vapor-phase experiments, was performed in a large-diameter tank filled with sand (see Figure 7). A fixed water table was set in the tank, and devices were installed to detect a simulated liquid JP-4 leak. In this experiment two separate parameters had to be analyzed: JP-4 in the aqueous phase, in 4 wells; and fuel layer thickness in all wells.

Aqueous phase sampling - Monitoring wells were constructed of stainless steel screens and casings, rather than from polyvinylchloride (PVC), to make certain that dissolved PVC would not contaminate the samples. The sampling ports were constructed of stainless steel tubing and fittings (as outlined for the vapor sampling ports above). The same sampling techniques used for vapor-phase sampling were used to collect aqueous phase samples, with the following exceptions:

(a) Only 10 cc of sample were collected.

(b) Aqueous samples were immediately transferred to clean, glass, vials with Teflon® cap liners. No headspace in the vials was allowed. Aqueous samples were refrigerated until they could be analyzed.

Produce thickness sampling - The collection method used to evaluate liquid-phase devices was a bench-scale study to determine the accuracy and response time for the devices. In this study liquid-phase detection devices were evaluated for their thickness detection limit to precisely calibrated JP-4 thicknesses. All measurements used to calibrate the test vessels for addition of JP-4 to form the desired product layer thickness, were taken with a caliper calibration to 0.025 inch. See Section III.F for a detailed test description.

b. Analytical Quality Assurance

The three different types of GC analyses performed to quantify JP-4 concentration were TOHC to quantify ppm TOHC as carbon; one temperature program analysis to quantify light, moderately heavy, and heavy hydrocarbons; and another temperature program analysis to quantify individual hydrocarbon constituents in the sample.

For all vapor analyses, sample injection volume was controlled through the use of a 1-cc stainless steel sample loop. The sample loop was purged with at least 5 cc of sample prior to making an injection. The procedure for injecting liquid samples is outlined in Section III.A.

(1) Calibration Procedures:

TOHC for vapor samples were calibrated against 1,000 ppm and 1-percent butane standards in helium (Alltech Associates, Inc., Deerfield, Illinois). The responses of the 1,000 ppm and 1-percent standards were nearly linear, so samples were quantified against the standard closest in concentration to the sample being analyzed. The standards were analyzed in duplicate daily. See Figure K-1 for sample chromatograms.

The quantification of light, moderately heavy, and heavy hydrocarbons was based on a standard mixture containing n-butane, n-pentane, n-heptane, n-octane, benzene, toluene, and o-xylene. This standard was analyzed daily. The samples were quantified as percent light, moderately heavy, and heavy hydrocarbon, based on the standard. See Figure K-2 for sample chromatogram.

Selected samples were quantified for individual components, ranging from propane to n-tetradecane, based on a 29-component National Bureau of Standards (NBS) standard (see Table K-1). The calibration table was entered into the GC integrator and sample peaks were correlated to the table for peak identification. Individual component NBS standards were periodically analyzed to check the calibration table. See Figure K-3 for sample NBS propane chromatogram.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. TESTING OF VAPOR-PHASE MONITORING DEVICES

To evaluate the vapor-phase monitoring devices, performance of the following products were tested:

- Fiber optic chemical sensors (FOCS) of FiberChem, Inc. (FCI)
- TCI Leak Detector System of Total Containment, Inc. (TCI)
- Petrochemical Release Monitor System of In Situ., Inc. (In Situ)
- Soil Sentry 17-100L of Arizona Instrument Corp. (AZI)
- Leak Alert of Universal Sensors and Devices, Inc. (USD)
- PPM 3000 of Red Jacket (RJ).

FCI's device consists of a fiber optic chemical sensor (FOCS) and a reader. TCI Leak Detector and In Situ systems have sensors that are product soluble. AZI and USD feature metal oxide semiconductor (MOS) sensors. RJ has diffusion-type adsistor sensors.

These vapor monitoring devices were tested for their responsiveness to JP-4 jet fuel leaks in sand under dry and wet conditions, in the presence and absence of background JP-4 contamination. During this study, there were no false positive alarms for all the devices that had audible and/or visual alarms (USD, RJ, AZI, TCI, and In Situ). The results are summarized in the following sections.

1. JP-4 Leak in Dry Sand Environment

The response of destructive type devices such as In Situ and TCI in detecting JP-4 vapors was rather poor. None of the six TCI probes responded to JP-4 vapors after exposure for over 250 hours. During this time, the JP-4 vapor concentration in the form of carbon increased from essentially zero to over 60,000 ppm. Only one of the two In Situ sensors responded under similar experimental conditions.

Accuracy of the non-destructive type sensors (USD, RJ, and AZI) depends on the concentration of hydrocarbon vapors. RJ devices were generally unresponsive to JP-4 vapors at the levels tested (<60,000 ppm as carbon) while

USD and AZI sensors were responsive. The AZI sensor consistently underpredicted organic vapor concentration while the USD sensor overpredicted the hydrocarbon concentrations (TOHC) early in the experimentation and then underpredicted. The overall median accuracies of the sensors indicate that the USD devices are the most accurate followed by AZI sensor and then the RJ sensor. Linear regression analysis relating to the device reading with the GC data resulted in slopes that are significant for both the USD and AZI sensors. This indicates, based on the analysis of all the data, that as the JP-4 vapor concentration increased the concentrations recorded by the USD and AZI sensors also increased.

The extent of overprediction or underprediction depends on the method of instrument calibration. It was found after discussions with the device manufacturers that different standards and methods were used to calibrate their devices. For example, AZI appears to use butane as the standard whereas USD uses a mixture of gasoline that yields an approximate molecular weight of 92. Also, discussions with USD revealed that a common conversion factor is used to calibrate all the sensors in a given batch. For quality control purposes, if these devices are to be used in Air Force facilities for underground leak monitoring systems, it is recommended that each sensor be calibrated for specific jet fuel vapors prior to installation by the manufacturer.

As an overall measure of the precision, a median value was calculated for the deviations that were estimated for each replicate pair of sensors. The test design and availability of data permitted only the comparison of USD and RJ among the nondestructive sensors; USD sensors appeared to have a relatively better precision than RJ sensors.

FCI data were not analyzed statistically because the calibration curves were not made available prior to data analysis. However, fluctuations of FCI readirgs and deviations of FCI values from the measured hydrocarbon values indicate that the prototype device has not been developed to a commercial level. At the present time it cannot be recommended for field installation at Air Force facilities.

2. JP-4 Leaks in Wet Sand Environments

As in the dry sand (moisture content of 0.005 percent) environment, destructive-type devices (In Situ and TCI) were not effective in detecting

JP-4 leaks in moist sand (moisture content 1.5 to 2.0 percent) environment. The nondestructive type devices responded to JP-4 vapors with varying degrees of accuracy and precision. In general, all the sensors (RJ, AZI, and USD) underpredicted the vapor concentrations except for USD sensors which overpredicted the TOHC levels during the first few hours of experimentation. Linear regression analysis of sensor readings and GC data for both USD and AZI indicate that, as the hydrocarbon vapor concentration increased, the concentrations recorded from the sensors also increased.

When the overall median accuracies were compared, AZI was the most accurate followed by the USD sensor and then the RJ sensor. The statistical analysis indicate that, although both devices were MOS type, the accuracy of AZI remained essentially the same for both dry and moist conditions. On the other hand, the accuracy of USD sensors declined noticeably in the presence of moisture. In the case of USD sensors, the probes that registered readings with relatively high accuracy during the dry sand test remained as the most accurate USD sensors during the wet sand test.

Comparison of precision data for replicate pairs of sensors showed that, as observed in the dry sand test, the USD sensors were more precise than the RJ sensors. It was also observed that the precision of USD sensors was lower for moist environment than for the dry conditions.

For both dry and wet sand studies, the effects of the location of USD sensors on the device response were consistent for the precision analysis but not for the accuracy analysis. These analyses were performed only on USD sensors because of USD's relatively high accuracy, precision, and response data as compared to RJ sensors. Since we used only one AZI sensor per tank, the effects of distance on AZI devices cannot be estimated. As mentioned in Sections I and III, more AZI devices could not be employed in this study. In the dry sand study, USD sensors located at 3 feet were more accurate than those located at 5.5 feet. In wet sand, however, the sensors located at 5.5 feet were slightly more accurate than those at 3 feet. Statistical analysis of data consistently shows that the USD sensors located at 5.5 feet were relatively more precise than those located at 3 feet for both dry and wet sand tests. Since the TOHC values were relatively low in the wells located at 5.5 feet, compared with those at 3 feet, one may speculate that the USD sensors respond more precisely at low concentrations. However, precision of the USD sensors decreased with increasing concentration of TOHC until about 40,000 ppm of TOHC in wet sand study. Further studies are recommended to test the effects of different components of JP-4 and different rates of the increase in vapor concentrations on the response of MOS devices.

3. JP-4 Leaks in Contaminated Backgrounds

This test was conducted to examine the response of devices to a JP-4 leak in the presence of background contamination. Aged JP-4 recovered from subsurface wells in the contaminated sites in Eglin AFB was used to spike the sand to yield 100 μg of JP-4 in 1 gram of sand, which is the allowable soil contamination in some states. Neither USD nor AZI responded effectively to a fresh JP-4 leak in the presence of background contamination. Apparently this background contamination (22,000 to 35,000 ppm of TOHC) was too high for these MOS-type devices. AZI technical personnel suggest that it can identify a leak if the background concentration does not exceed 500 ppm of the device reading. However, the test setup used in this study was not capable of performing such examinations because of the high TOHC concentrations established.

The response of RJ devices was significantly different from those observed in previous tests. In earlier tests, RJ devices did not respond adequately for fresh JP-4 vapors in the absence of background JP-4 contaminations. In this test, however, RJ devices performed fairly well in the presence of high-background contaminations. The manufacturer of the RJ device indicated that the sensor is designed so that it will not be interfered with or give false alarms to background contamination or interfering gases. This may explain why the device was not responsive to fresh JP-4 vapors in the previous tests utilizing dry and wet sand. Although the RJ device appears to have potential for leak monitoring in contaminated sites, its low response to JP-4 indicates that further studies will be required to investigate how these sensors will be affected by the fluctuation of background jet fuel vapors in the absence of a leak. Based on the manufacturer's literature, tracer-based technologies (e.g., Trace Tight Method by Tracer Research Corporation, Tucson, Arizona) appears to have a potential for detecting leaks in contaminated backgrounds. Specific tracers can be detected that are not components of petroleum hydrocarbons.

B. TESTING OF LIQUID-PHASE MONITORING DEVICES

To evaluate the liquid-phase monitoring devices, performance of the following units were tested:

1. FOCS system of FiberChem, Inc. (FCI)
2. TCI leak detector system of Total Containment, Inc. (TCI)
3. Leak-X system of Leak-X Corporation (Leak-X)
4. In-Situ system of In Situ, Inc. (In Situ)
5. Soil Sentry 17-100L of Arizona Instruments Corporation (AZI)

Leak-X Systems is a continuous liquid-phase detection system based on the principle of electrical conductivity. Brief description of the operating principles for the other devices are given in the previous section (Section II.B.). Because of the operational difficulties associated with the prototype FCI instrumentation/devices, this system was removed from the present test by the manufacturer following the initiation of the experiments. Therefore, data will be discussed only for the other monitoring devices.

During this study, JP-4 was released at a rate of 0.05 gal/h at the tank center just above the water tables. Leak detection devices were installed in a total of 17 monitoring wells located at 3 and 5.5 feet (radial distances) from the JP-4 release point. Temperatures during this test remained at 19-20°C. Overall analysis of data indicated that 83 percent of the Leak-X detectors responded to a 0.25-inch thick layer of JP-4 and 100 percent responded to a 1.5-inch thick layer. None of the TCI devices alarmed for a free-product thickness less than 2 inches. Only 50 percent of the devices responded to 2-4 inch thick layers and 100 percent responded to 2-9.9 inch thick layers. In Situ probes responded rather quickly for floating JP-4. Both sensors tested in this study responded to a layer less than or equal to 0.25 inch. One In Situ sensor was observed to respond even to a thickness of <0.06 inch. The AZI sensor recorded high vapor concentrations well before the appearance of free-products in the monitoring well. This device may work more effectively than other passive MOS devices in detecting free-floating products. Since these devices respond to hydrocarbon vapors even in the absence of free-floating fuel in the monitoring well, their effectiveness cannot be compared with the thickness of fuel layer.

The accuracy, response time, and precision for the liquid-phase devices were determined in the laboratory using a recent draft of the US EPA method with some minor modifications. Each test was conducted in five replicates with each of the TCI, In Situ, and Leak-X devices. The In Situ device was tested for free JP-4 layers of 1/4, 1/8, 1/16, 1/32, and 1/64 inch. For each thickness, In Situ devices responded within 1 minute. TCI devices responded to all the thicknesses (1/4, 1/8, 1/16, and 1/32 inch) generally, in 2-3 hours. Response time decreased with increasing thickness of JP-4 layer. For the layers greater than or equal to 1/64 inch with In Situ and 1/32 inch with TCI, both of these devices were 100 percent accurate. The precision, however, was slightly higher for TCI devices. It was later found out that the TCI sensors used in this test had smaller insulation material than those used in the liquid-phase tank test. Consequently, the probes used in the laboratory test had a smaller response time for lower JP-4 thickness.

The Leak-X sensors did not respond to JP-4 thicknesses of 1/8 and 1/4 inch. Leak-X appeared to be 100 percent accurate for thicknesses above 15/32 inch.

Experimental data indicate that In Situ devices responded to low free-product thicknesses (such as 1/32 inch) rather quickly. TCI devices responded slightly less rapidly. However, these results are based on response to fresh JP-4. It is important to test whether these low detection levels are also true for aged JP-4 or free product after passage through soils.

C. EFFECTS OF BACKGROUND INTERFERENCES ON VAPOR-PHASE DEVICES

The effects of background interfering gases on the vapor-phase devices were tested in a closed stainless steel cylinder. The gases tested included carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), methane (CH_4), and trichloroethylene (TCE). Each device was tested for four or more different gas/vapor concentration and was exposed to each of the gas concentrations for at least 3 hours. Carbon dioxide did not affect any of the devices except FCI. Both USD and AZI responded to CO. FCI interfered with CO at 9,900 ppm level. Hydrogen sulfide appeared to have a very noticeable effect on USD, AZI, and FCI devices. One USD sensor recorded 9,999 ppm, its maximum possible reading, for a H_2S concentration of 450 ppm. The effects of methane on all the devices appeared to be insignificant. Trichloroethylene vapors were detected by the USD, AZI, and FCI sensors. Both the AZI and USD devices recorded at least three times the TCE level at concentrations exceeding 600 ppm.

The results summarized in Table 6 indicate that USD, AZI, and FCI devices will be subjected to interfering effects from TCE vapors and gases such as H_2S and CO. However, even at very high concentrations, none of the tested gases or vapors interfered with or were detected by RJ sensors.

D. TRANSPORT OF JET FUEL IN SUBSURFACE

1. JP-4 Vapor Transport in the Subsurface

The experiments conducted in a large sand tank with a simulated jet fuel leak in the center of the tank indicated that when the organic vapor concentrations were relatively low (i.e., when the TOHC concentrations were less than 1,000 ppm as carbon), the vapor transport appeared to be mainly governed by molecular diffusion. However, as the concentration increased, vapor transport was controlled by both diffusion and density-driven flow. The stratification resulting from density-driven advective flow became more noticeable at TOHC concentrations above 60,000 ppm. The density effects on transport were observed with low molecular-weight components (such as propane, butane, and pentane) as well as medium (benzene, heptane, and toluene), and high (ethylbenzene, nonane, and decane) molecular-weight hydrocarbons.

Chemical analysis of soil gas in sand tank indicated that low molecular-weight hydrocarbons appeared in the intersticial spaces much earlier than the higher molecular-weight hydrocarbons. This may be attributed to their relative rates of volatilization and diffusion as well as lower retardation in sand bed. The presence of moisture in the porous media retarded the migration of some hydrocarbons. The degree of retardation was more noticeable only for the relatively water-soluble components. At the early stages of a leak, where the soil gas concentrations are low, the lighter hydrocarbons tend to accumulate at shallow depths, whereas the medium to high molecular-weight compounds migrated to deeper levels in the vadose zone.

The results of the sand and soil column experiments indicate that soil organic matter can result in significant retardation of all JP-4 constituents. This retardation increased from dry sand (very little retardation), to wet soil, to dry soil (very large retardation). The presence of moisture in the unsaturated zone will decrease sorption capacity and,

TABLE 6. EFFECTS OF BACKGROUND GASES/VAPORS

Device	CO_2	CO	H_2S	CH_4	TCE
USD	NE	E	E	E^1	E
RJ	NE	NE	NE	NE	E^1
AZI	NE	E	E	E^1	E
FCI	NE	E	E	NE	E
TCI	NE	NE	NE	NE	NE
In Situ	NE	NE	NE	NE	NE

NE = No effect.
E = Effect.
E^1 = Slight effect.

therefore, decrease retardation compared with dry soil. One dimensional transport model was successful in predicting the distribution of vapor components in sand and soil columns.

Retardation factors for a particular site can be determined experimentally using soil column studies. Then, these retardation factors can be used as input parameters to a two- or three-dimensional model to compute the rate of fuel vapor transport as a function of time and spatial coordinates.

The implication of this study, with respect to monitoring of JP-4 releases in the subsurface, is that small leaks may go undetected by vapor sensors for much longer in organic soil than in sand. Therefore, use of sand instead of native soil as backfill material for USTs and placement of vapor sensors in or very close to the backfill area is recommended as the most effective JP-4 release detection approach.

2. Transport of JP-4 in Porous Media

Transport of JP-4 fuel (non-aqueous phase liquid [NAPL]) was not uniform in the large sand tank. The experimental data indicate that the distribution of JP-4 liquid following a leak is rather unpredictable. For example, JP-4 liquid first appeared in a well located at 5.5 feet from the leak within 120 hours whereas the liquid did not migrate to another well located at the same radial distance for almost 500 hours. Therefore, it will be rather difficult to place a liquid monitoring well in the field where it would assure an early detection of a leak from a UST. It is advisable, however, to place the monitoring wells in downgradient of groundwater flow. In any event, there is a possibility that the free floating liquid plume may not intersect the monitoring well and a leak may go undetected if the leak detection is performed only by liquid-phase monitoring devices. Therefore, vapor monitoring wells should be provided in addition to the liquid-phase monitoring wells to assure a more reliable leak detection system.

A relatively accurate estimate of free liquid retained in pore spaces should be obtained prior to cleanup of the sites contaminated with petroleum hydrocarbons. There are several models available to estimate the recoverable free liquids in pore spaces. A recently developed model, OILEQUIL (Parker et al., 1987), along with the SOILPROP (Mishra, 1988) program, was tested using the experimental data obtained for the large sand tanks. The parameter estimation procedure by van Genuchten followed by use of OILEQUIL gave a fairly accurate estimate of free liquid present in the pore spaces.

3. Transport of Dissolved JP-4 in Soil and Sand

The results of the dissolved JP-4 study indicated that benzene, toluene, xylenes, and ethylbenzene (BTX&E) were the most soluble components in water. No other components were observed in measurable quantities in the column effluent. No retardation of BTX&E was observed in sand columns, whereas some retardation was observed in the soil column. Retardation factors increased with molecular-weight and decreasing solubility of JP-4 components. Retardation factors ranging from 1.0 to 3.8 were determined for the soil column and followed an increasing trend with molecular size: benzene < toluene < xylenes. This trend was consistent with increasing sorption and with increasing molecular size or decreasing solubility. The observed higher retardation factors for soil were caused by the higher organic carbon content of soil compared with that of sand. Higher organic carbon content resulted in higher sorption coefficient which resulted in higher retardation factor values.

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APPENDIX A

CHEMICAL ANALYSIS OF JP-4

TABLE A-1. DISTRIBUTION OF MAJOR CHEMICAL COMPONENTS IN JP-4

Chemical Compound	Concentration, g/L				
	Fresh JP-4		Used JP-4[a]	Aged JP-4	
	Analysis of Vapor	Analysis of Fuel Dissolved in CS_2	Analysis of vapor	Analysis of Vapor	Analysis of Fuel Dissolved in CS_2
n-butane	4.92	4.17	0.44	ND[b]	ND
iso-pentane	2.60	2.16	0.67	ND	ND
n-pentane	2.07	ND	0.78	ND	ND
2-methylpentane	7.43	2.44	5.91	0.9	1.43
3-methylpentane	6.48	9.83	4.93	0.96	1.78
n-hexane	17.9	28.1	15.9	1.18	1.74
methylcyclopentane	11.6	19.3	12.5	1.44	2.77
benzene	7.82	4.39	8.40	ND	ND
cyclohexane	9.63	15.3	9.22	0.79	1.55
2-methylhexane	28.0	44.0	31.5	3.01	6.14
3-methylhexane	27.1	42.7	31.2	3.15	6.28
dimethylpentane	6.21	10.1	19.2	2.31	1.98
n-heptane	33.1	53.4	40.8	2.76	5.56
methylcyclohexane	22.0	35.4	26.4	4.58	8.45
toluene	10.7	17.8	15.0	ND	0.90
2-methylheptane	16.5	25.8	22.6	7.79	12.4
3-methylheptane	12.4	17.5	17.0	7.05	14.3
n-octane	21.3	37.2	29.4	8.20	17.5
ethylbenzene	9.89	5.12	29.5	5.55	0.98
m- and p-xylene	12.5	27.1	19.5	13.1	30.8
o-xylene	2.04	1.23	8.08	0.98	2.22
n-nonane	1.54	2.50	2.94	1.20	3.15
n-decane	5.22	19.0	12.9	3.84	11.2
n-undecane	2.68	16.4	10.0	3.24	14.8
naphthalene	ND	ND	ND	2.02	5.23
n-dodecane	ND	12.8	ND	1.67	16.0
n-tridecane	ND	10.9	ND	ND	14.3
n-tetradecane	ND	3.55	ND	ND	7.31

[a] Used JP-4 - Jet fuel collected in the central JP-4 distribution and containment unit at the end of dry sand vapor phase study.

[b] ND - not detected.

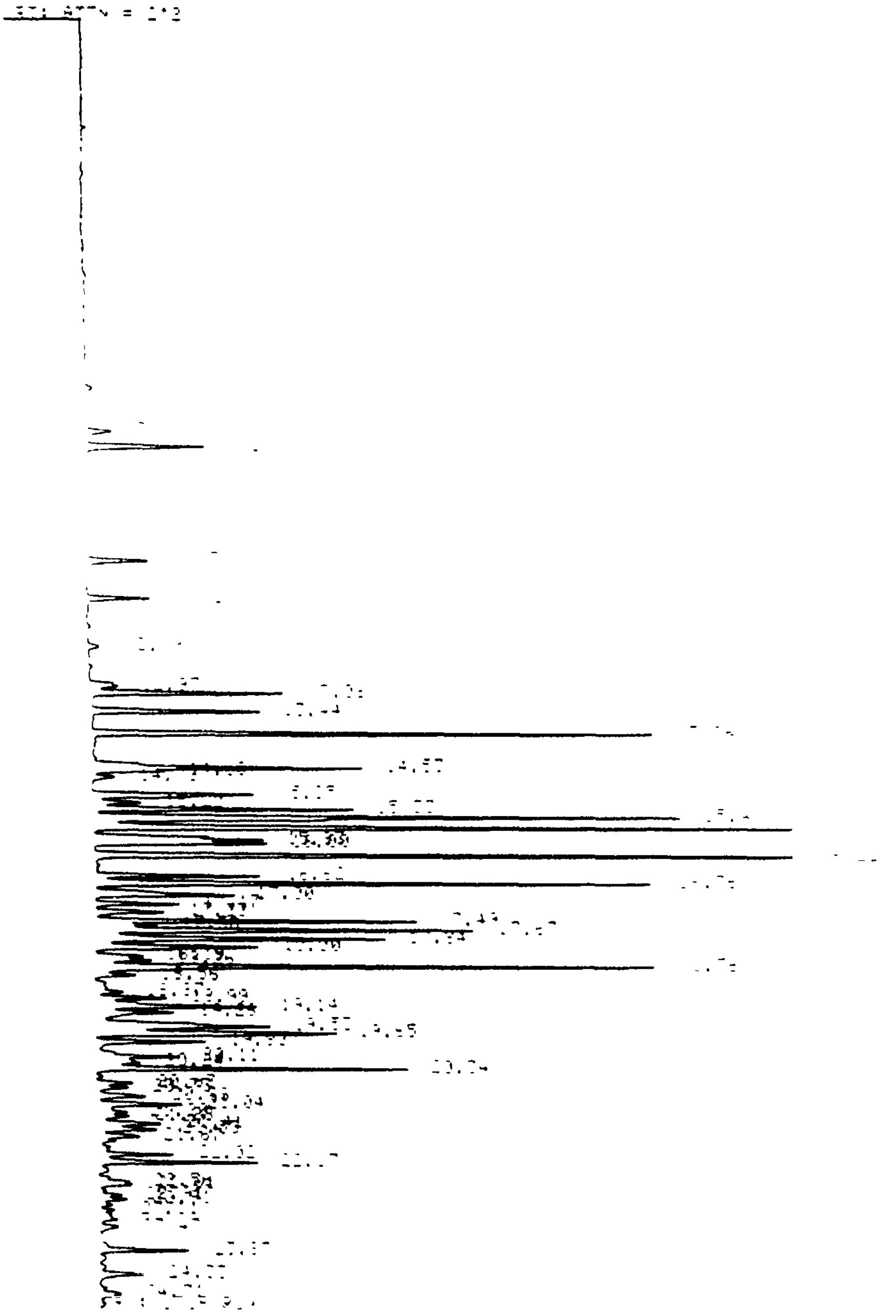

Figure A-1. Chromatogram for Vaporized Fresh JP-4 Sample.

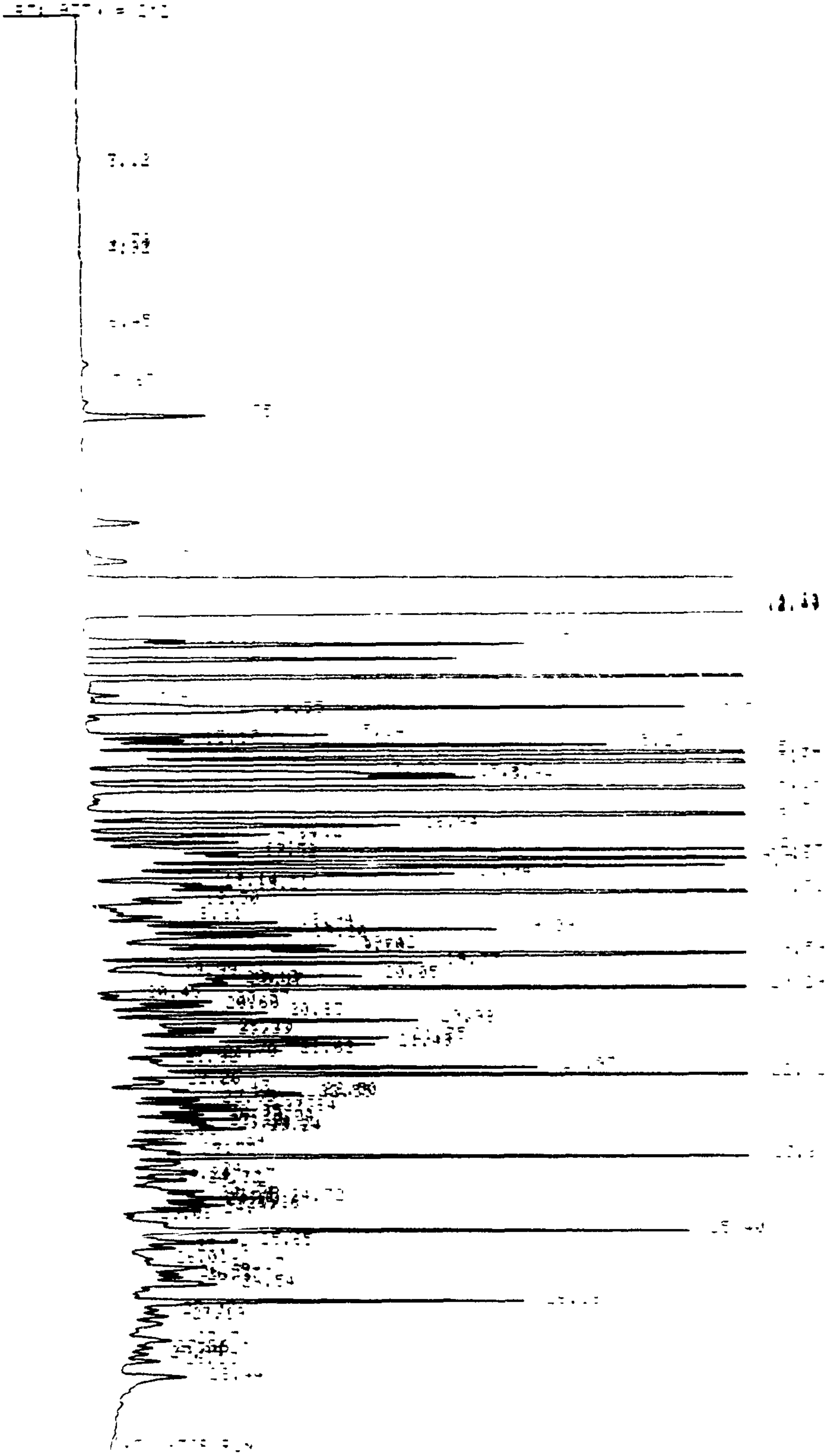

Figure A-2. Chromatogram for Fresh JP-4 Dissolved in CS_2.

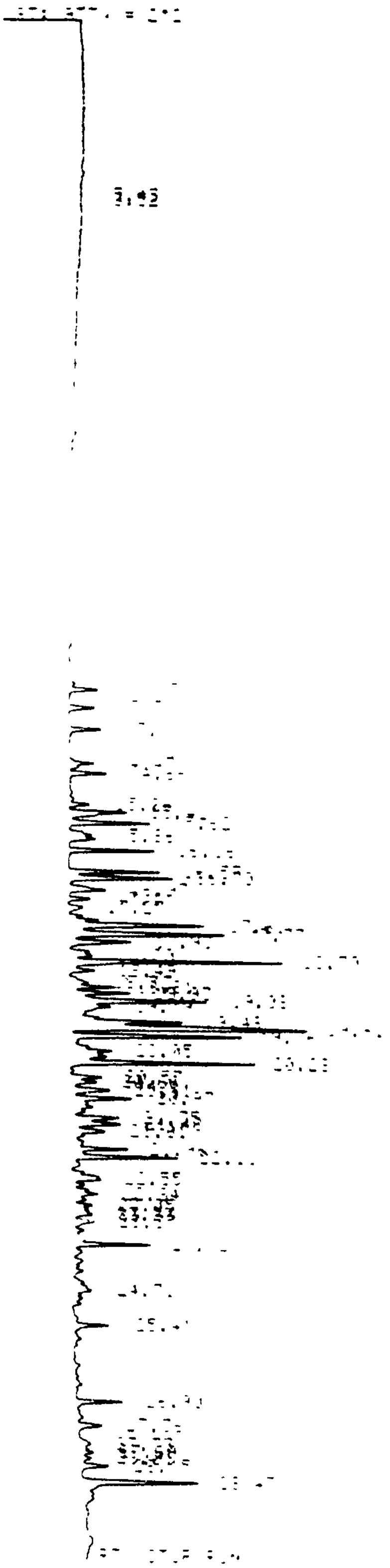

Figure A-3. Chromatogram for Vaporized Aged JP-4 Sample.

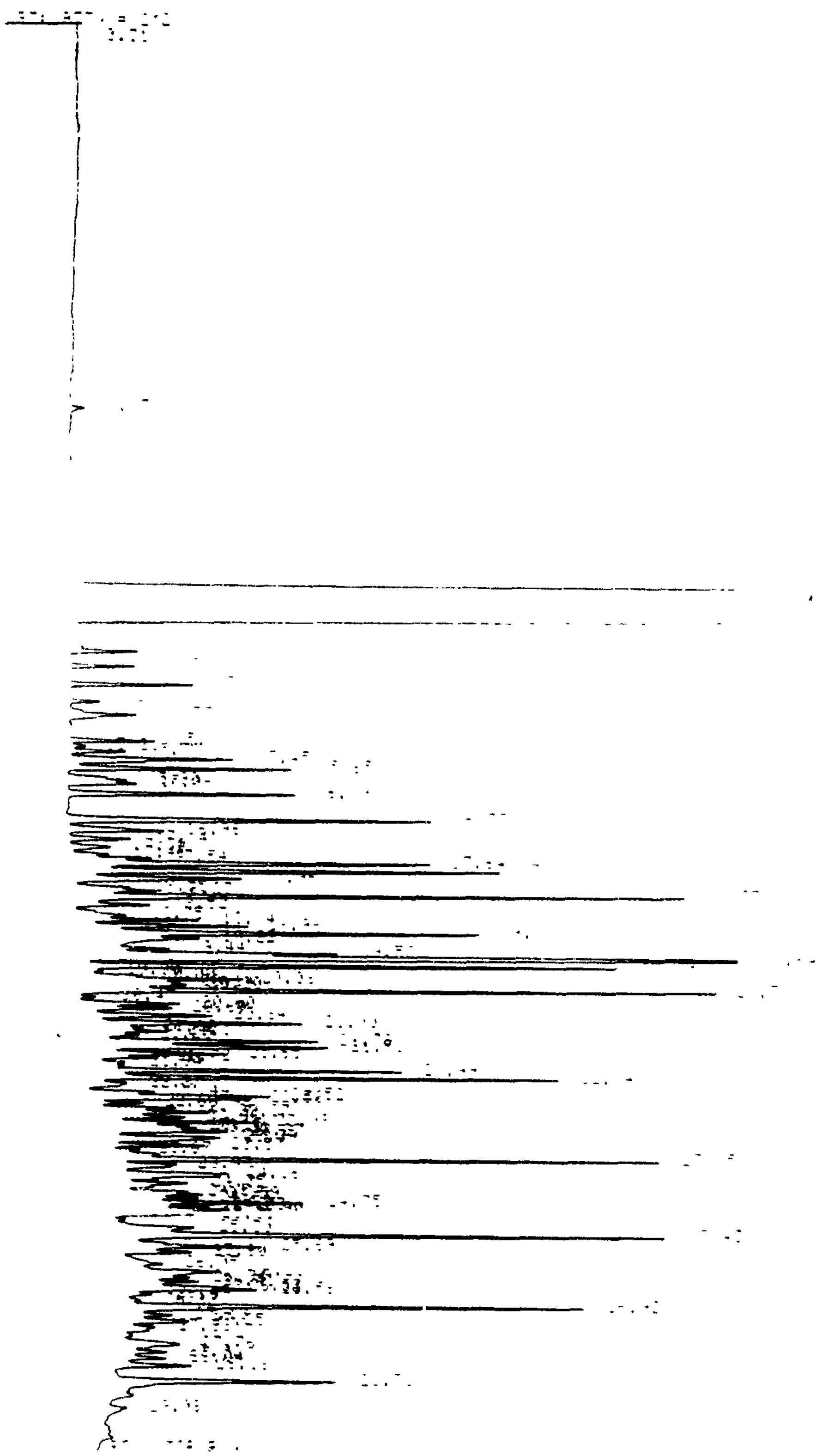

Figure A-4. Chromatogram for Aged JP-4 Dissolved in CS_2.

APPENDIX B

SAND AND SOIL CHARACTERISTICS

TABLE B-1. GRADATION OF SAND

Screen Number	Percent Passing			
	Sample 1	Sample 2	Sample 3	Sample 4
# 16	100	100	100	100
# 20	94	93.3	93.7	93.9
# 30	52.1	49.2	48.7	51.4
# 40	5.6	5.7	4.5	5.4
# 200	0.2	0.7	0.0	0.7

TABLE B-2. PARTICLE SIZE DISTRIBUTION OF ORGANIC SOIL

Particle Size, mm	% Weight Dry Soil Column Vapor Study	% Weight Wet Soil Column Vapor Study	% Weight Dissolved JP-4 Study
> 0.85	0.6	1.7	4.1
0.85 - 0.425	20.6	33.7	28.9
0.425 - 0.15	39.0	44.2	40.9
0.15 - 0.106	8.9	4.4	10.0
0.106 - 0.075	18.4	11.5	9.3
< 0.075	12.5	4.5	6.8
	100.0	100.0	100.0

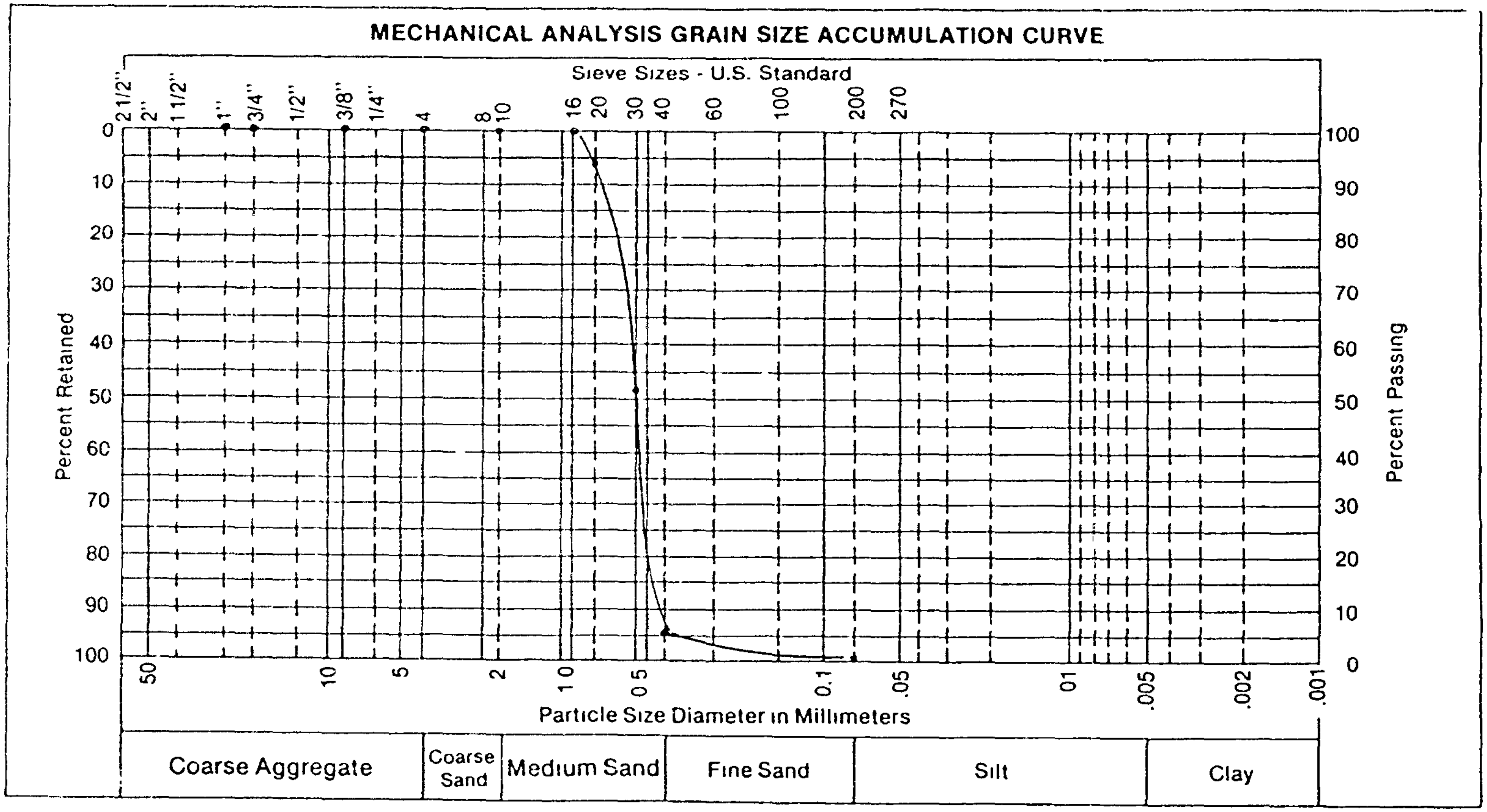

Figure B-1. Particle Size Distribution for Sand

APPENDIX C

RESULTS OF FRESH JP-4/DRY AND WET SAND TANK TESTS

TABLE C-1. TEMPERATURE DATA FOR FRESH JP-4 DRY SAND VAPOR-PHASE STUDY

TIME (hours)	ROOM TEMP (°C)	SAND TEMP 1 (°C)	SAND TEMP 2 (°C)
0.00	20	21	20
24.00	21	21	20
72.00	20	21	21
96.00	21	21	21
123.00	20	21	21
196.00	22	21	20
265.00	23	21	21

TABLE C-2. MOISTURE CONTENT DATA FOR WET SAND FRESH JP-4 STUDIES

Sample Depth (inches)	Time (hours)	% Moisture[a]
0-6	0	1.65
6-11	0	2.14
11-16	0	2.08
11-16* duplicate	0	2.03
16-21	0	1.96
21-26	0	1.75
26-31	0	1.59
31-36	0	1.75
36-41	0	2.07
0-6	16	1.85
0-6* duplicate	16	1.80
6-11	16	2.08
6-11* duplicate	16	1.83
11-16	16	2.03
11-16* duplicate	16	2.06
16-21	16	2.08
21-26	16	1.80
26-31	16	1.92
31-36	16	2.36
36-41	16	4.72
0-6	166.5	1.15
6-11	166.5	1.60
11-16	166.5	1.72
16-21	166.5	2.02
21-26	166.5	1.82
26-31	166.5	1.55
31-36	166.5	1.63
36-41	166.5	1.89
36-41* duplicate	166.5	1.87

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[a] % MOISTURE = [Sample wet wt. - Sample dry wt.)/Sample dry wt.] x 100

TABLE C-3. TEMPERATURE DATA FOR FRESH JP-4 WET SAND VAPOR-PHASE STUDY

TIME (hours)	ROOM TEMP (°C)	SAND TEMP 1 (°C)	SAND TEMP 2 (°C)
0.00	20	18	18
24.00	20	18	19
72.00	20	18	18
120.00	20	19	19
168.00	17	19	20
192.00	21	19	19
240.00	22	18	19
264.00	23	19	19
288.00	22	19	19
312.00	21	19	19

TABLE C-4. STATISTICAL COMPARISON OF THE SLOPES OF REPLICATE USD SENSORS

Distance from JP-4 release point (ft)	Well identification code	USD replicate sensor number	Slopes*	
			Dry sand test	Wet sand test
3	d	5	1.16*(A)	0.16(A)
	b	1	1.37(B)	0.07(B)
	c	4	0.78(C)	0.075(C)
	c	3	0.36(D)	0.014(C)
	b	2	0.26(E)	0.011(C)
	d	6	0.05(F)	0.010(C)
5.5	g	9	0.37(A)	0.13(A)
	f	8	0.27(A,B)	0.09(B)
	h	11	0.23(B)	0.09(B)
	f	7	0.09(C)	0.03(C)
	h	12	0.09(C)	0.05(C,D)
	g	10	0.11(C)	0.05(D)

* Similar letters in parentheses represent sensors with similar slopes at P = 0.05.

+ Replicate Sensors No. 5 under dry conditions had a slope which did not deviate significantly from the slope for a 100 percent accurate sensor.

RESPONSE OF USD: WELL B

VAPOR-PHASE / FRESH JP-4 / DRY SAND

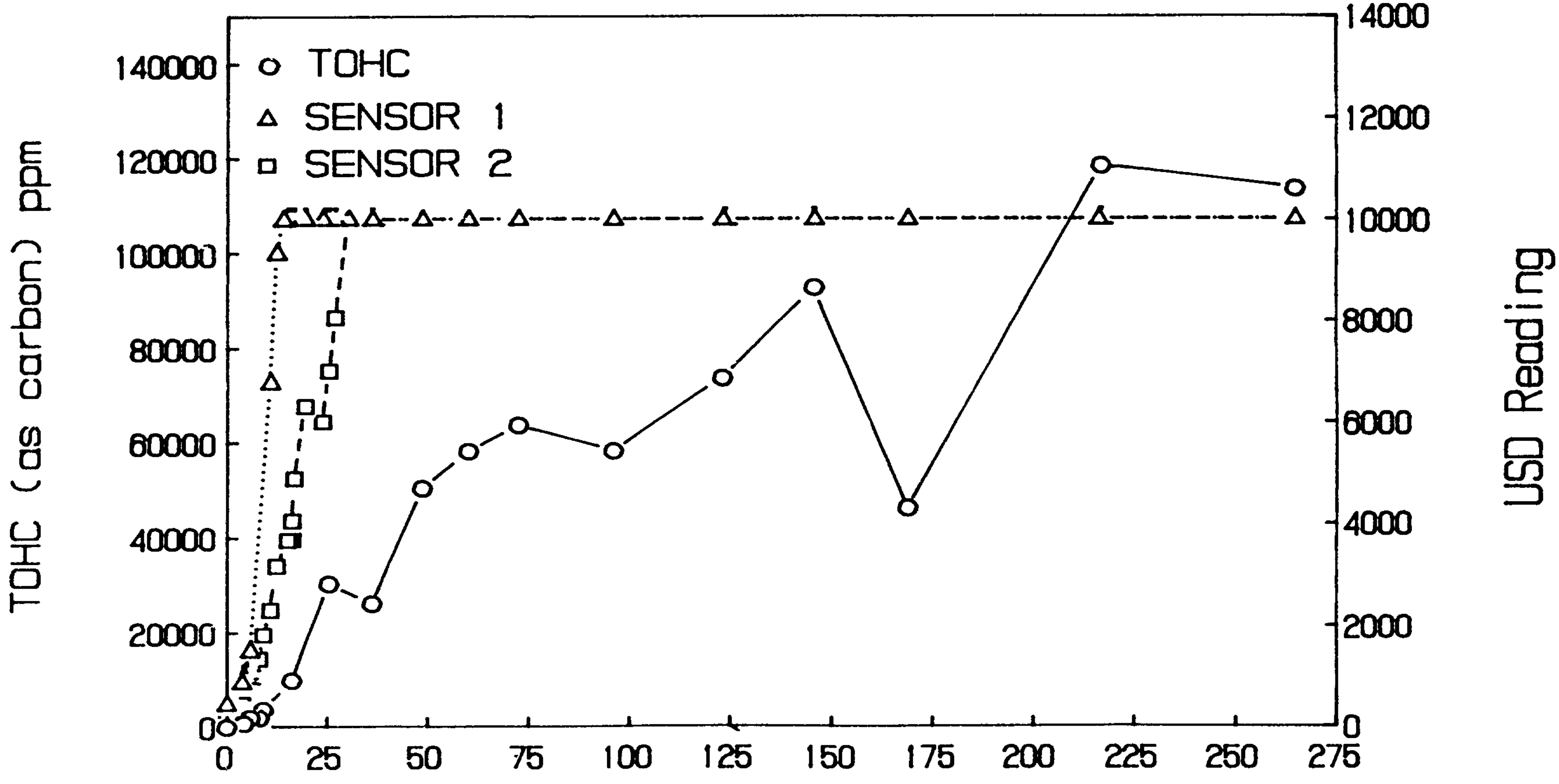


FIGURE C-1

RESPONSE OF USD: WELL B

VAPOR-PHASE / FRESH JP-4 / DRY SAND

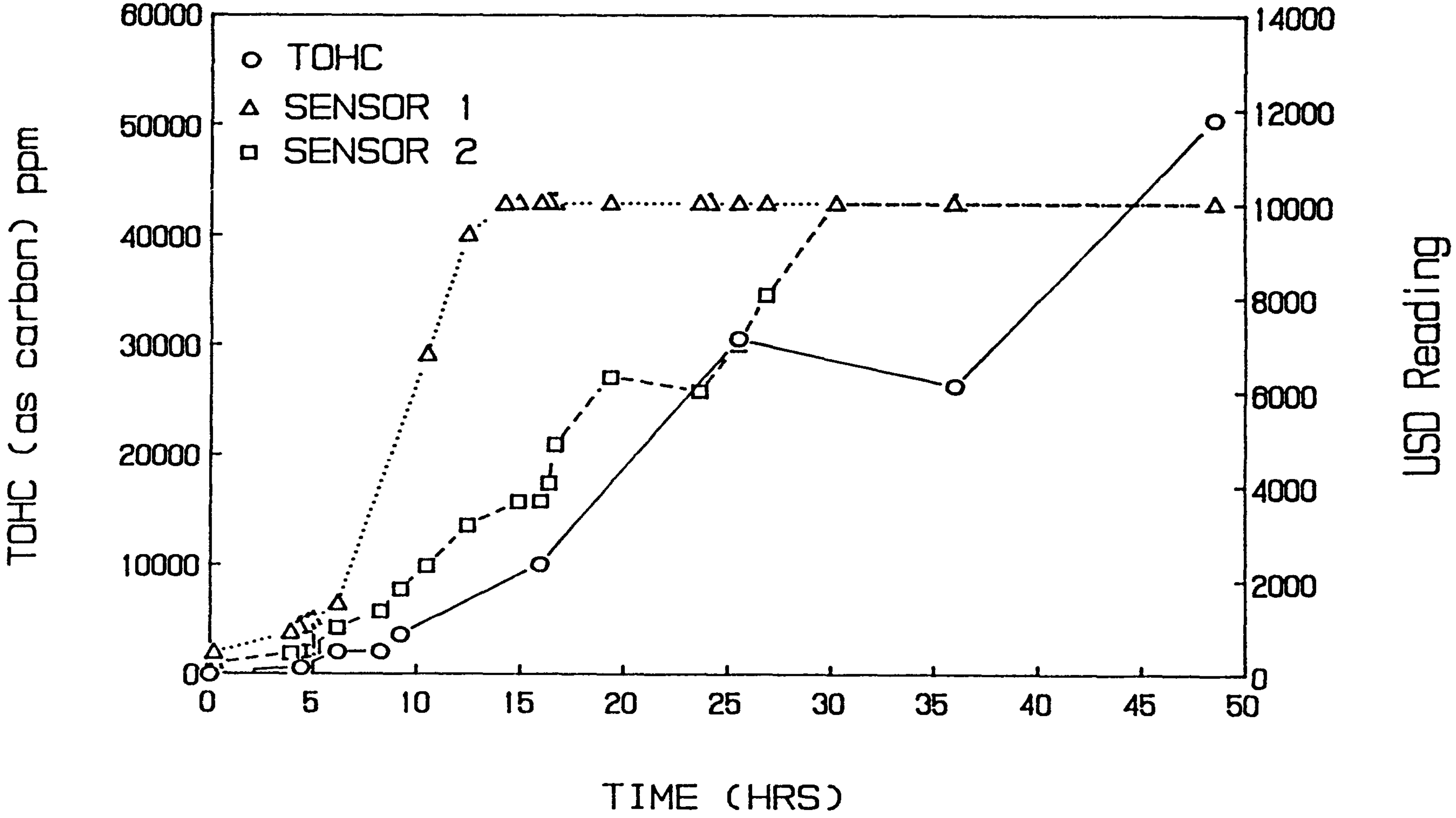


FIGURE C-2

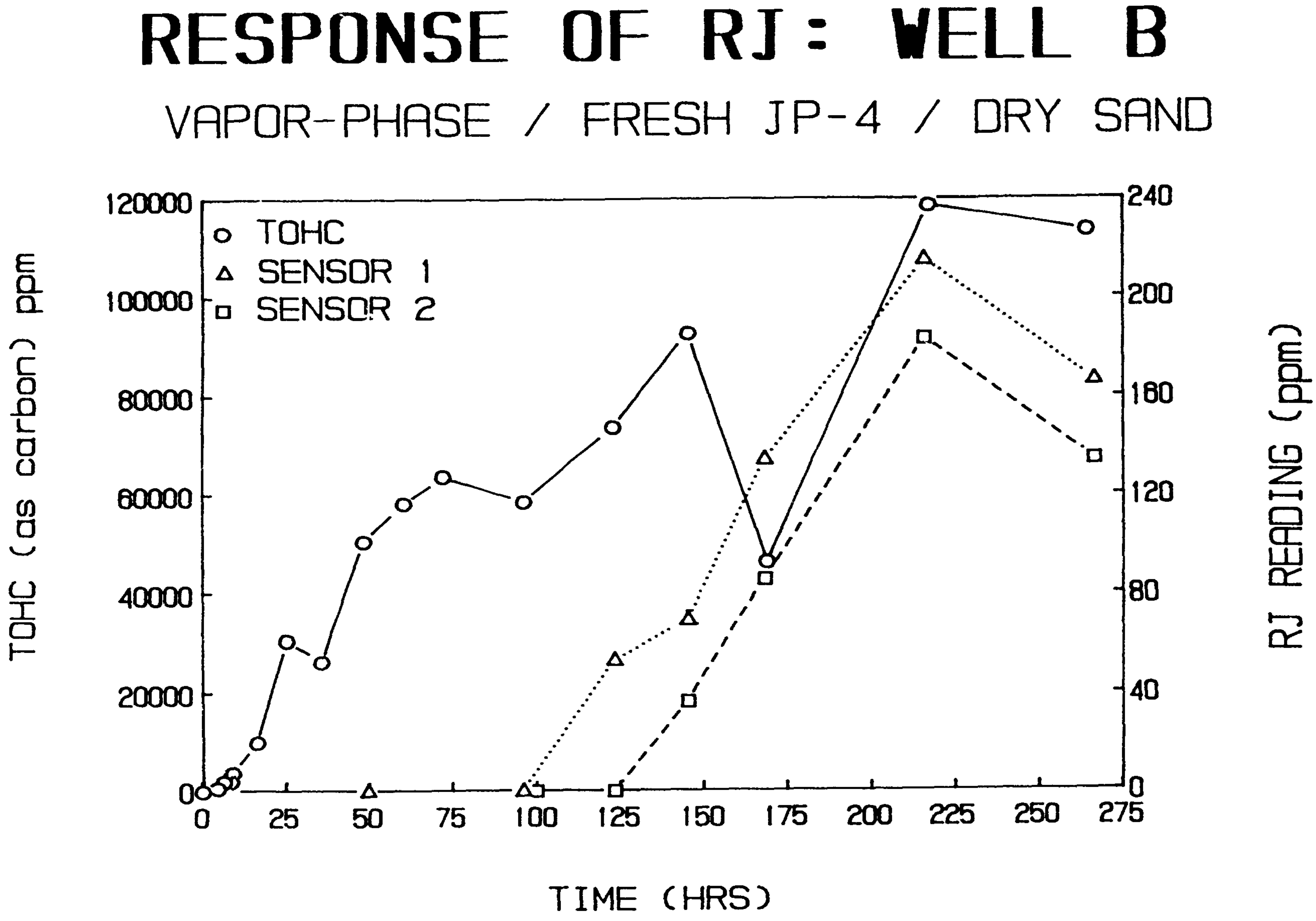

RESPONSE OF RJ: WELL B
VAPOR-PHASE / FRESH JP-4 / DRY SAND
TOHC
SENSOR 1
SENSOR 2
TOHC (as carbon) ppm
0
20000
40000
60000
80000
100000
120000
RJ READING (ppm)
0
40
80
120
160
200
240
0
25
50
75
100
125
150
175
200
225
250
275
TIME (HRS)

FIGURE C-3

RESPONSE OF USD: WELL C

VAPOR-PHASE / FRESH JP-4 / DRY SAND

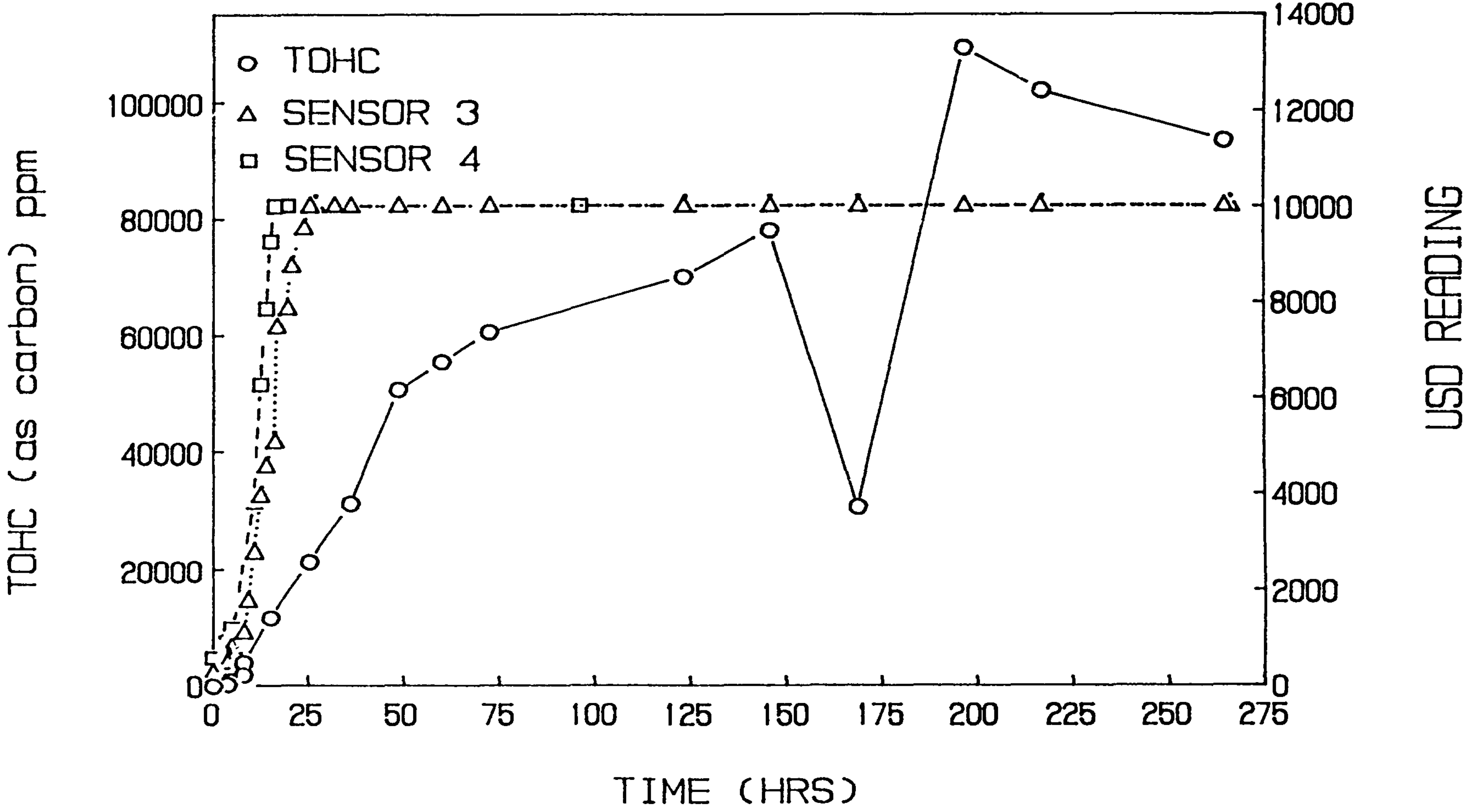


FIGURE C-4

RESPONSE OF USD: WELL C

VAPOR PHASE / FRESH JP-4 / DRY SAND

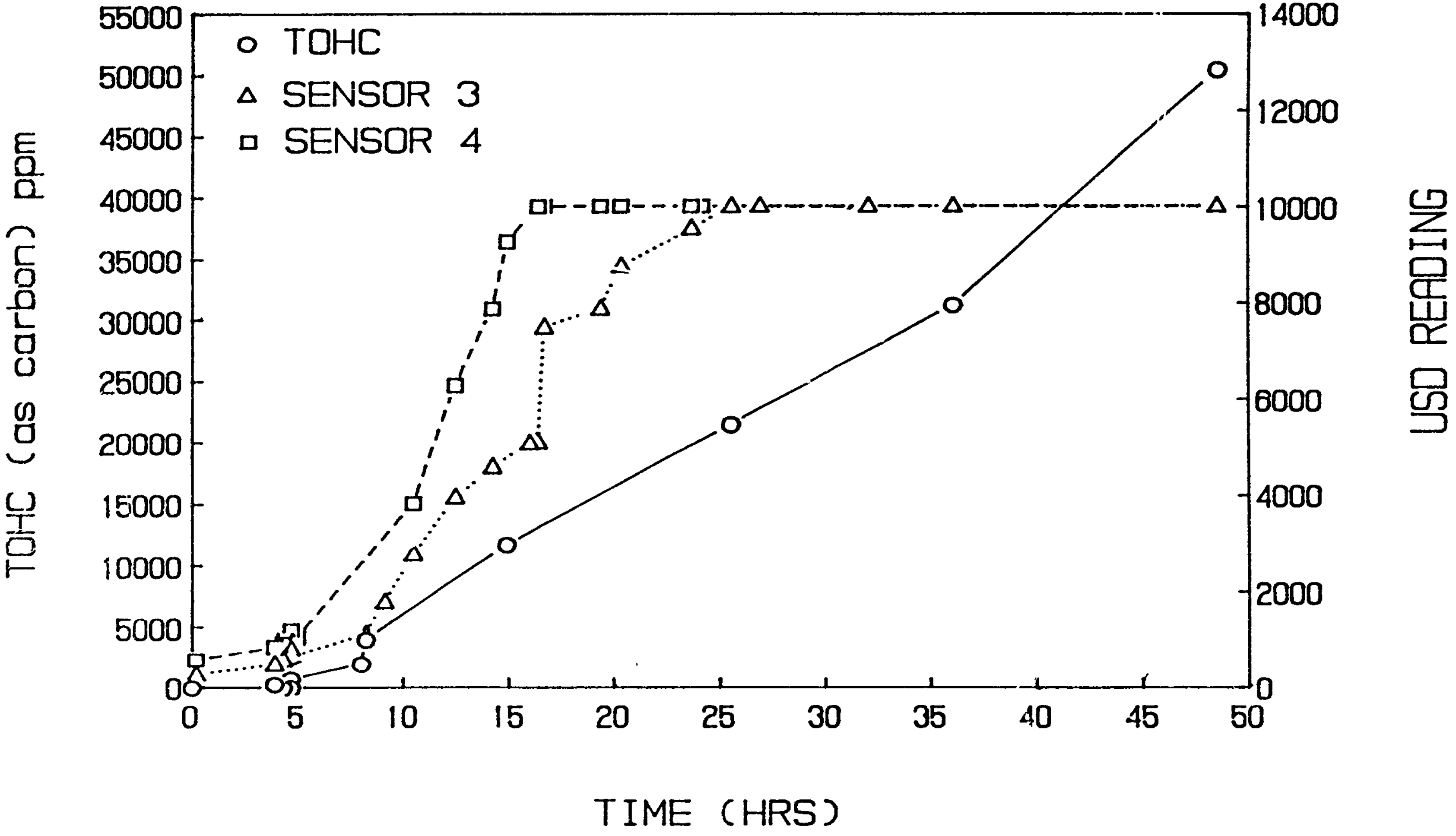


FIGURE C-5

RESPONSE OF RJ: WELL C

VAPOR-PHASE / FRESH JP-4 / DRY SAND

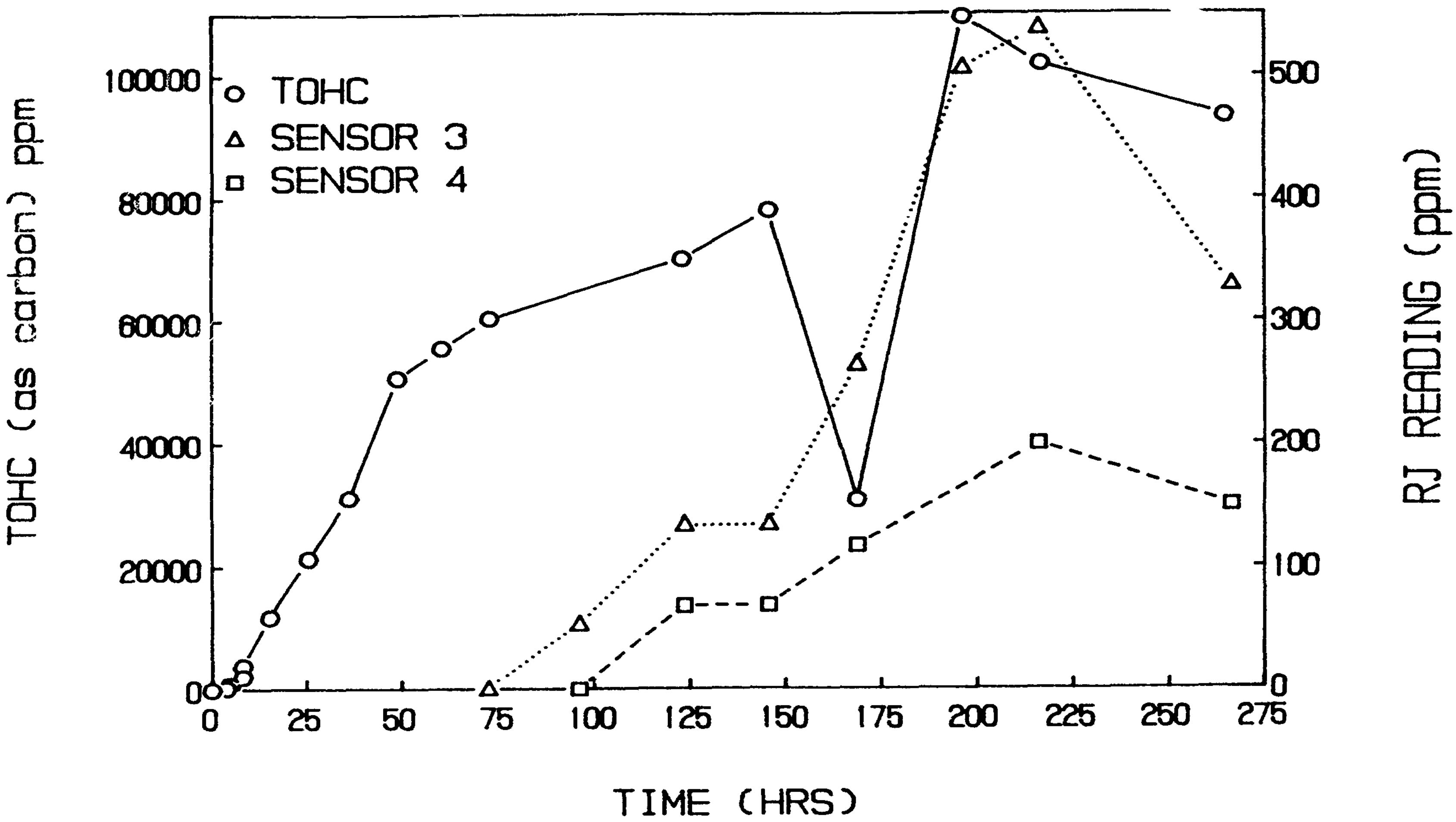


FIGURE C-6

RESPONSE OF USD: WELL D

VAPOR-PHASE / FRESH JP-4 / DRY SAND

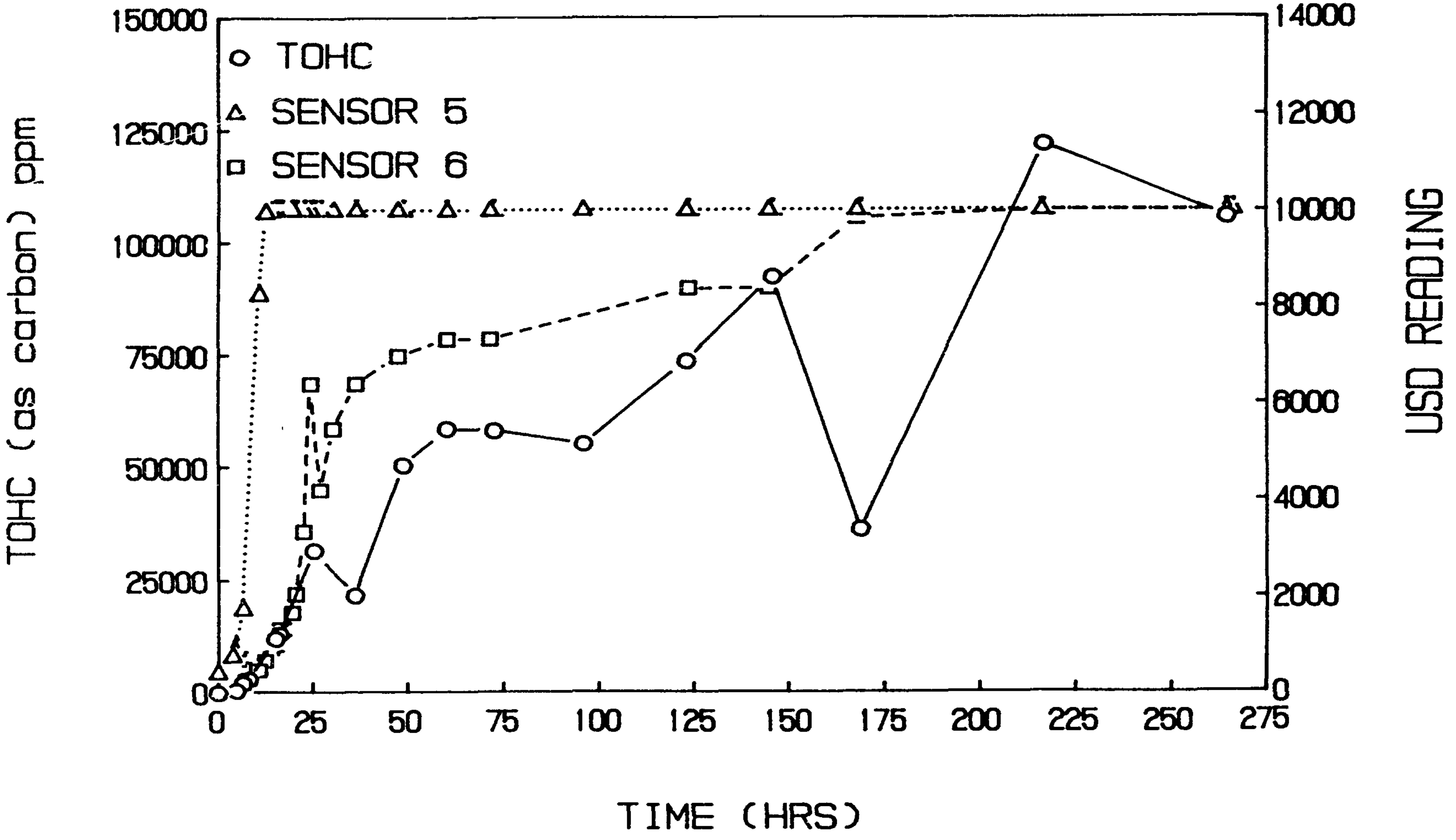


FIGURE C-7

RESPONSE OF RJ: WELL D

VAPOR-PHASE / FRESH JP-4 / DRY SAND

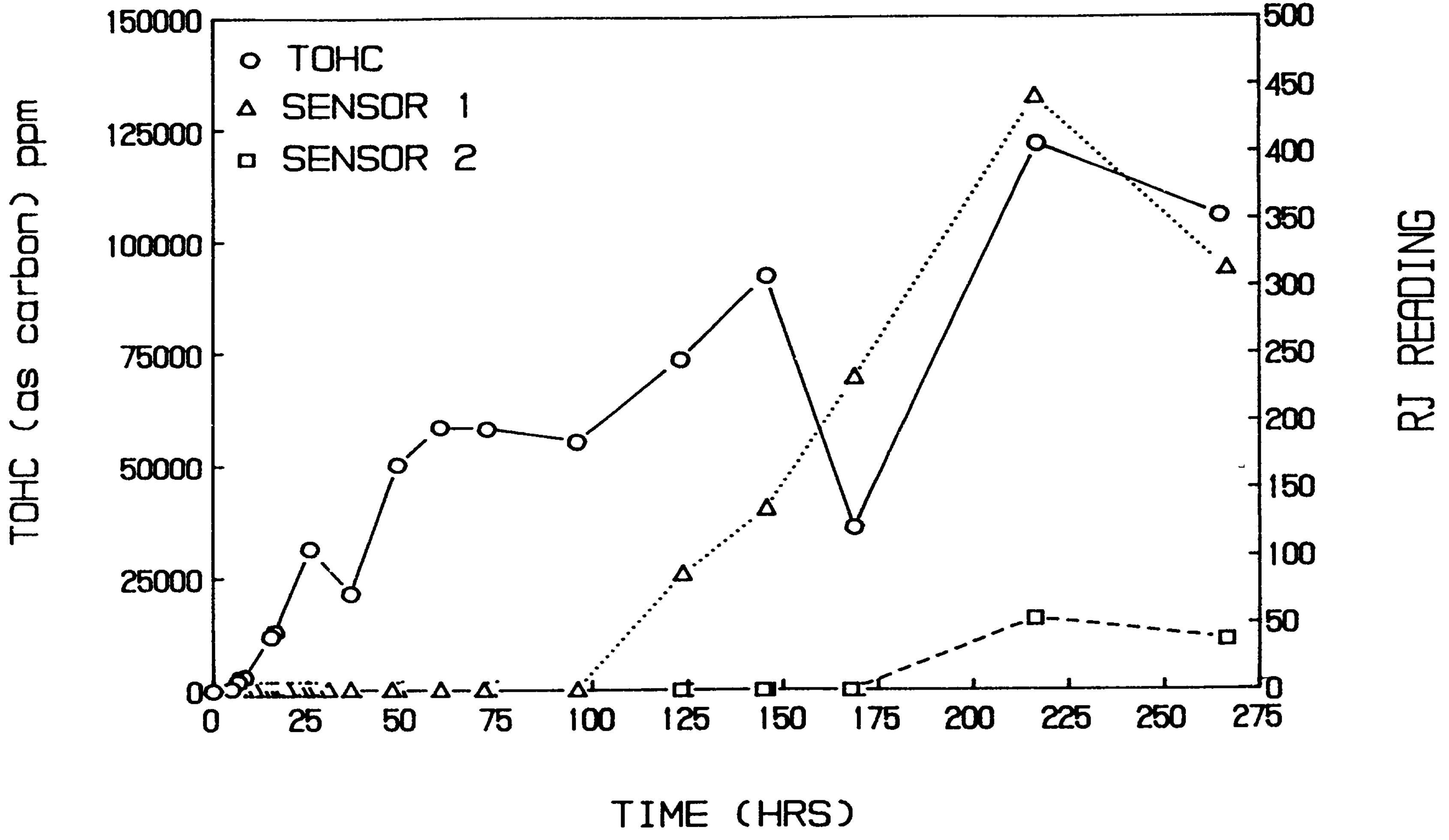
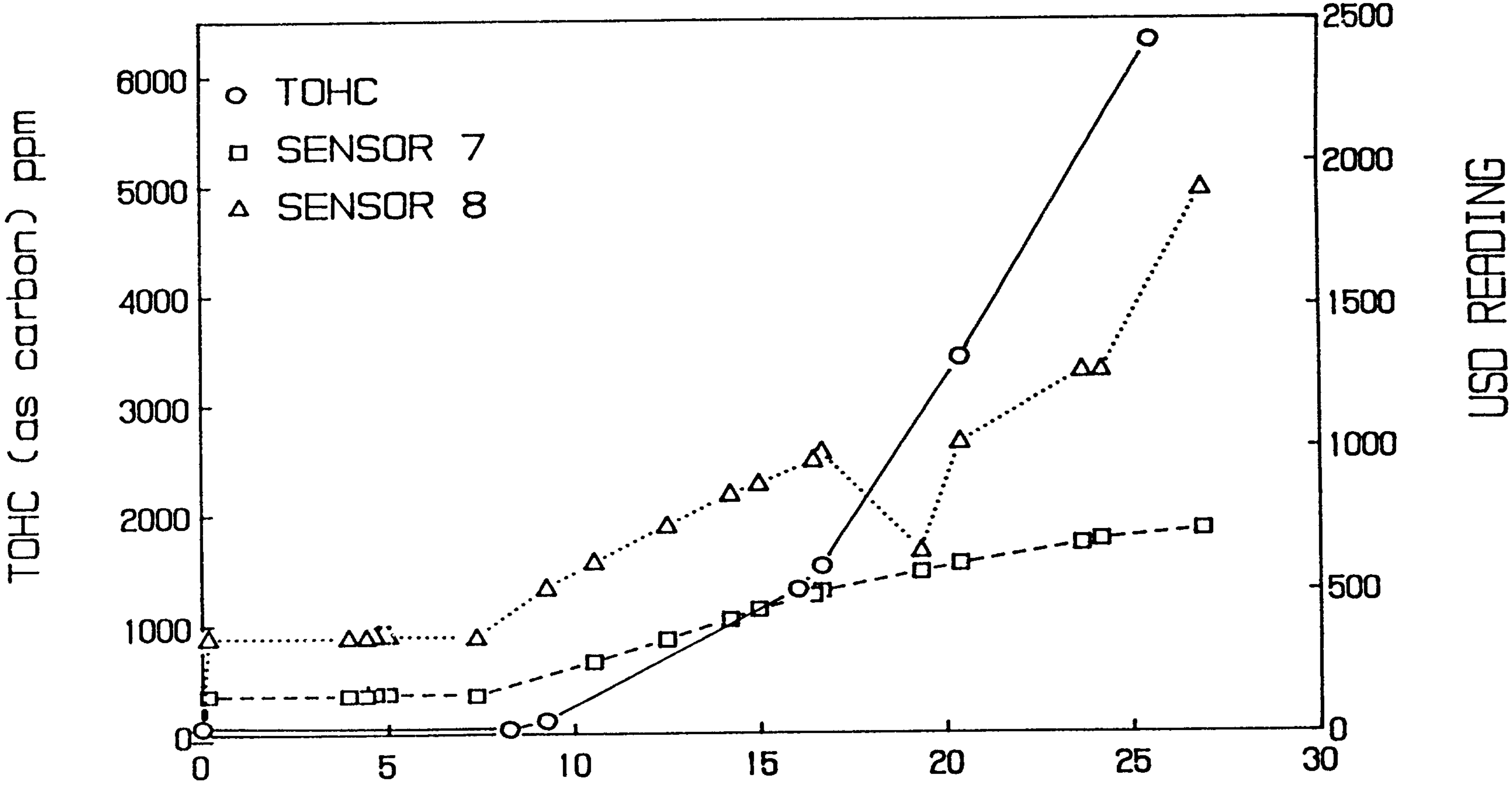


FIGURE C-8

RESPONSE OF USD: WELL F

VAPOR PHASE / FRESH JP-4 / DRY SAND



TIME (HRS)

FIGURE C-9

RESPONSE OF RJ: WELL F

VAPOR-PHASE / FRESH JP-4 / DRY SAND

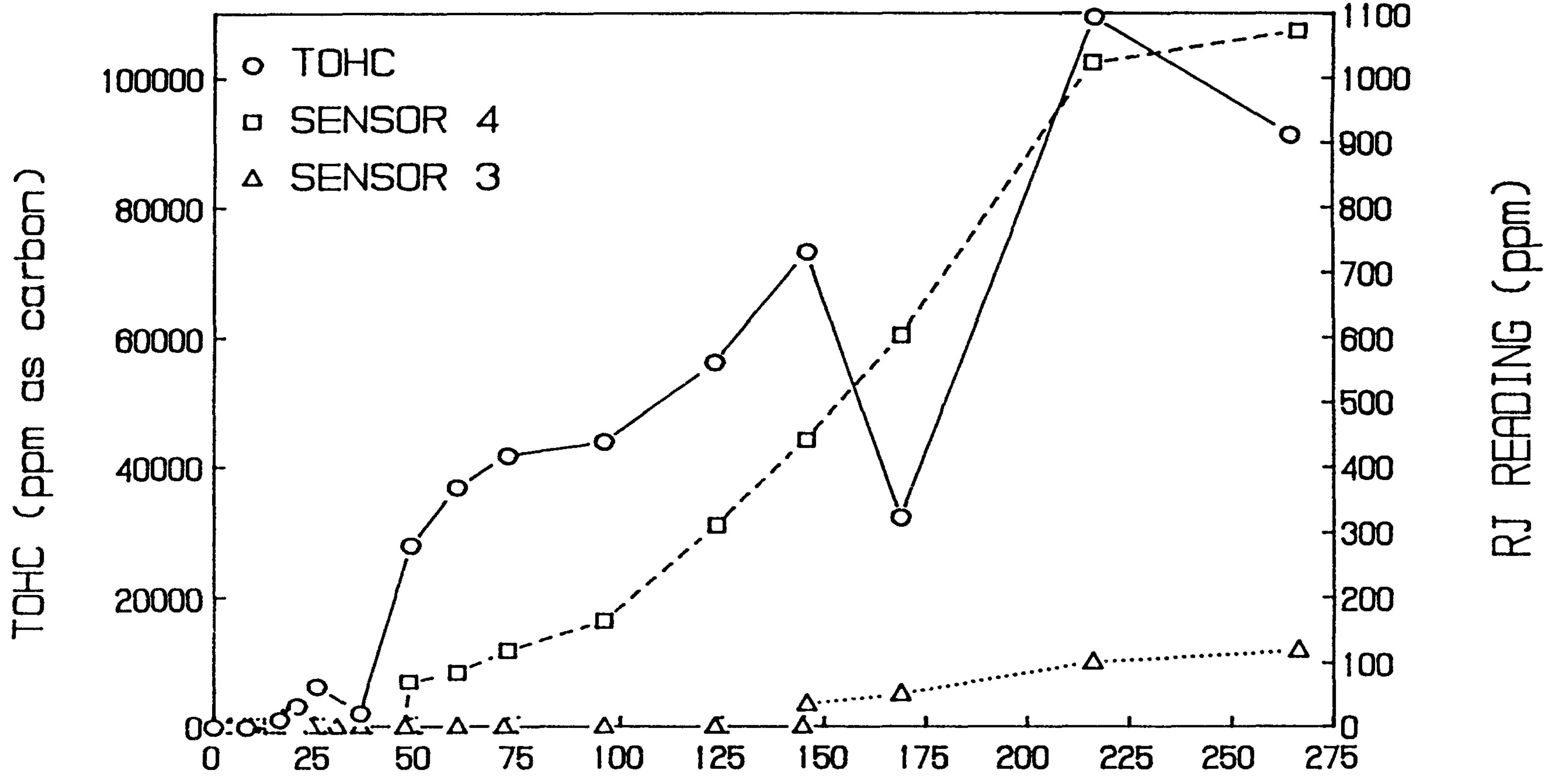


FIGURE C-10

RESPONSE OF USD: WELL G

VAPOR-PHASE / FRESH JP-4 / DRY SAND.

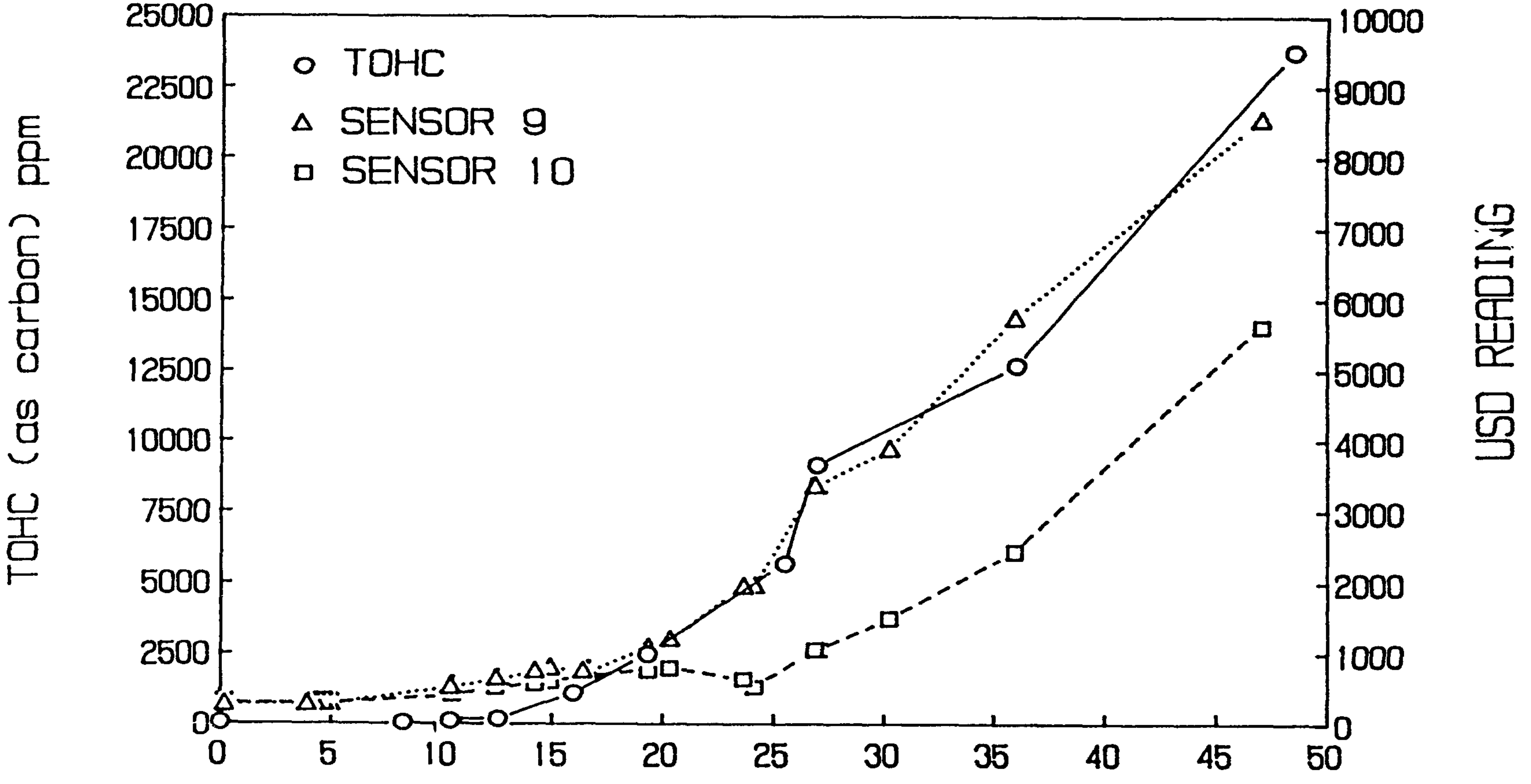


FIGURE C-11

RESPONSE OF RJ : WELL G

VAPOR-PHASE / FRESH JP-4 / DRY SAND

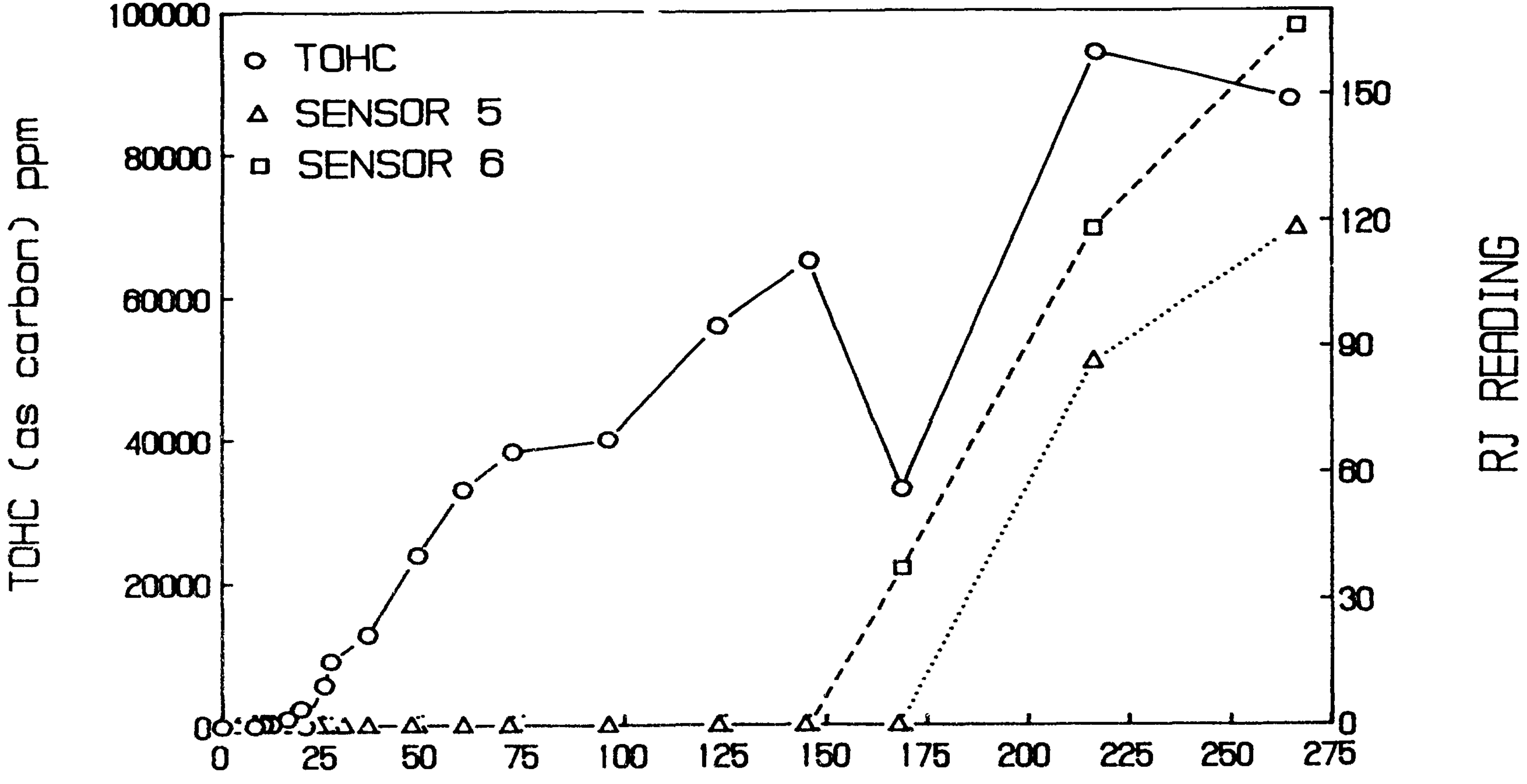


FIGURE C-12

RESPONSE OF USD: WELL H

VAPOR-PHASE / FRESH JP-4 / DRY SAND

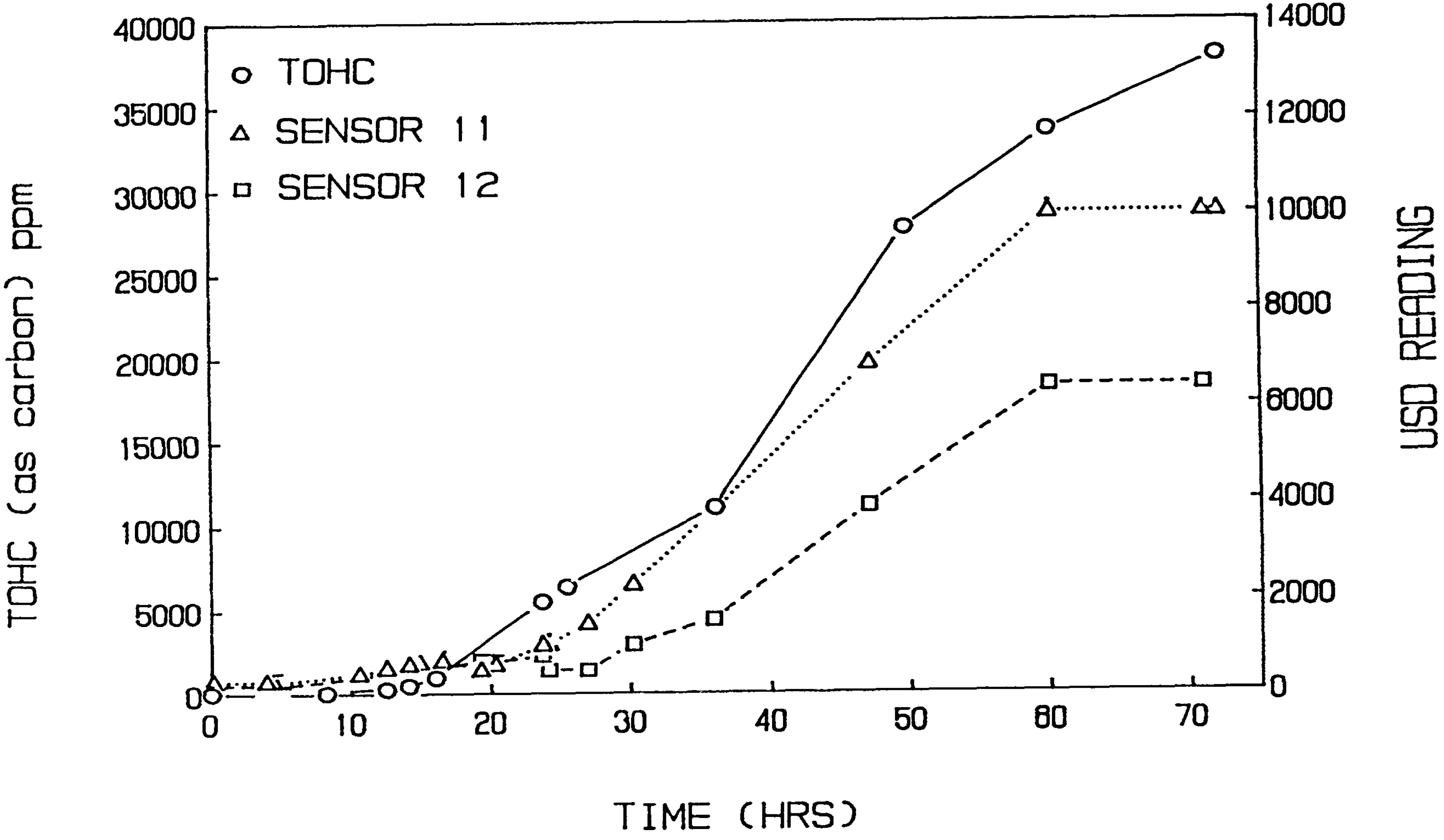


FIGURE C-13

RESPONSE OF RJ: WELL H

VAPOR-PHASE / FRESH JP-4 / DRY SAND

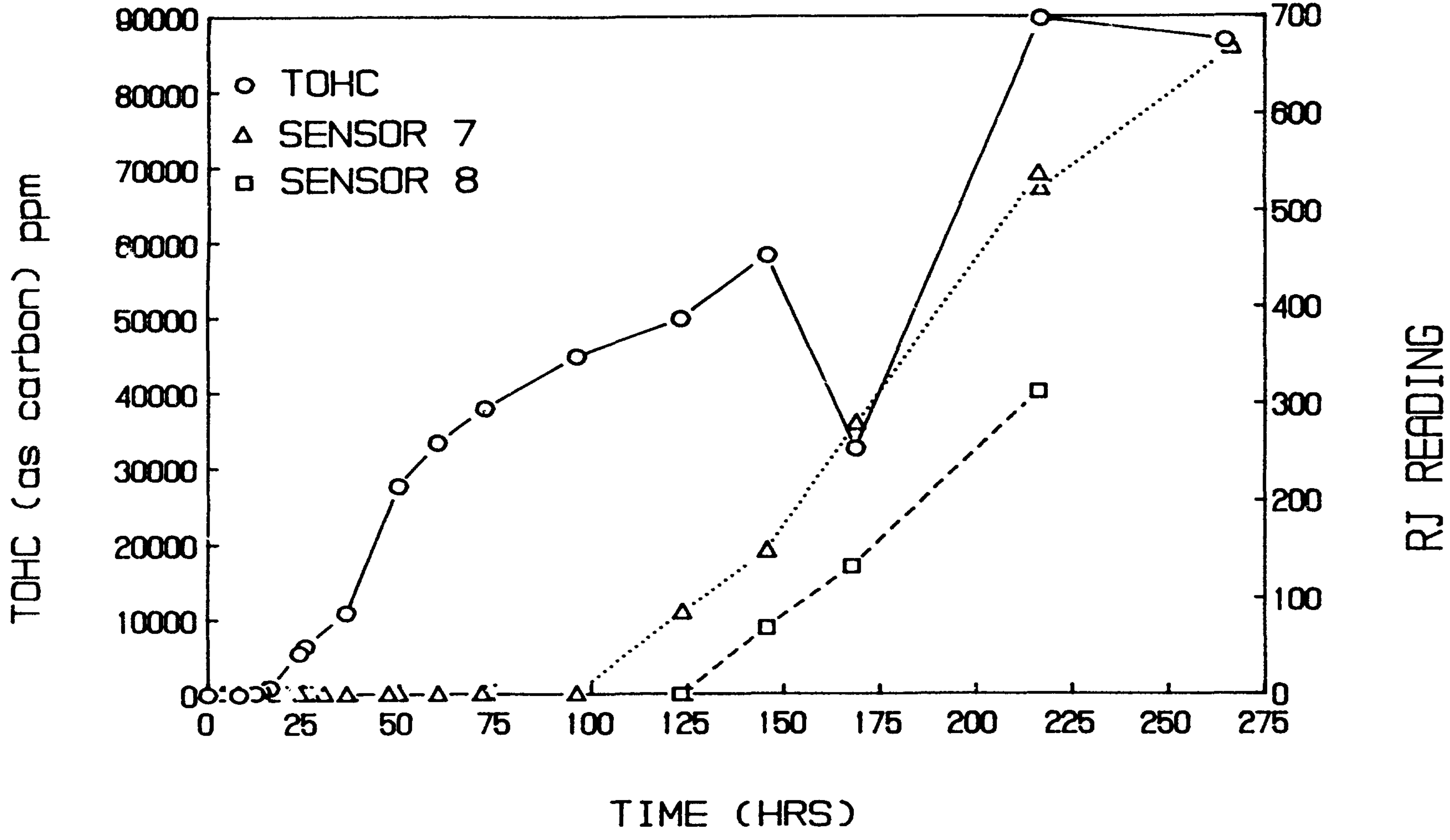


FIGURE C-14

RESPONSE OF AZI: WELL K

VAPOR-PHASE / FRESH JP-4 / DRY SAND

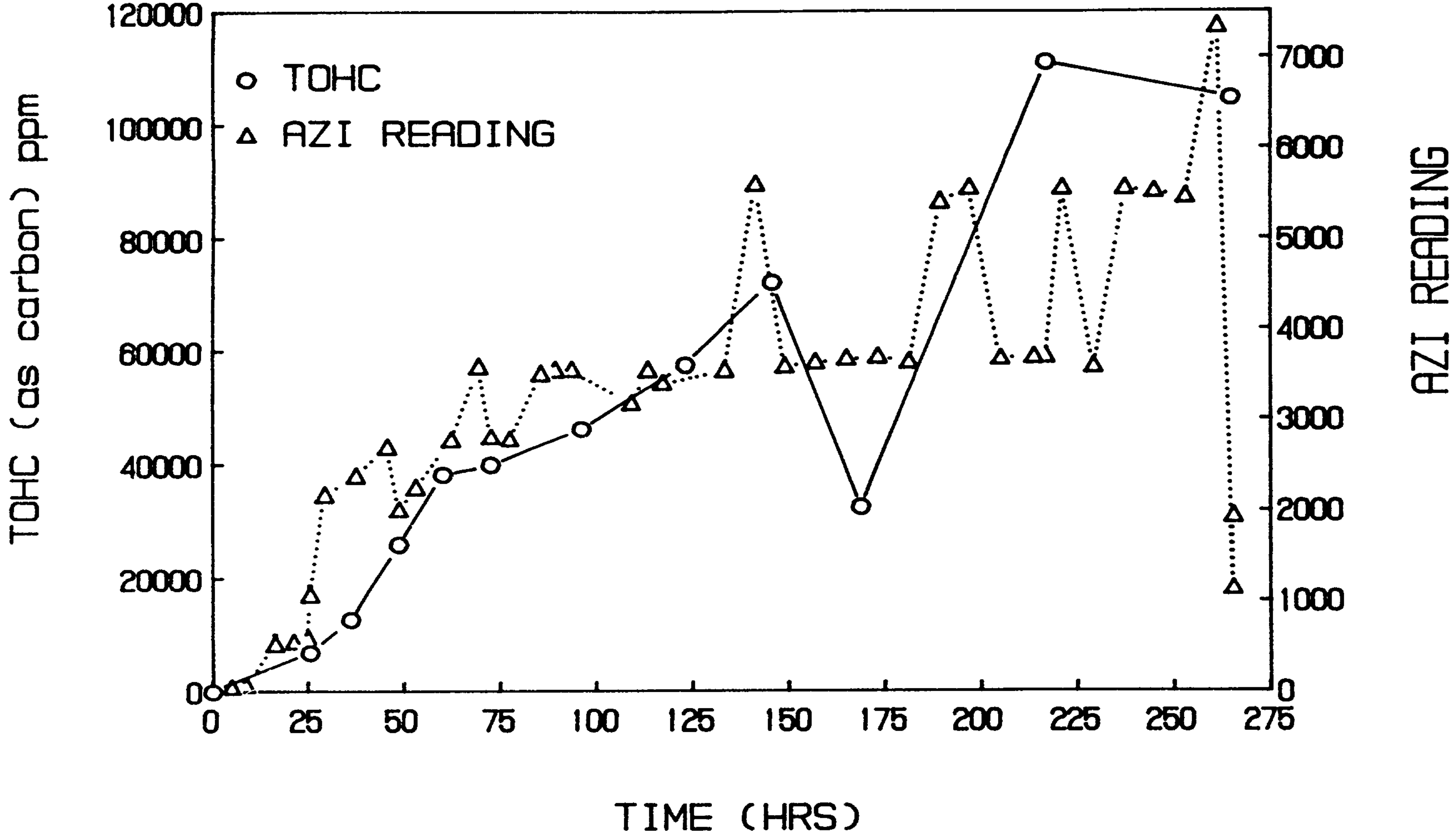


FIGURE C-15

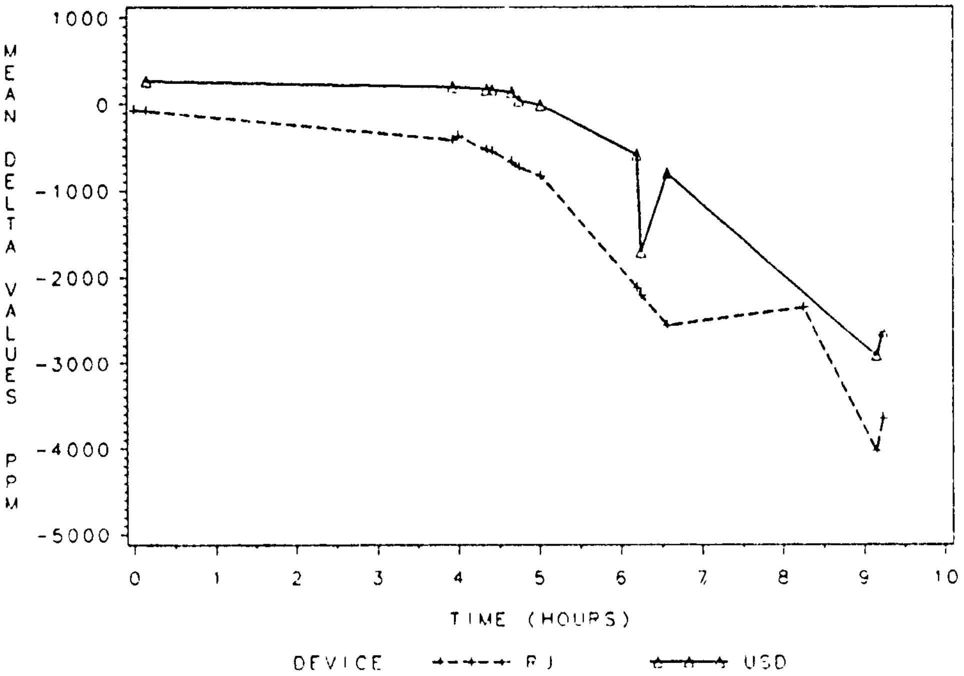


Figure C-16. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) For RJ and USD Sensors Located 3 Feet From the Source of JP-4 For the First 10 Hours of the Vapor-Phase - Dry Sand Experiment.

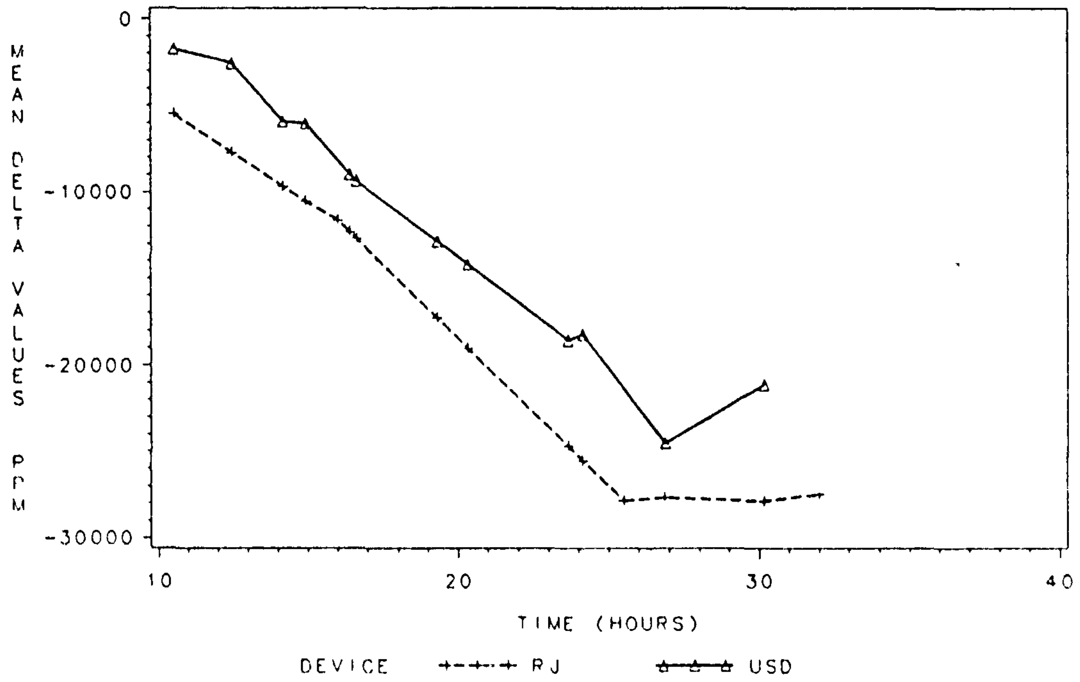


Figure C-17. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) For RJ and USD Sensors Located 3 Feet From the Source of JP-4 For the Hours 10 Through 40 of the Vapor–Phase - Dry Sand Experiment.

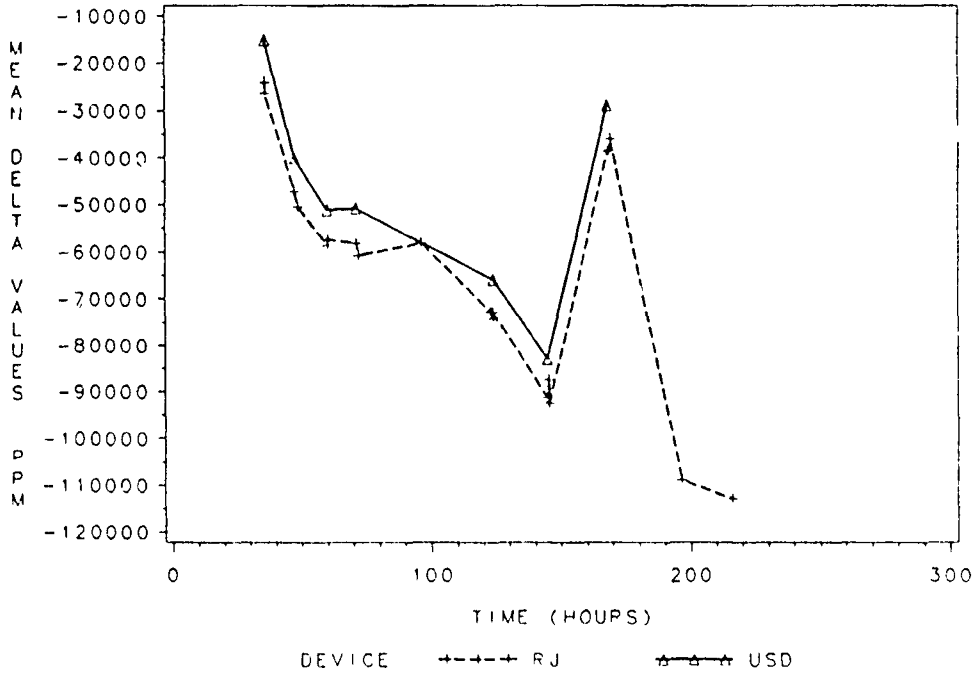


Figure C-18. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) For RJ and USD Sensors Located 3 Feet From the Source of JP-4 For the Hours 40 Through 220 of the Vapor-Phase - Dry Sand Experiment.

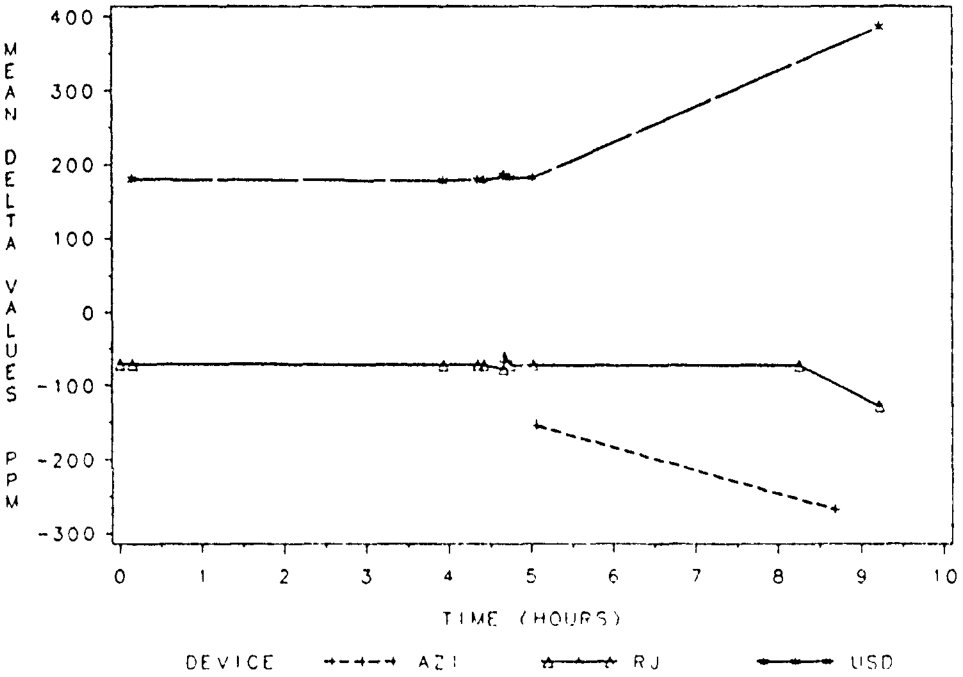


Figure C-19. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) For RJ and USD Sensors Located 5.5 Feet From the Source of JP-4 For the First 10 Hours of the Vapor-Phase - Dry Sand Experiment.

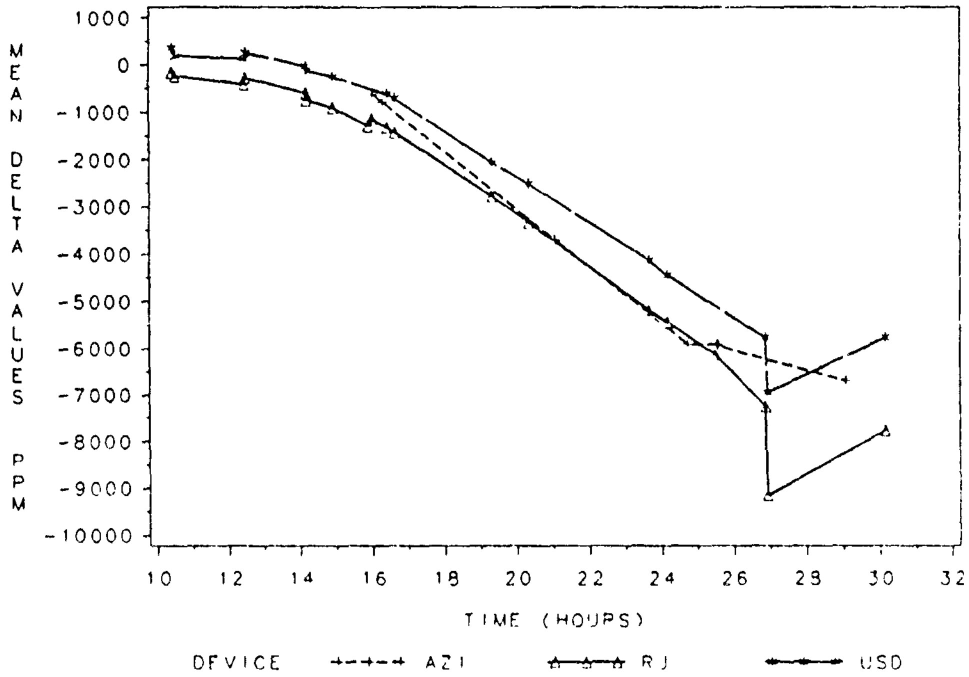


Figure C-20. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) For RJ and USD Sensors Located 5.5 Feet From the Source of JP-4 For the Hours 10 Through 40 of the Vapor-Phase - Dry Sand Experiment.

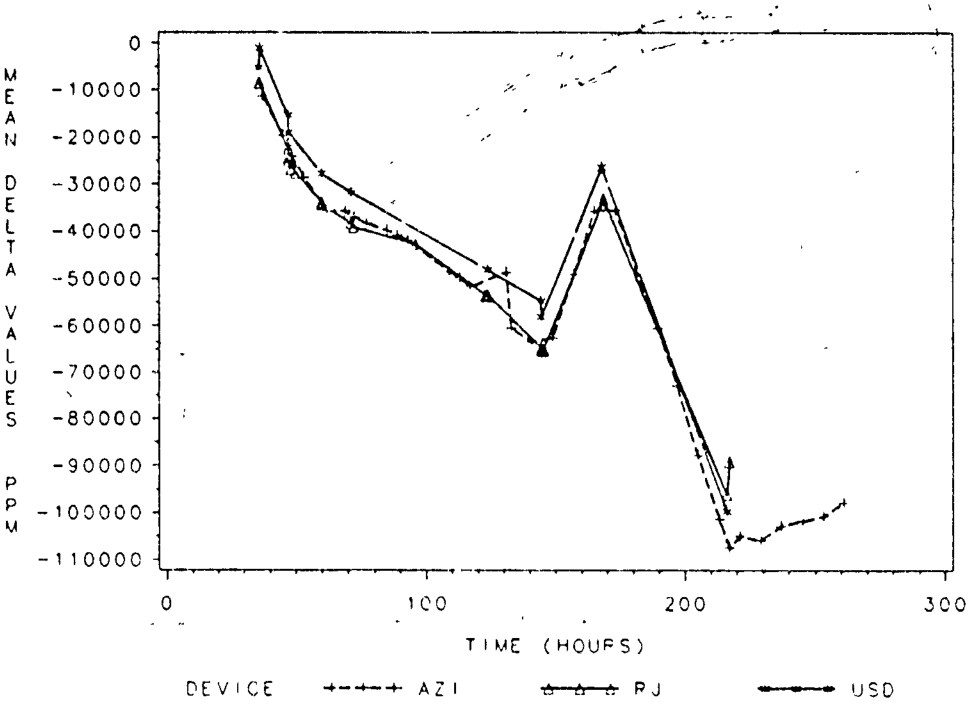


Figure C-21. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) For RJ and USD Sensors Located 5.5 Feet From the Source of JP-4 For the Hours 40 Through 220 of the Vapor-Phase - Dry Sand Experiment.

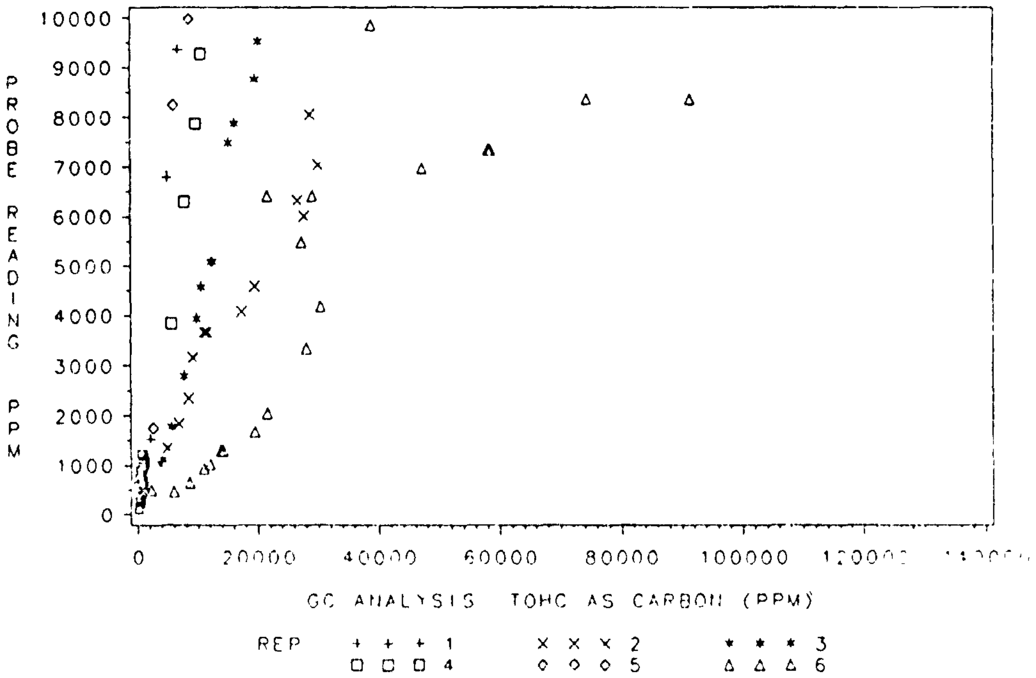


Figure C-22. TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From Each USD Sensor 3 Feet From the Source of JP-4.

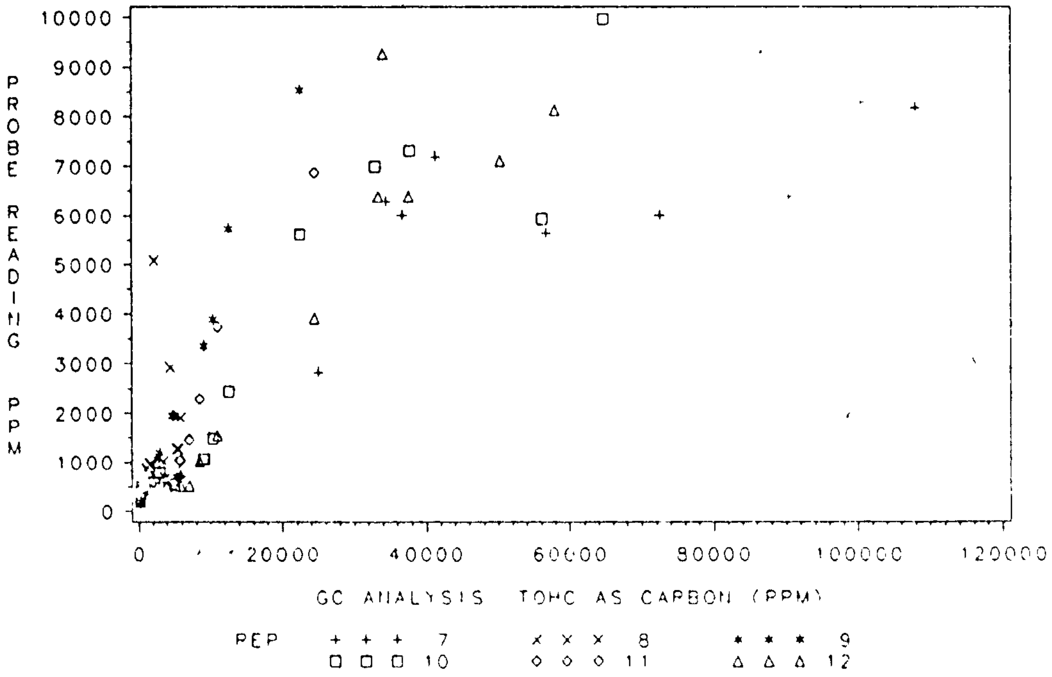


Figure C-23. TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From Each USD Sensor 5.5 Feet From the Source of JP-4.

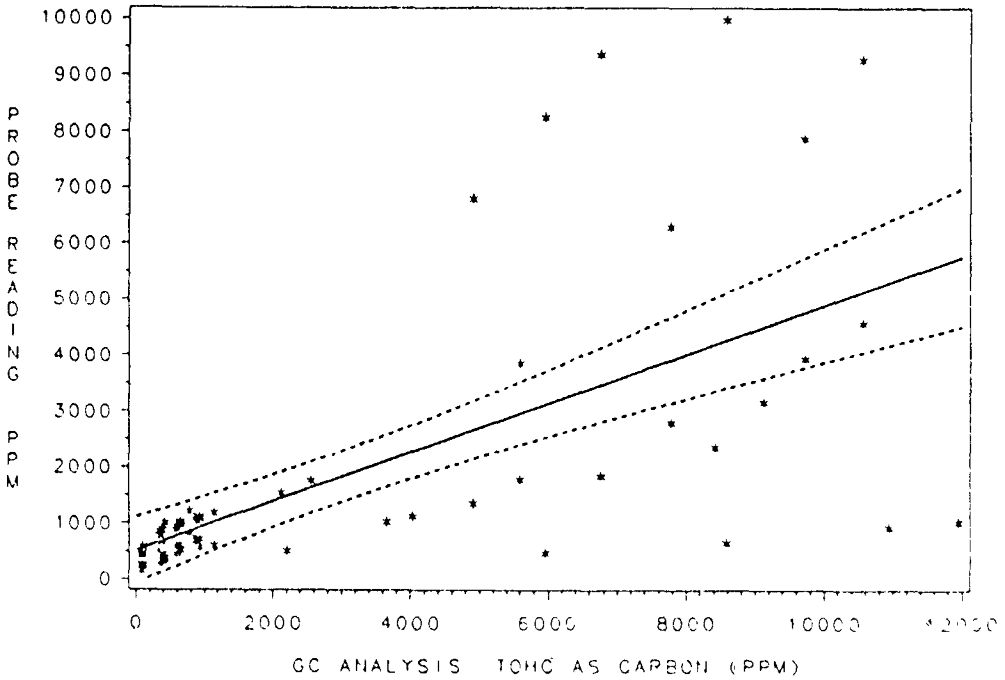


Figure C-24. Linear Regression and Associated 95% Confidence Intervals For the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the USD Sensors 3 Feet From the Source of JP-4 (See Text for the Regression Equation).

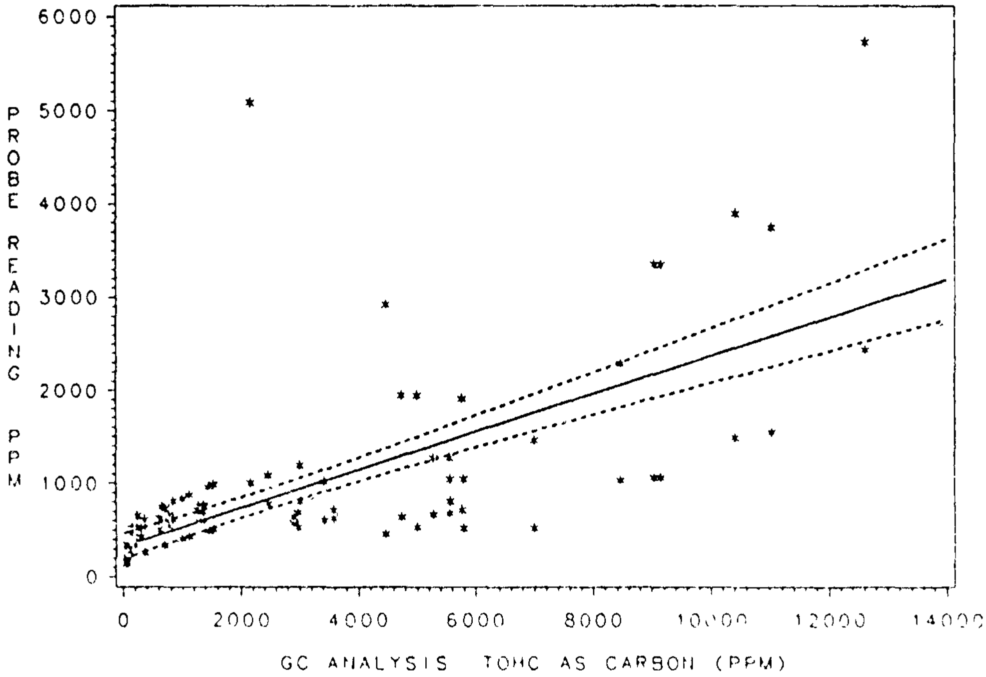


Figure C-25. Linear Regression and Associated 95% Confidence Intervals For the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the USD Sensors 5.5 Feet From the Source of JP-4 (See Text for the Regression Equation).

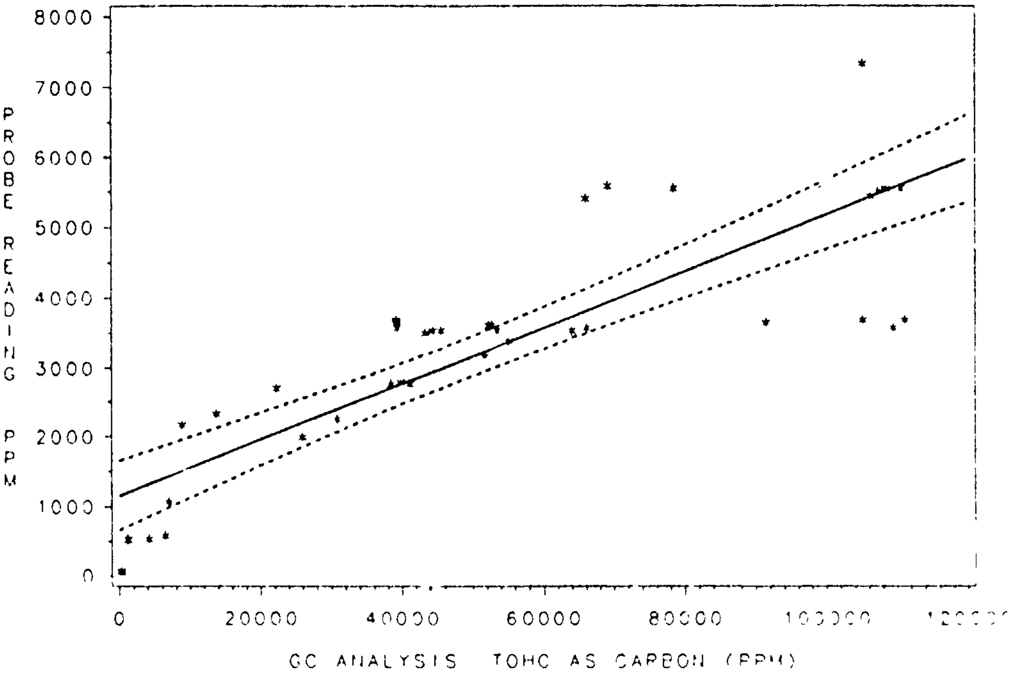


Figure C-26. Linear Regression and Associated 95% Confidence Intervals For the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the AZI Sensors 5.5 Feet From the Source of JP-4 (See Text for the Regression Equation).

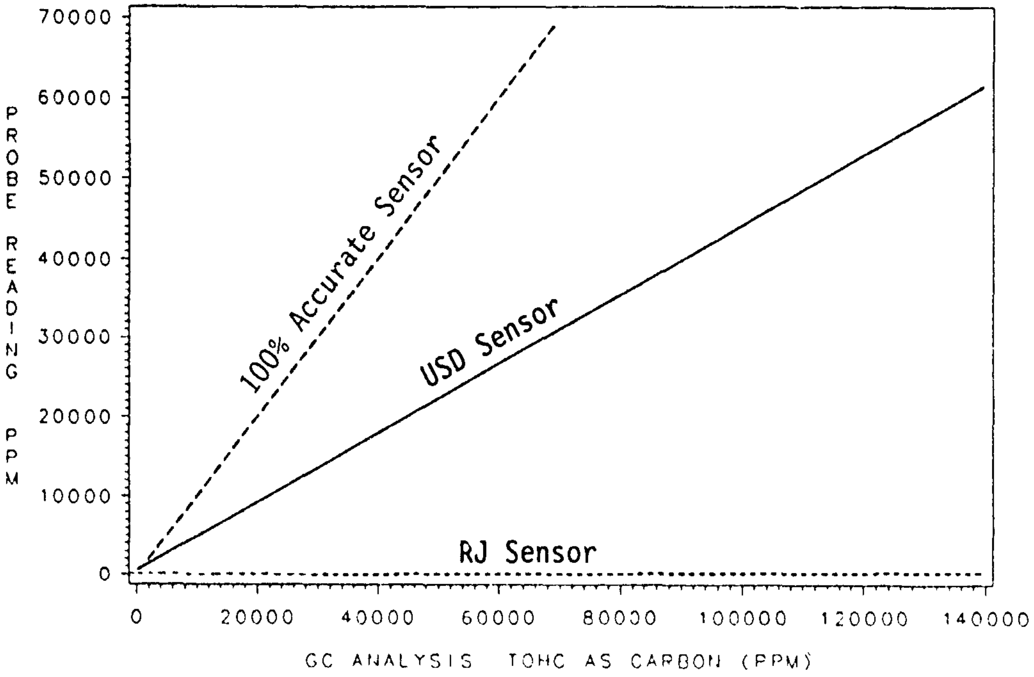


Figure C-27. Predicted Values from the Regressions of TOHC Concentrations from GC Analyses Versus Concentrations Recorded from the Sensors 3 Feet from the Source of JP-4 Relative to a Hypothetical Sensor Which is 100 Percent Accurate.

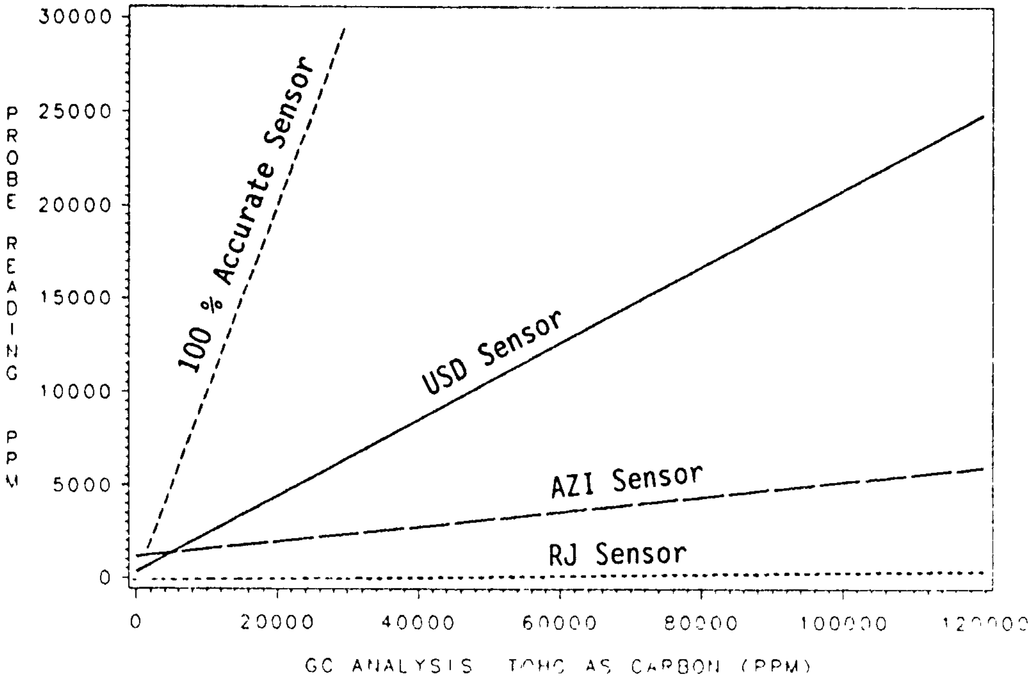


Figure C-28. Predicted Values From the Regressions of TOHC Concentrations From the GC Analyses Versus Concentrations Recorded From the Sensors 5.5 Feet From the Source of JP-4 Relative to a Hypothetical Sensor Which is 100% Accurate.

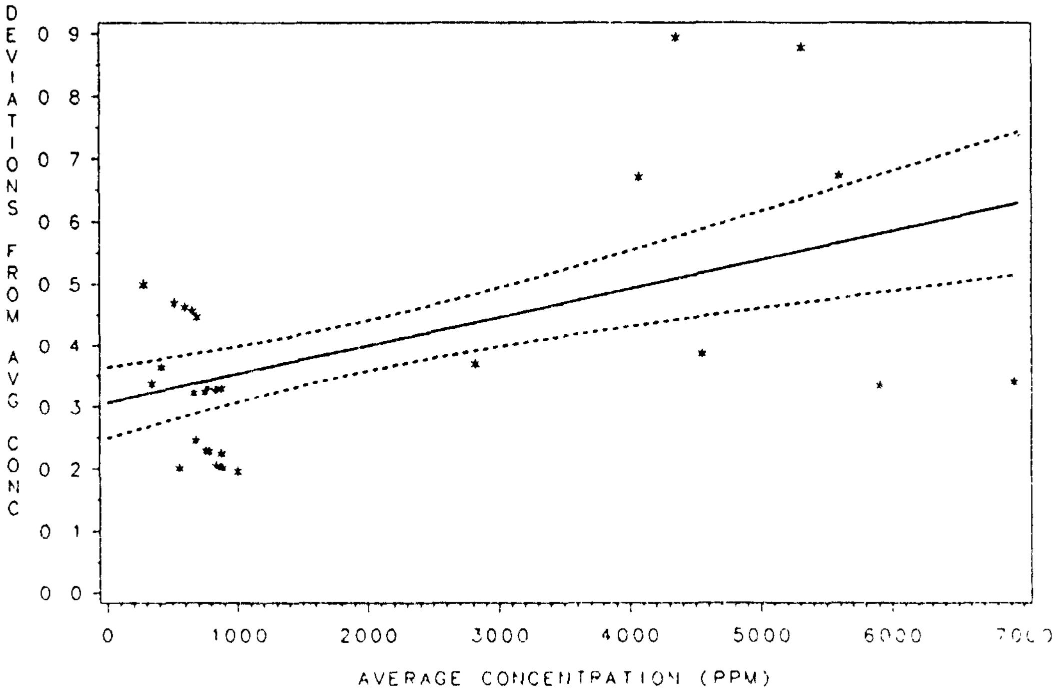


Figure C-29. Linear Regression and Associated 95% Confidence Intervals For the Deviation Values (Differences Between Concentrations Recorded From Replicate Sensors) Versus Average Concentrations Recorded by Replicate USD Sensors 3.0 Feet From the Source of JP-4 (See Text For the Regression Equation).

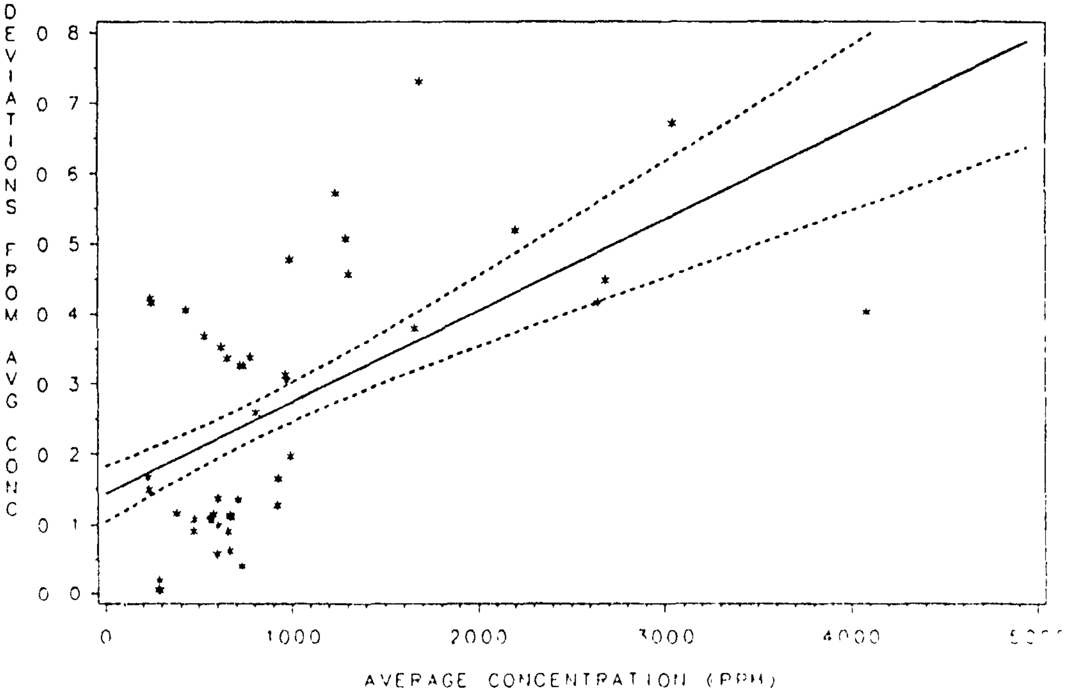


Figure C-30. Linear Regression and Associated 95% Confidence Intervals For the Deviation Values (Differences Between Concentrations Recorded From Replicate Sensors) Versus Average Concentrations Recorded by Replicate USD Sensors 5.5 Feet From the Source of JP-4 (See Text For the Regression Equation).

RESPONSE OF USD: WELL B

VAPOR-PHASE / FRESH JP-4 / WET SAND

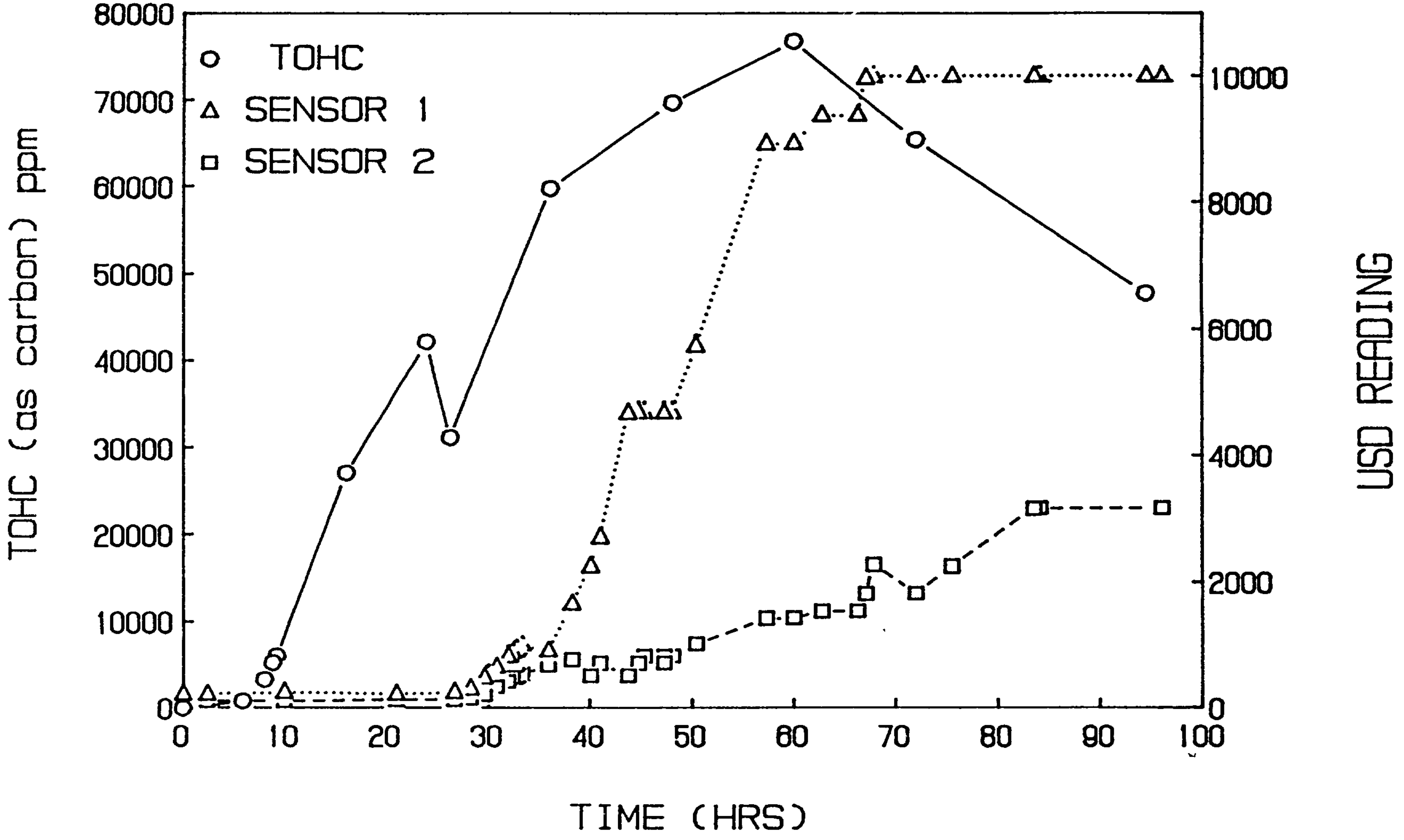


FIGURE C-31

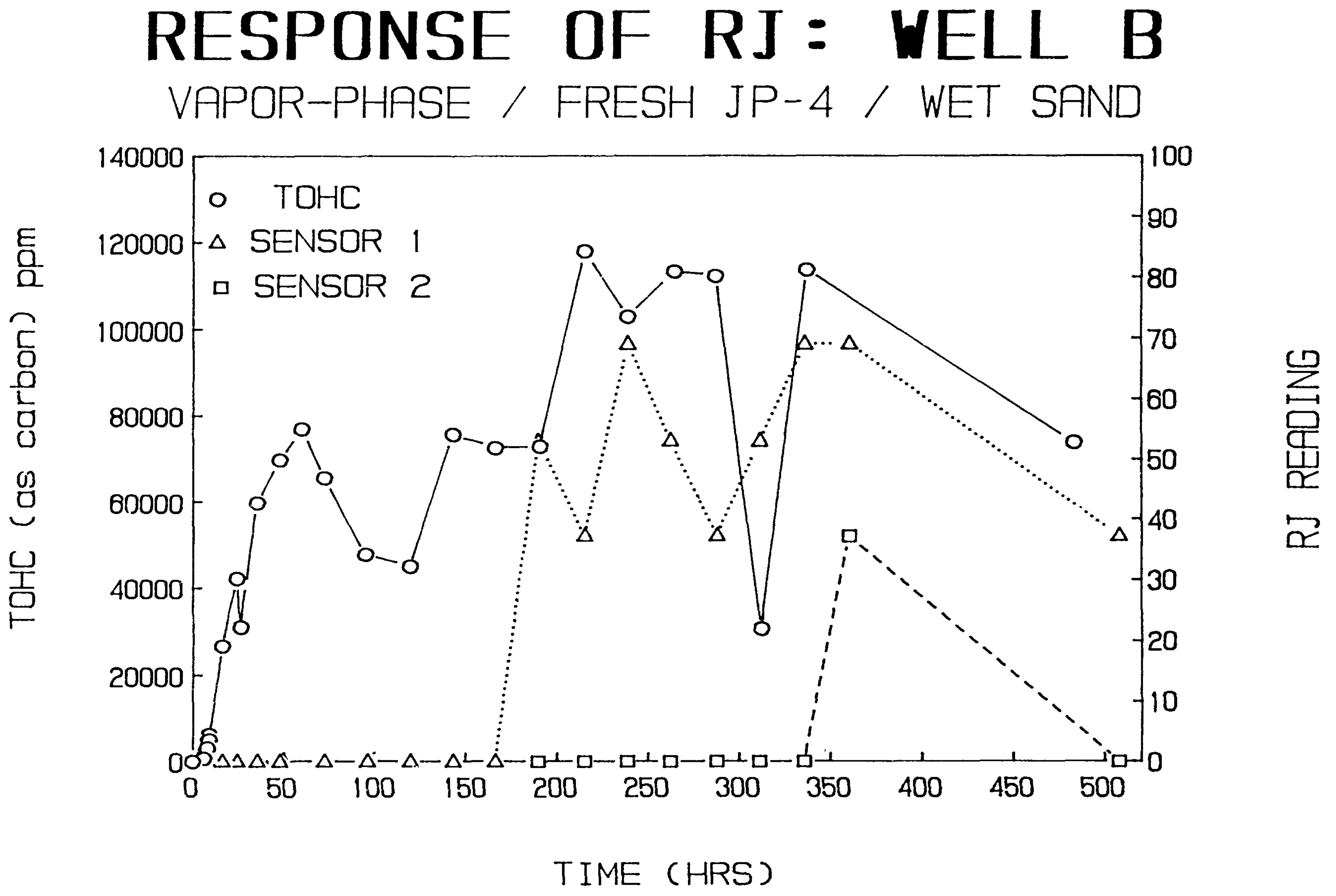

RESPONSE OF RJ: WELL B
VAPOR-PHASE / FRESH JP-4 / WET SAND
TOHC
SENSOR 1
SENSOR 2
TOHC (as carbon) ppm
0
20000
40000
60000
80000
100000
120000
140000
RJ READING
0
10
20
30
40
50
60
70
80
90
100
TIME (HRS)
0
50
100
150
200
250
300
350
400
450
500

FIGURE C-32

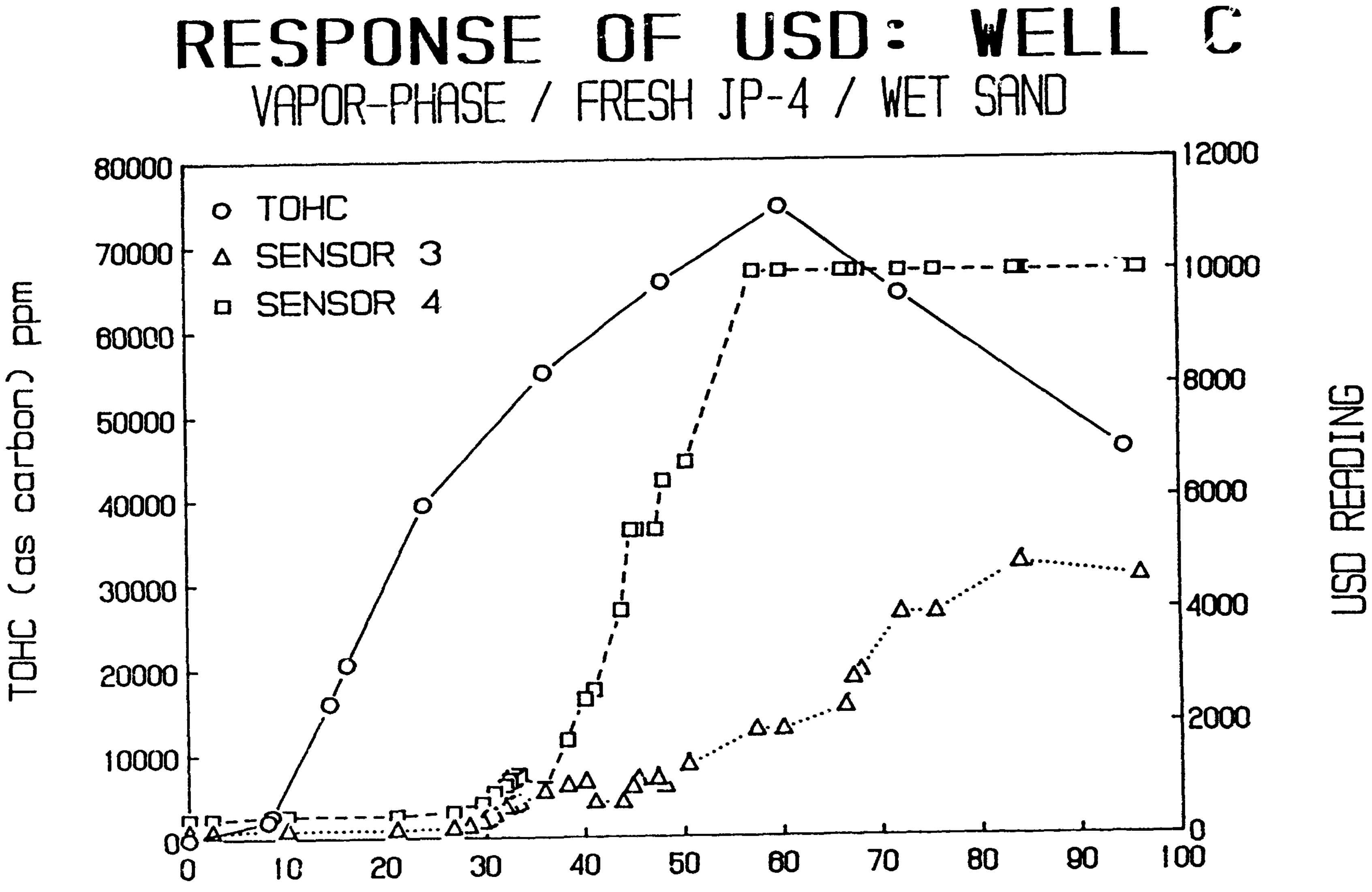

RESPONSE OF USD: WELL C
VAPOR-PHASE / FRESH JP-4 / WET SAND
○ TOHC
△ SENSOR 3
□ SENSOR 4
TOHC (as carbon) ppm
0
10000
20000
30000
40000
50000
60000
70000
80000
USD READING
0
2000
4000
6000
8000
10000
12000
TIME (HRS)
0
10
20
30
40
50
60
70
80
90
100

FIGURE C-33

RESPONSE OF RJ: WELL C

VAPOR-PHASE / FRESH JP-4 / WET SAND

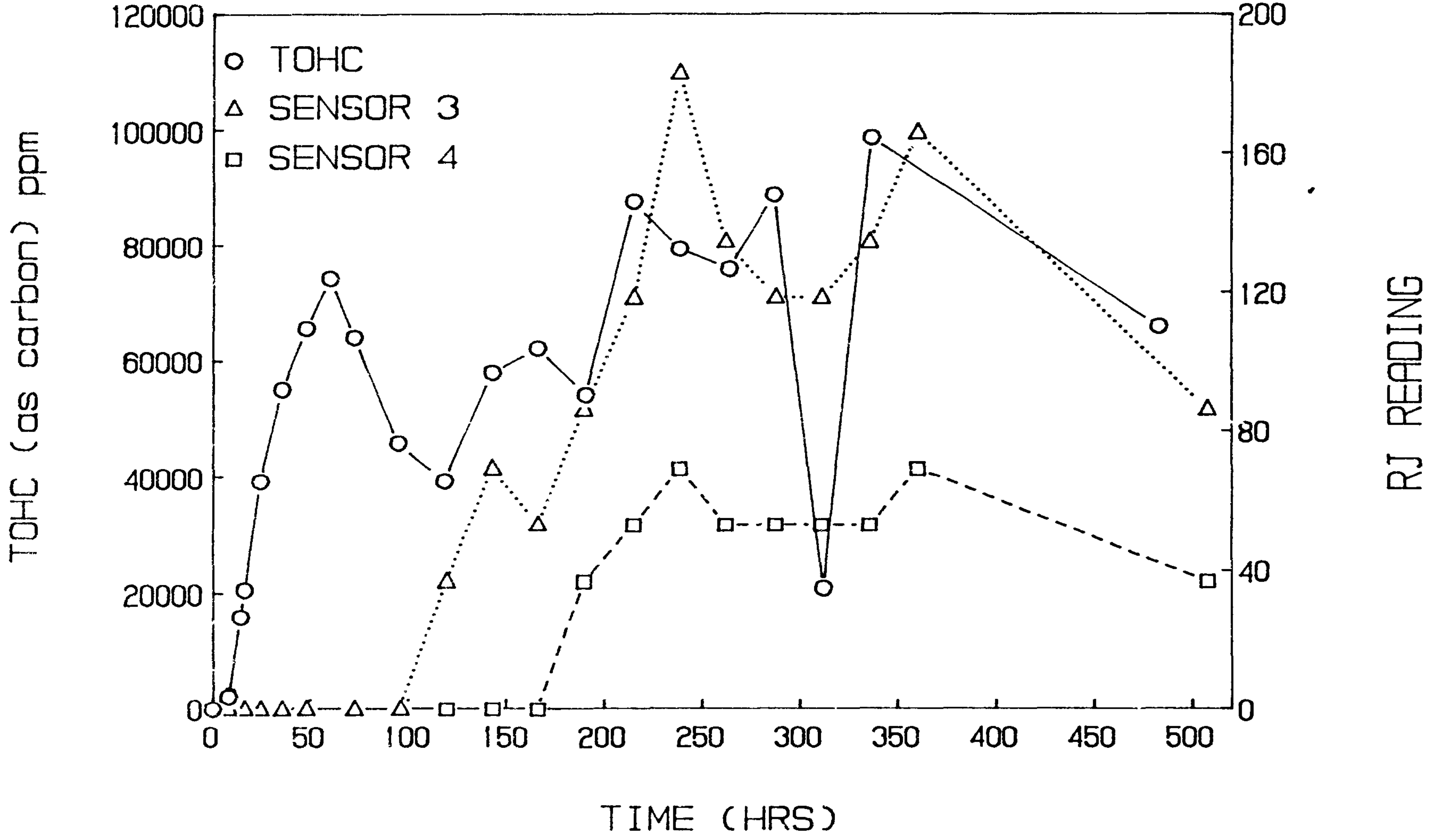


FIGURE C-34

RESPONSE OF USD: WELL D

VAPOR-PHASE / FRESH JP-4 / WET SAND

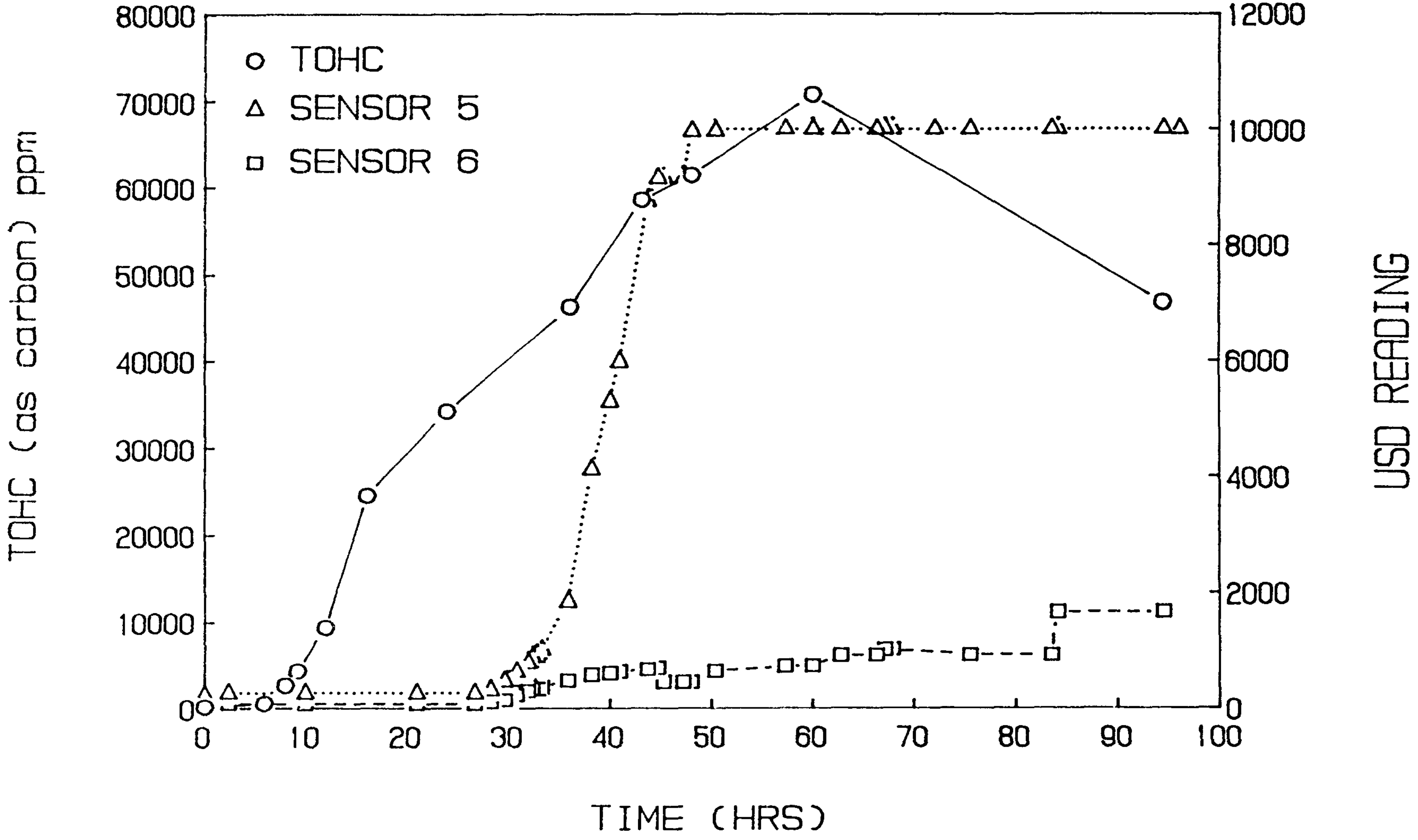


FIGURE C-35

RESPONSE OF RJ: WELL D

VAPOR-PHASE / FRESH JP-4 / WET SAND

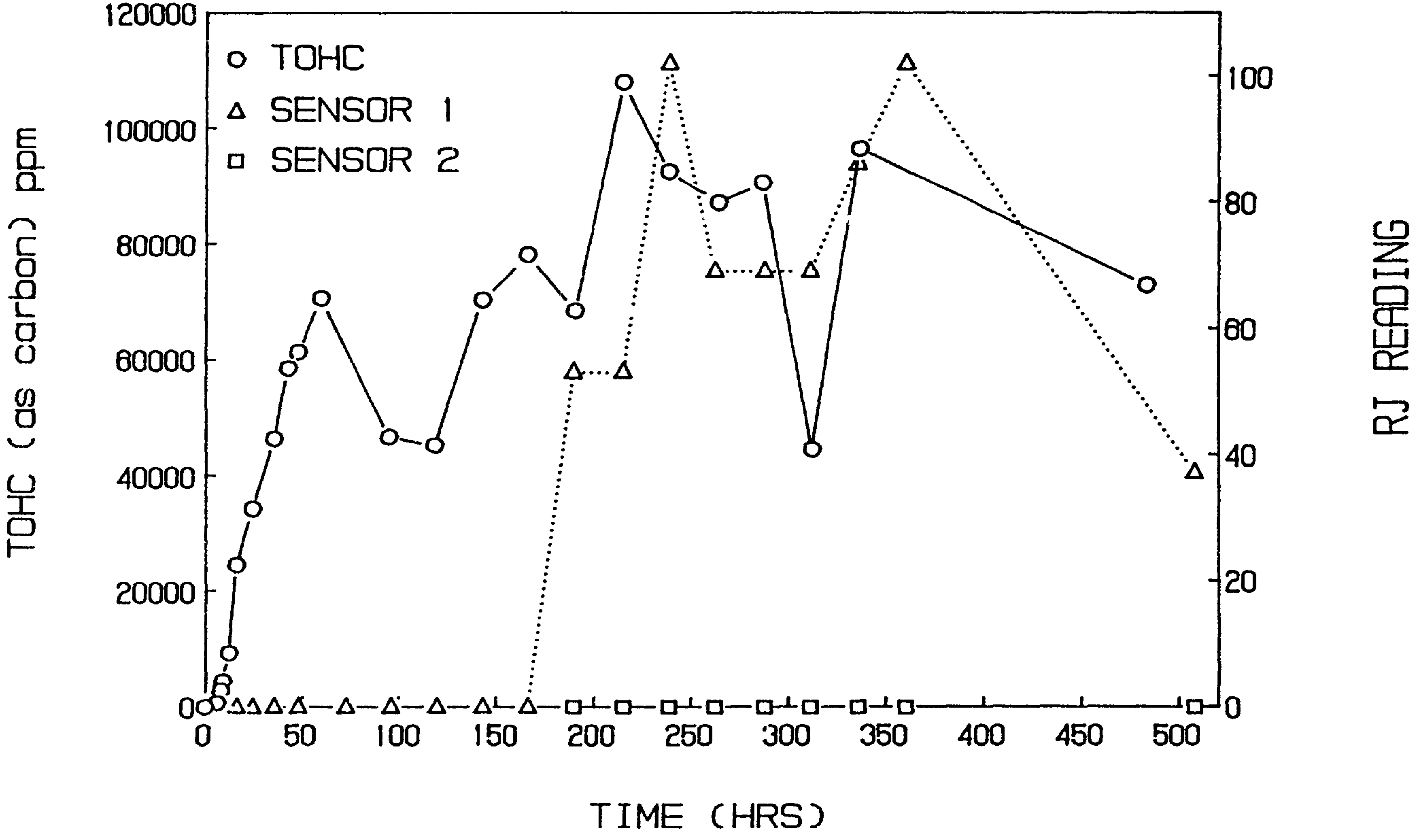


FIGURE C-36

RESPONSE OF USD: WELL F

VAPOR-PHASE / FRESH JP-4 / WET SAND

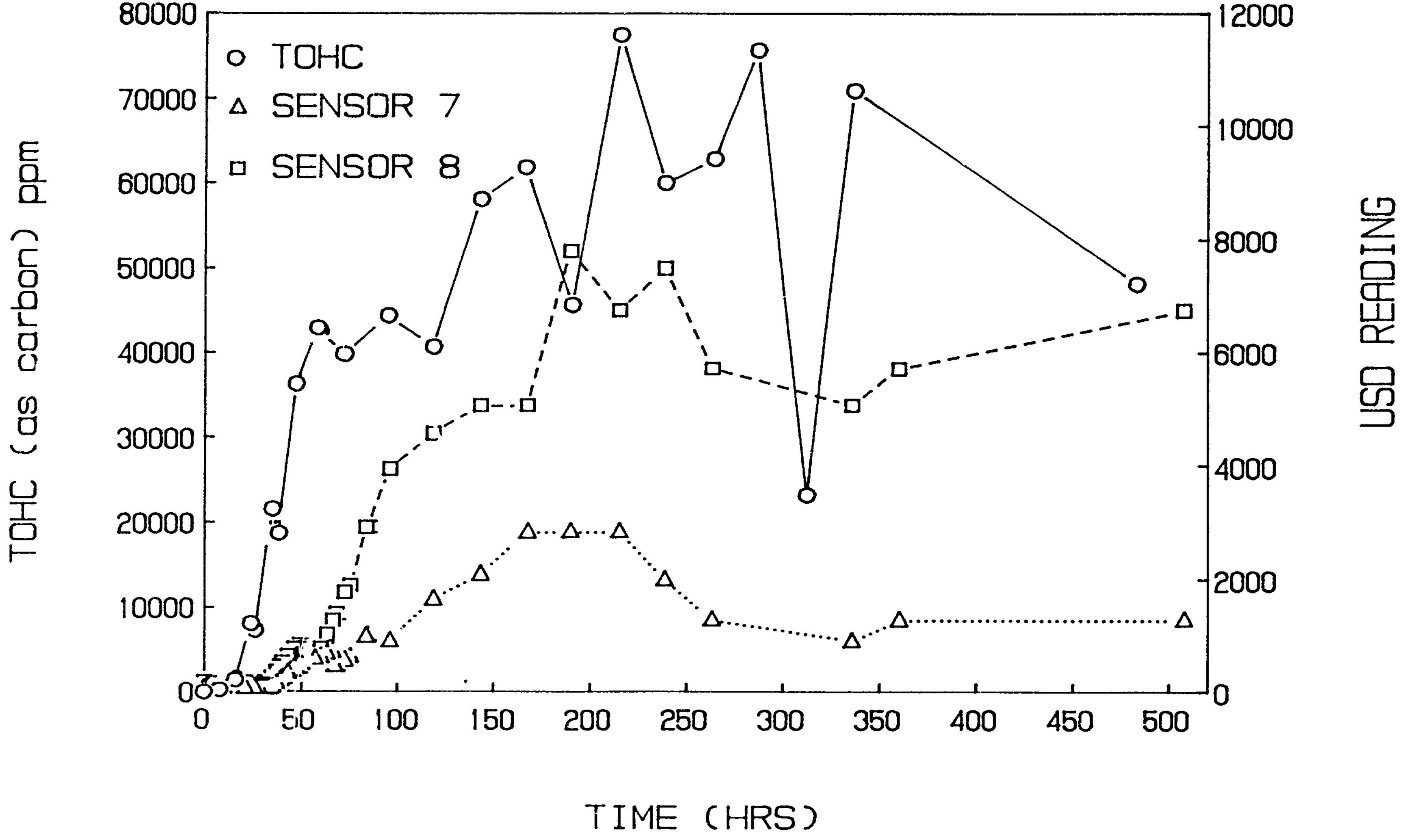
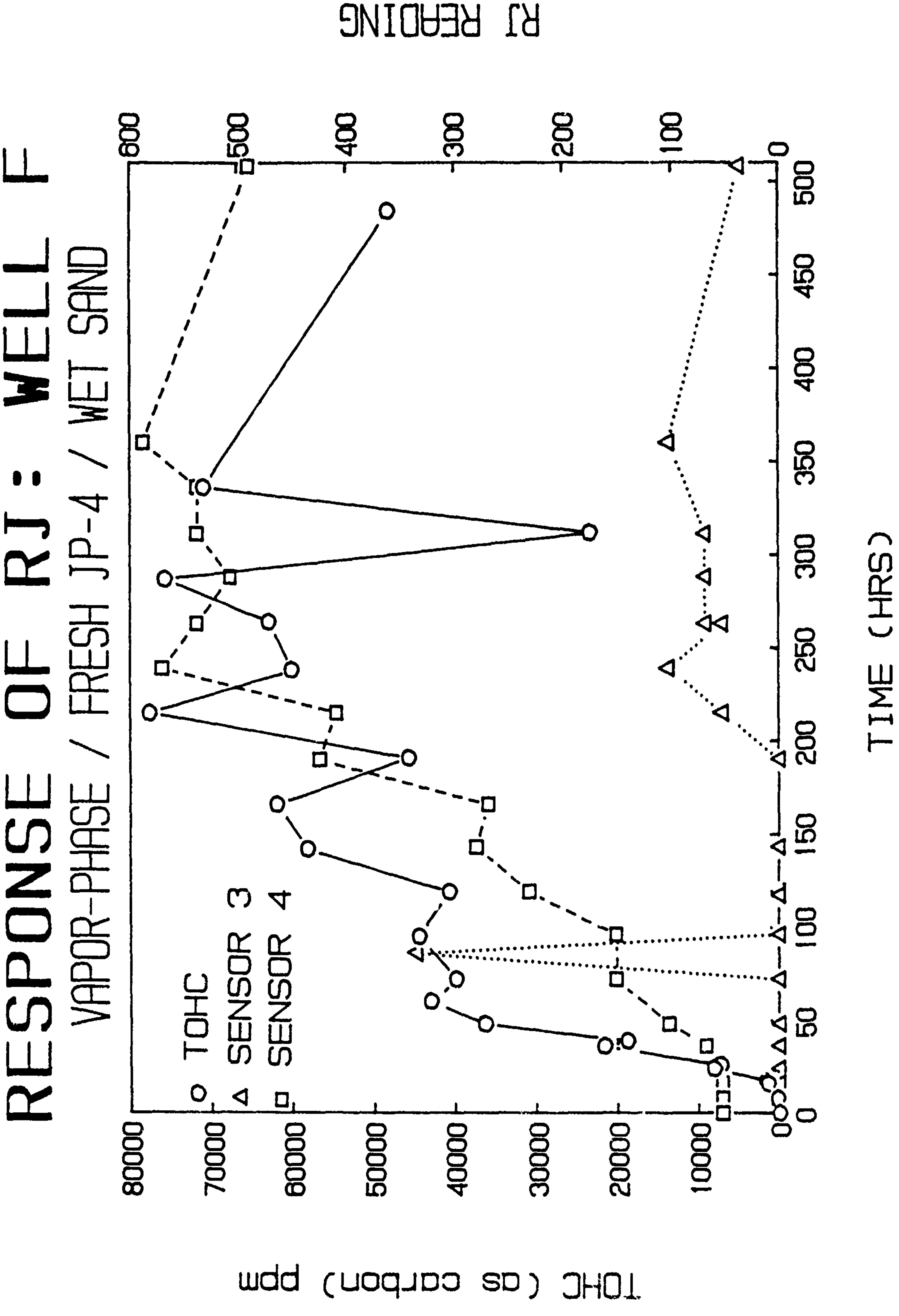


FIGURE C-37



RESPONSE OF RJ: WELL F

VAPOR-PHASE / FRESH JP-4 / WET SAND

FIGURE C-38

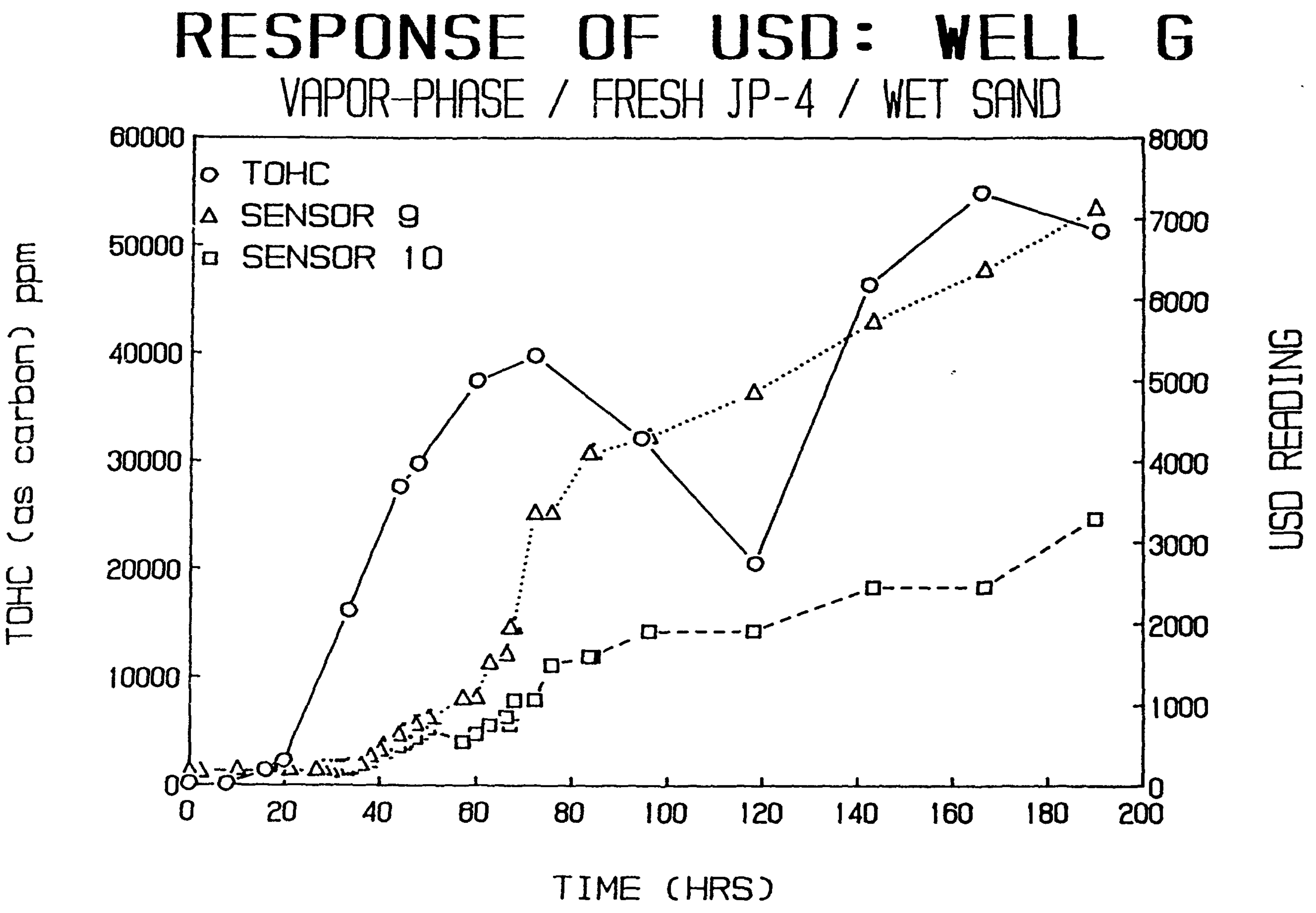

RESPONSE OF USD: WELL G
VAPOR-PHASE / FRESH JP-4 / WET SAND
TOHC
SENSOR 9
SENSOR 10
TOHC (as carbon) ppm
0
10000
20000
30000
40000
50000
60000
USD READING
0
1000
2000
3000
4000
5000
6000
7000
8000
0
20
40
60
80
100
120
140
160
180
200
TIME (HRS)

FIGURE C-39

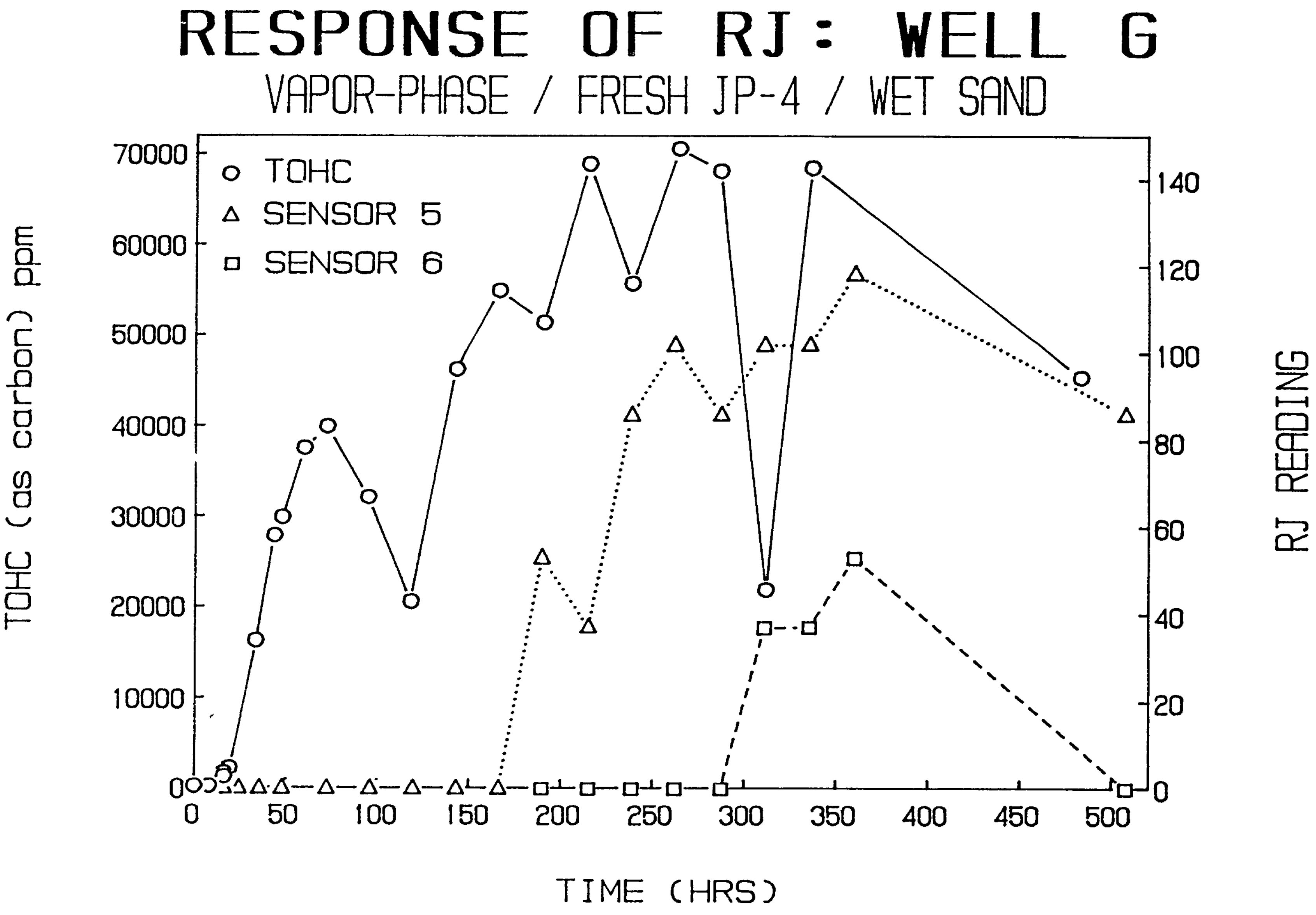

RESPONSE OF RJ: WELL G
VAPOR-PHASE / FRESH JP-4 / WET SAND
○ TOHC
△ SENSOR 5
□ SENSOR 6
TOHC (as carbon) ppm
70000
60000
50000
40000
30000
20000
10000
0
RJ READING
140
120
100
80
60
40
20
0
TIME (HRS)
0
50
100
150
200
250
300
350
400
450
500

FIGURE C-40

RESPONSE OF USD: WELL H

VAPOR-PHASE / FRESH JP-4 / WET SAND

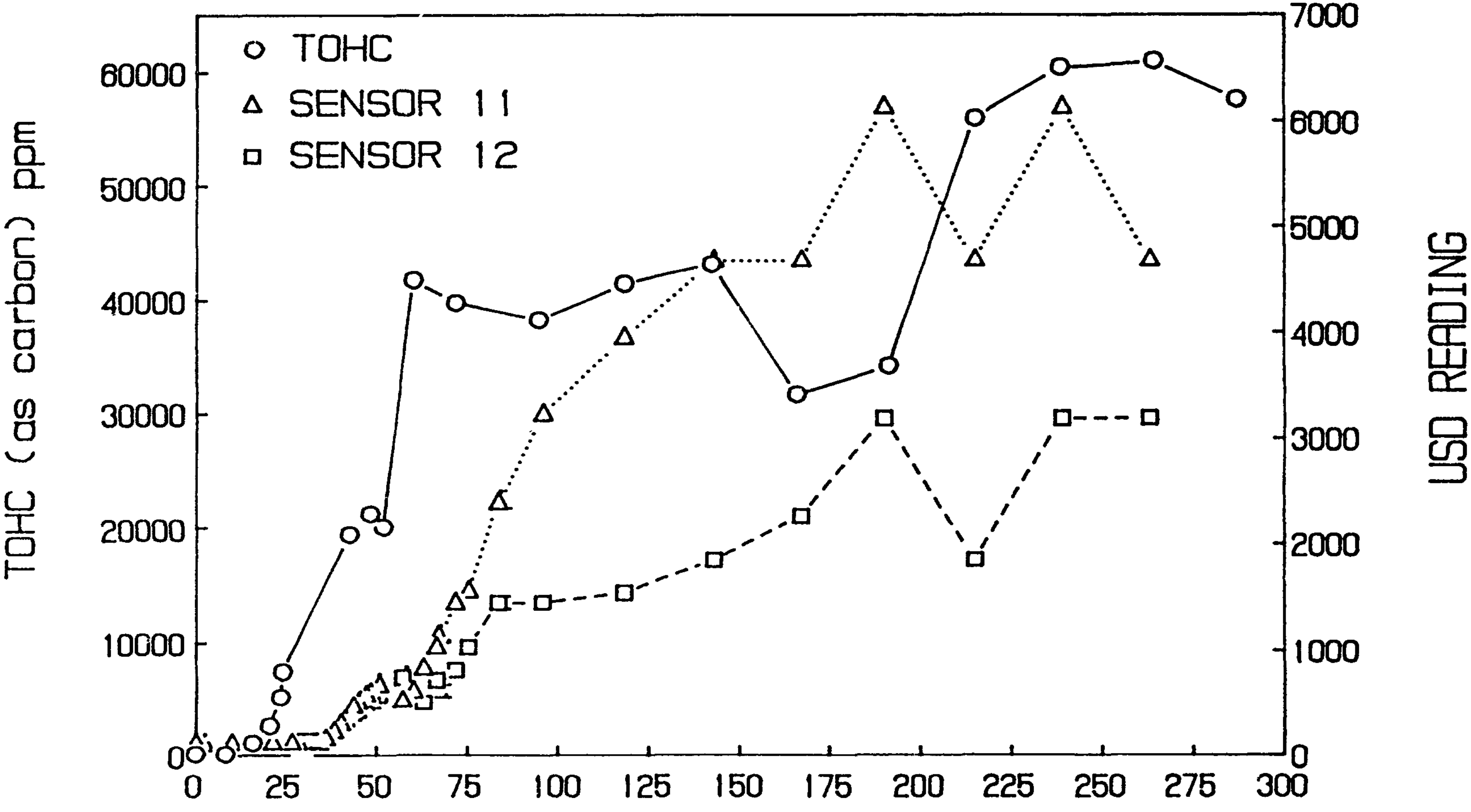


FIGURE C-41

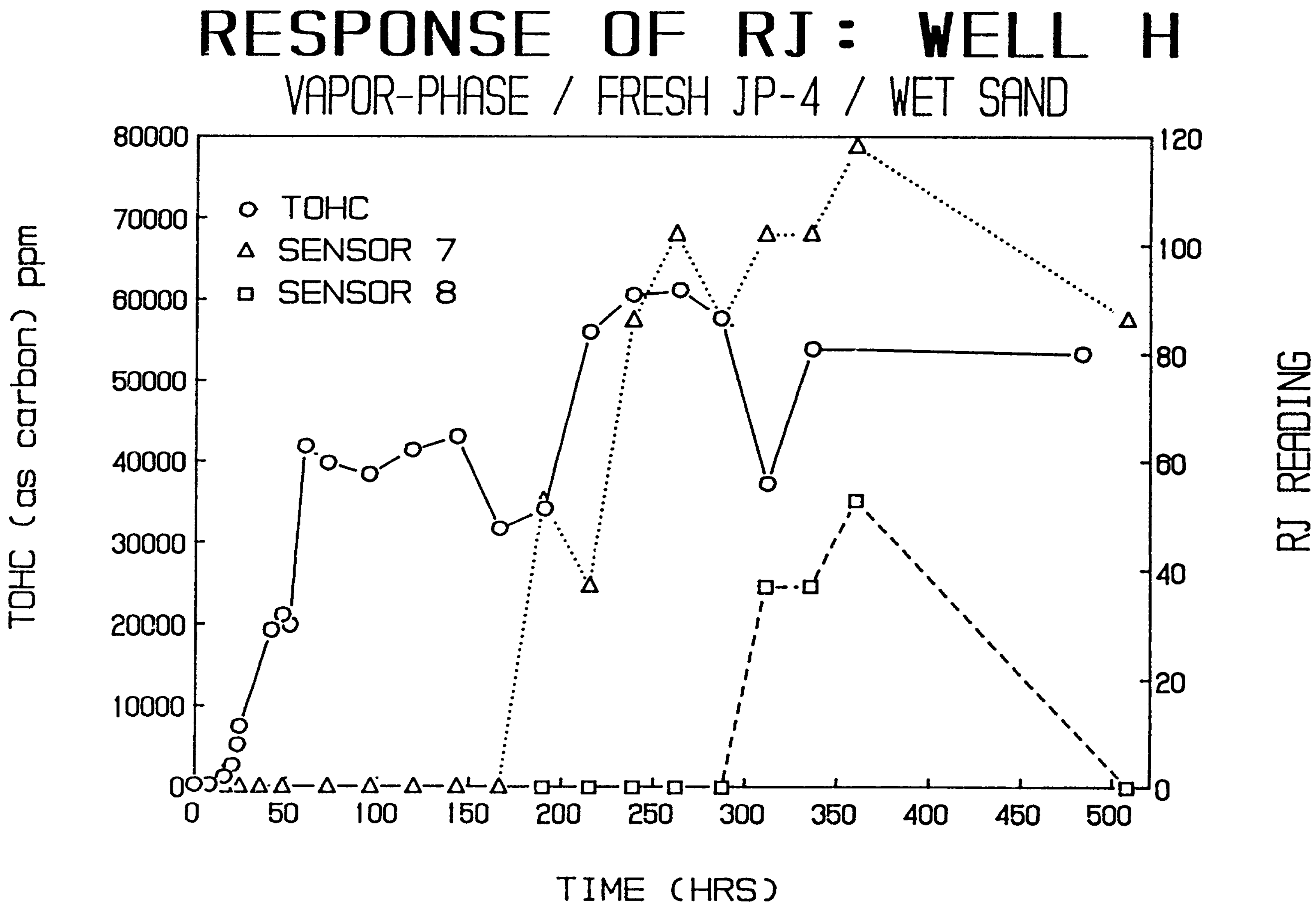

RESPONSE OF RJ: WELL H
VAPOR-PHASE / FRESH JP-4 / WET SAND
TOHC
SENSOR 7
SENSOR 8
TOHC (as carbon) ppm
0
10000
20000
30000
40000
50000
60000
70000
80000
RJ READING
0
20
40
60
80
100
120
TIME (HRS)
0
50
100
150
200
250
300
350
400
450
500

FIGURE C-42

RESPONSE OF AZI: WELL K

VAPOR-PHASE / FRESH JP-4 / WET SAND

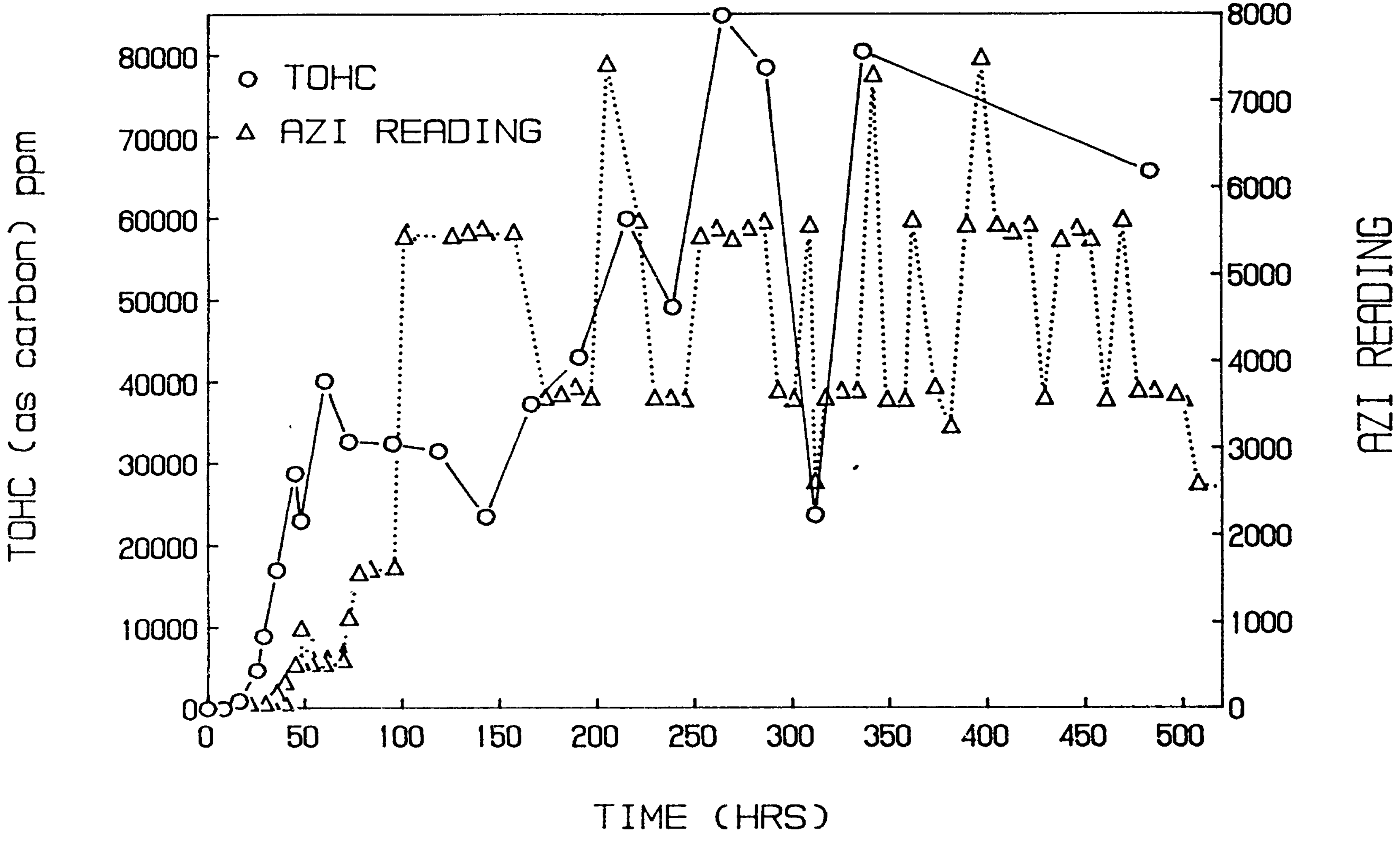


FIGURE C-43

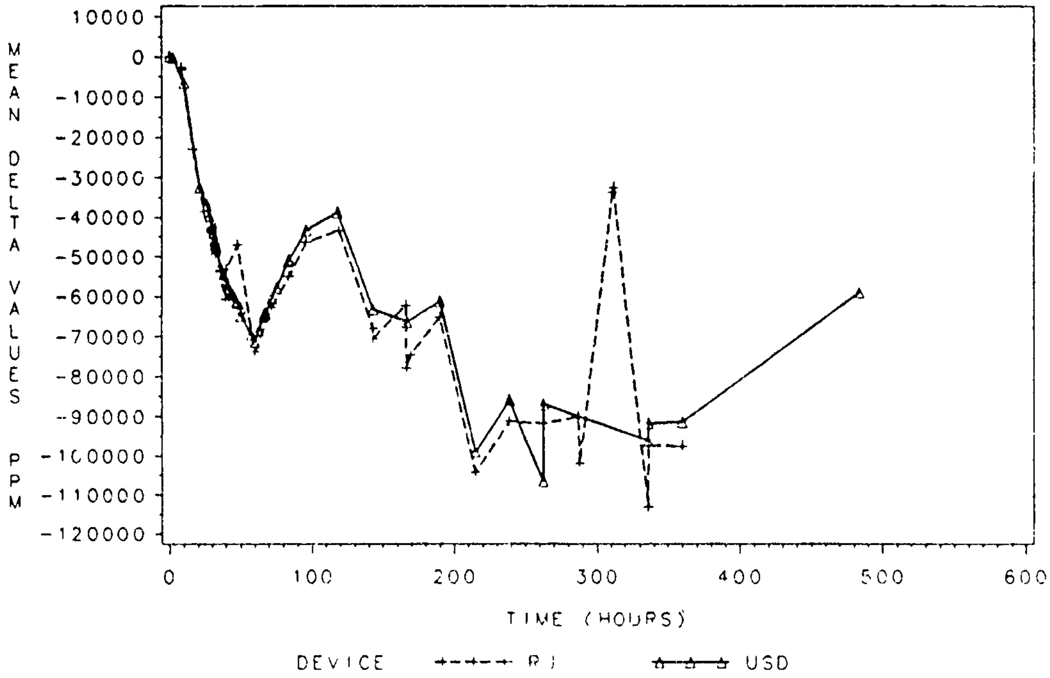


Figure C-44. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) for RJ and USD Sensors Located 3 Feet From the Source of JP-4 During the Vapor-Phase - Wet Sand Experiment.

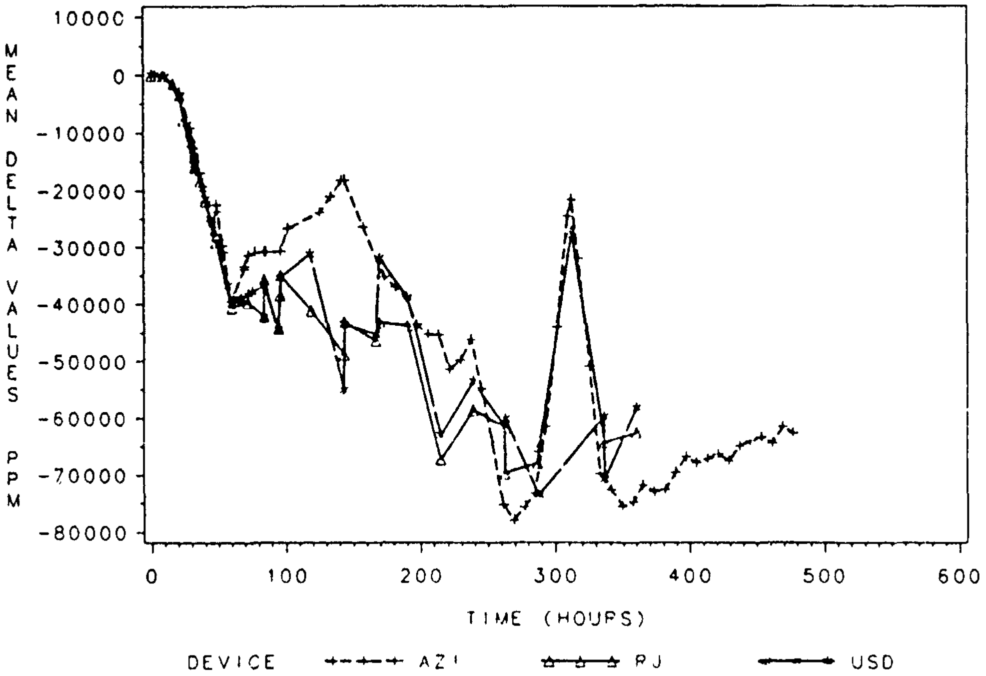


Figure C-45. Delta Values (Differences Between Concentrations Recorded From the GC Analyses and Those Recorded From the Sensors) for AZI, RJ, and USD Sensors Located 5.5 Feet From the Source of JP-4 During the Vapor-Phase - Wet Sand Experiment.

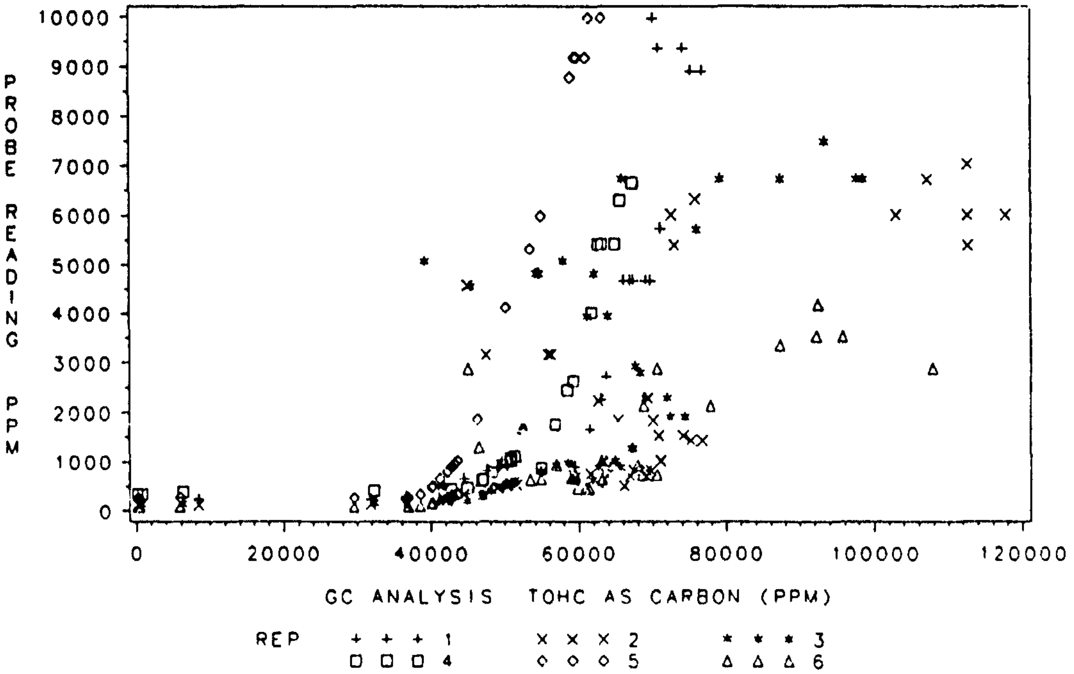


Figure C-46. TOHC Concentrations Recorded from GC Analyses Versus Concentrations Recorded From USD Sensors 3 Feet From the Source of JP-4.

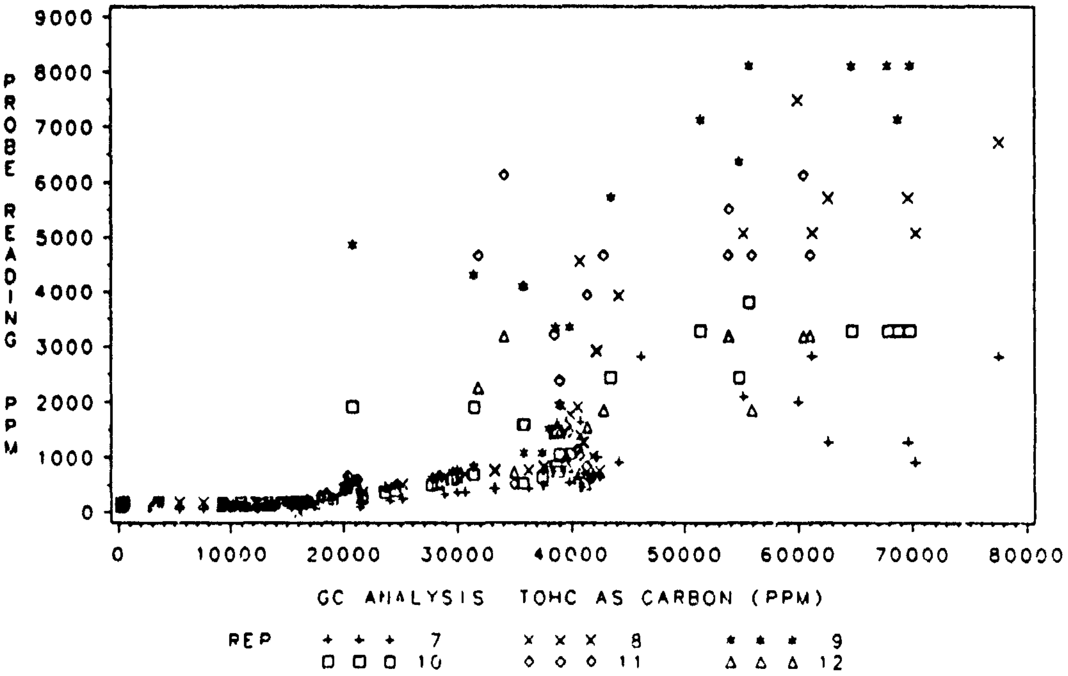


Figure C-47. TOHC Concentrations Recorded from GC Analyses Versus Concentrations Recorded From USD Sensors 5.5 Feet From the Source of JP-4.

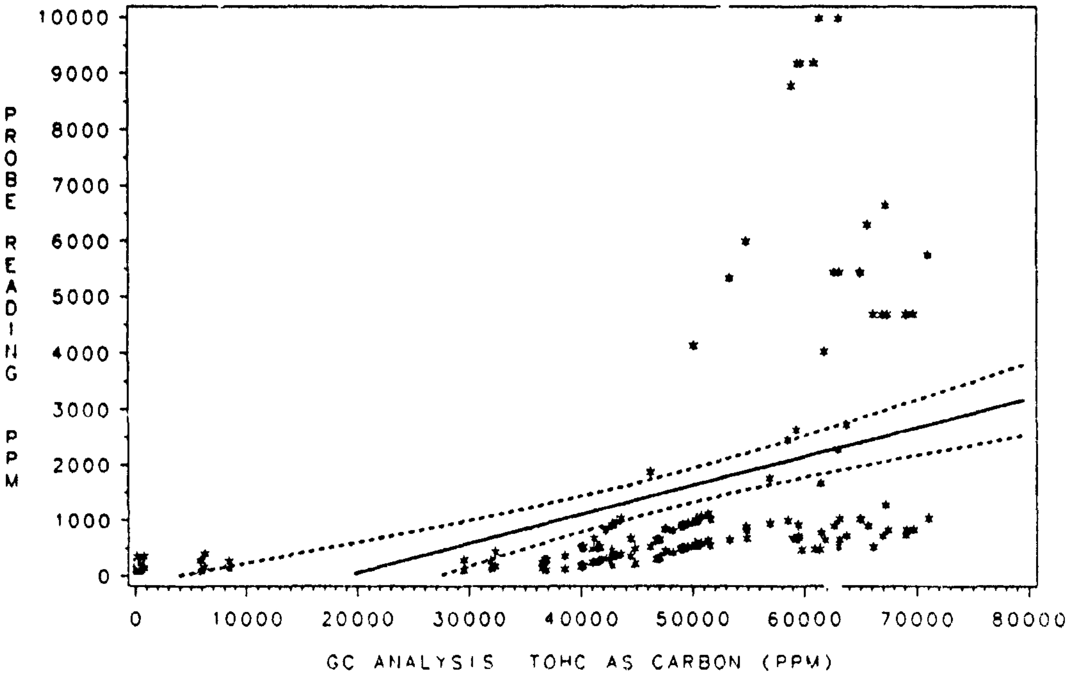


Figure C-48. Linear Regression and Associated 95% Confidence Intervals for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the USD Sensors 3 Feet From the Source of JP-4 (See Text for the Regression Equation).

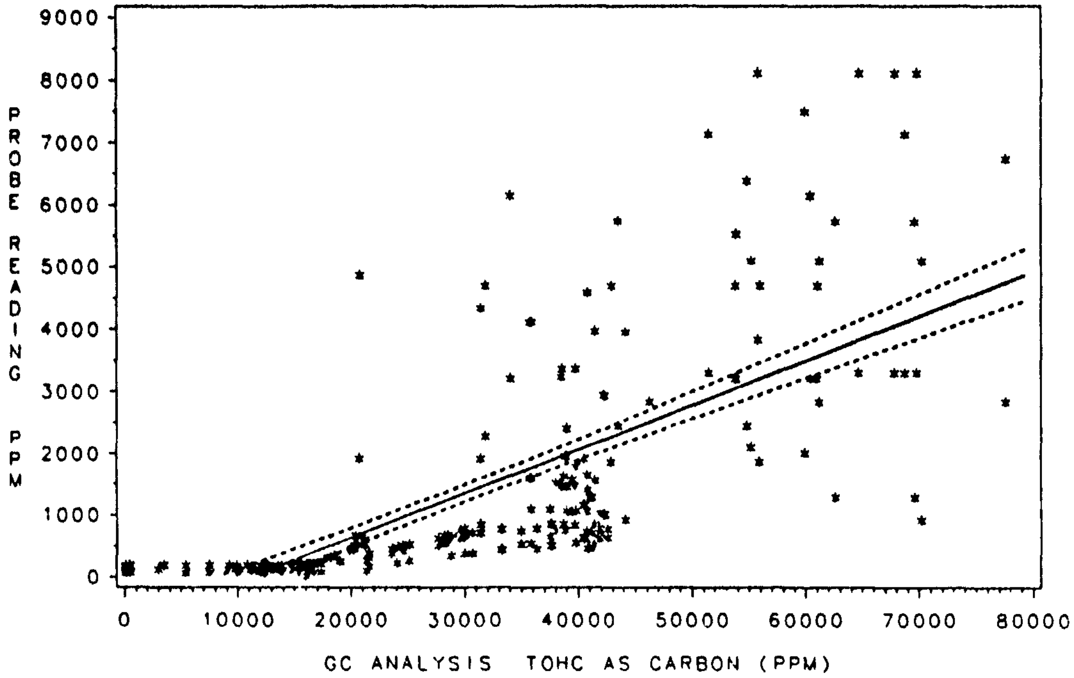


Figure C-49. Linear Regression and Associated 95% Confidence Intervals for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the USD Sensors 5.5 Feet From the Source of JP-4 (See Text for the Regression Equation).

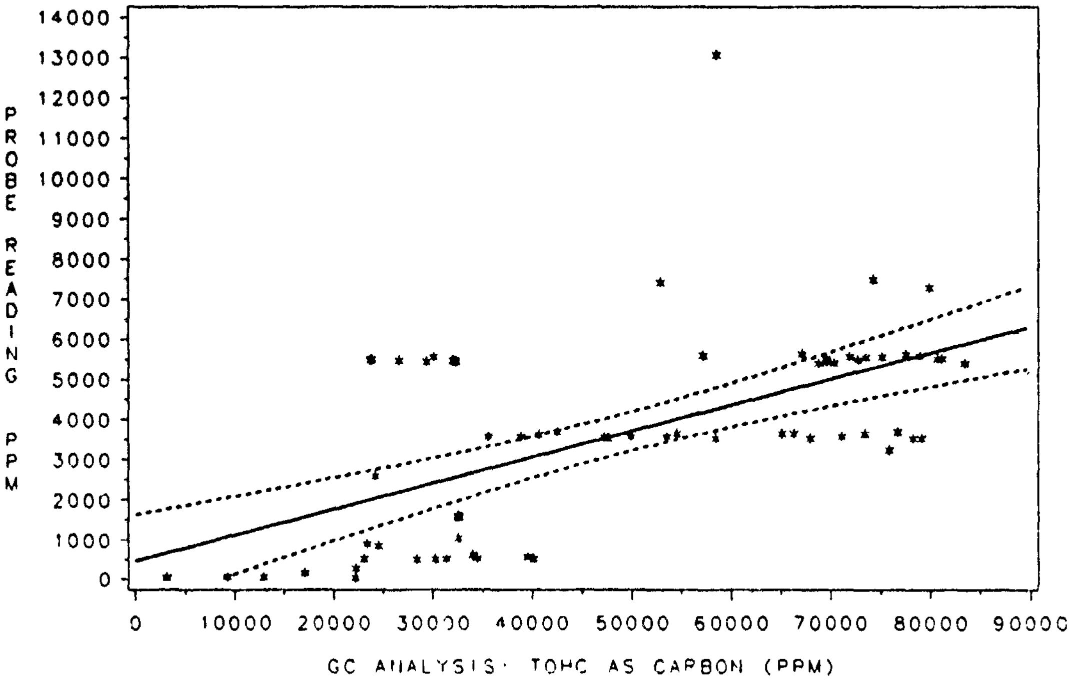


Figure C-50. Linear Regression and Associated 95% Confidence Intervals for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the AZI Sensors 5.5 Feet From the Source of JP-4 (See Text for the Regression Equation).

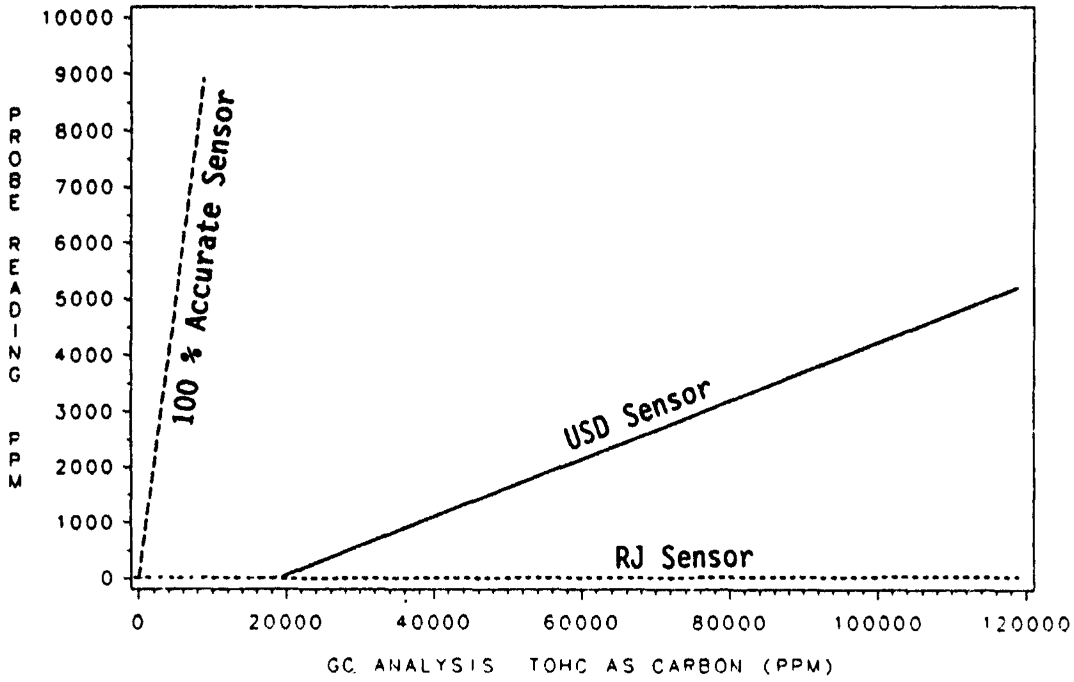


Figure C-51. Predicted Values From the Regressions of TOHC Concentrations From the GC Analyses Versus Concentrations Recorded From the Sensors 3 Feet From the Source of JP-4 Relative to a Hypothetical Sensor Which is 100% Accurate.

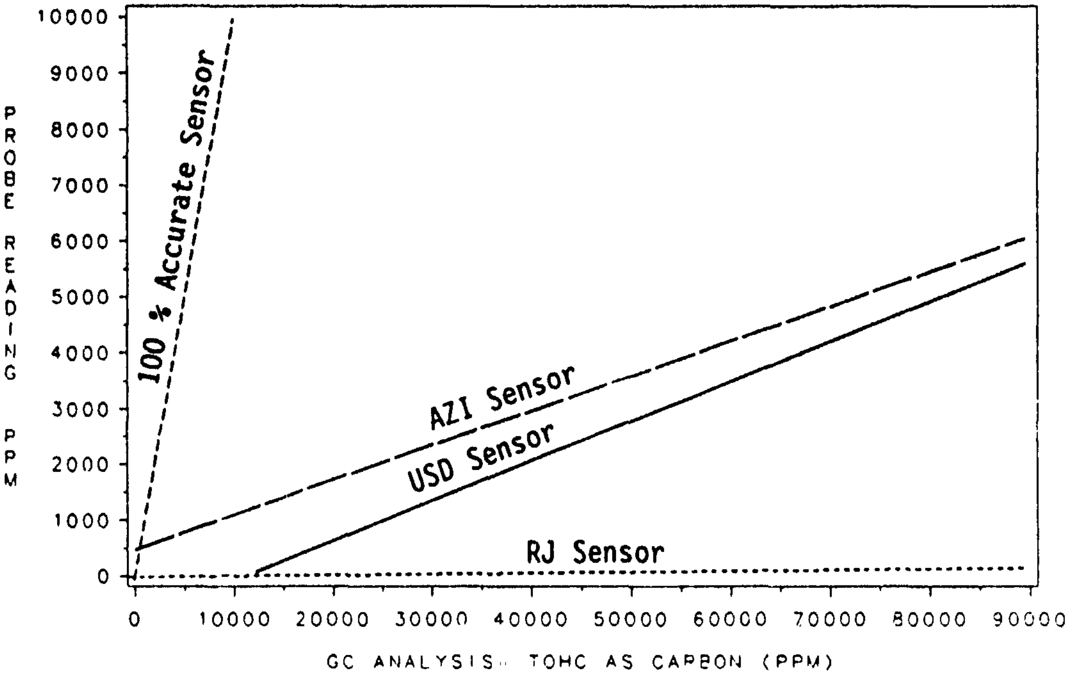


Figure C-52. Predicted Values From the Regressions of TOHC Concentrations From the GC Analyses Versus Concentrations Recorded From the Sensors 5.5 Feet From the Source of JP-4 Relative to a Hypothetical Sensor Which is 100% Accurate.

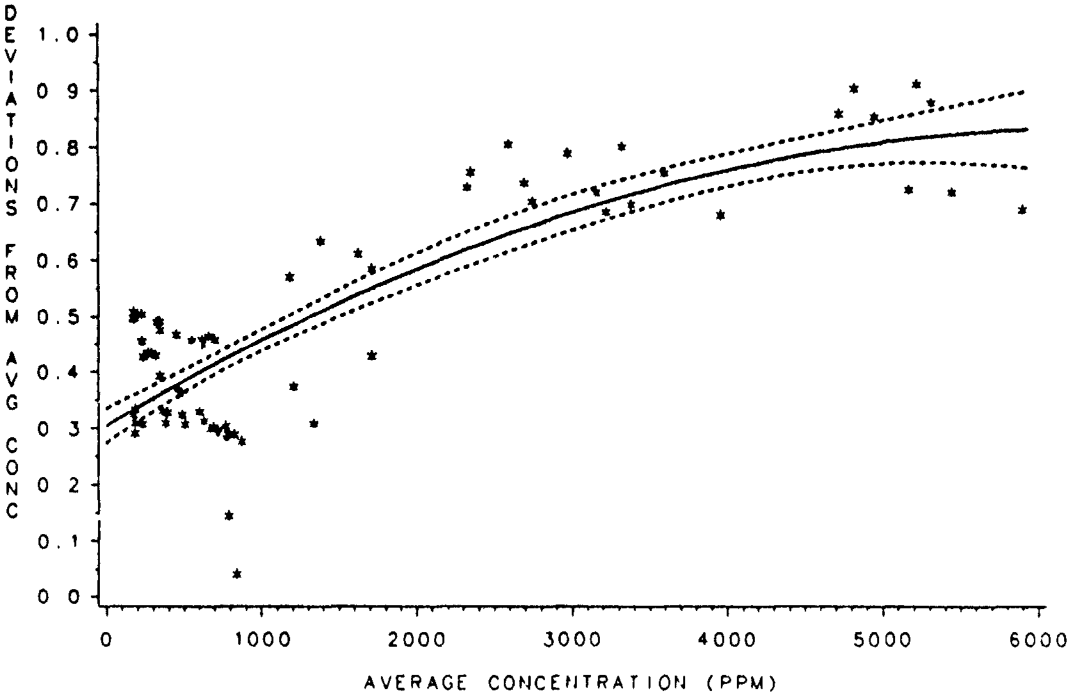


Figure C-53. Quadratic Regression and Associated 95% Confidence Intervals for the Deviation Values (Differences Between Concentrations Recorded From Replicate Sensors) Versus Average Concentrations Recorded by Replicate USD Sensors 3.0 Feet From the Source of JP-4 (See Text for the Regression Equation).

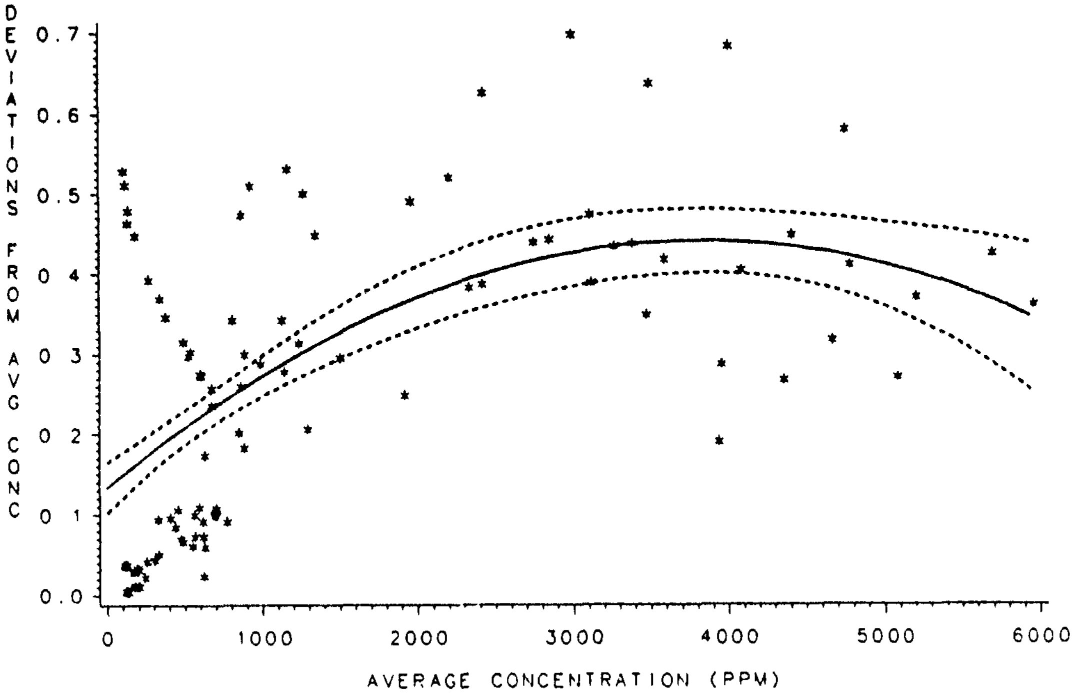


Figure C-54. Quadratic Regression and Associated 95% Confidence Intervals for the Deviation Values (Differences Between Concentrations Recorded From Replicate Sensors) Versus Average Concentrations Recorded by Replicate USD Sensors 5.5 Feet From the Source of JP-4 (See Text for the Regression Equation).

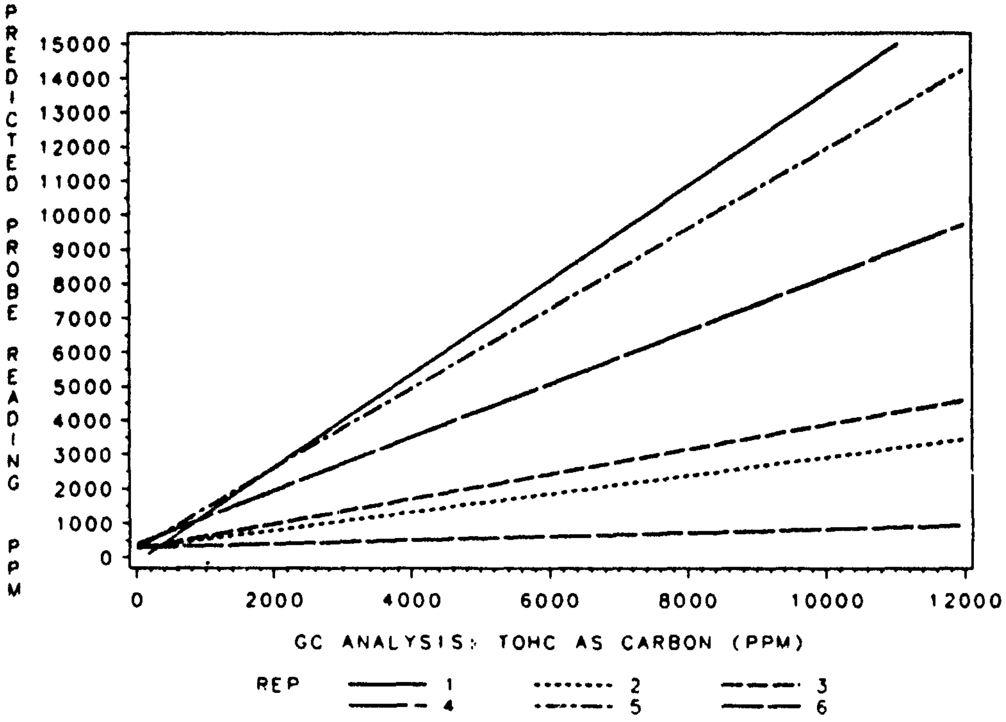


Figure C-55. Linear Regression of Device Readings and TOHC Values for Each of the USD Sensors Located at 3 Feet From the Source in Vapor-Phase Dry Sand Study.

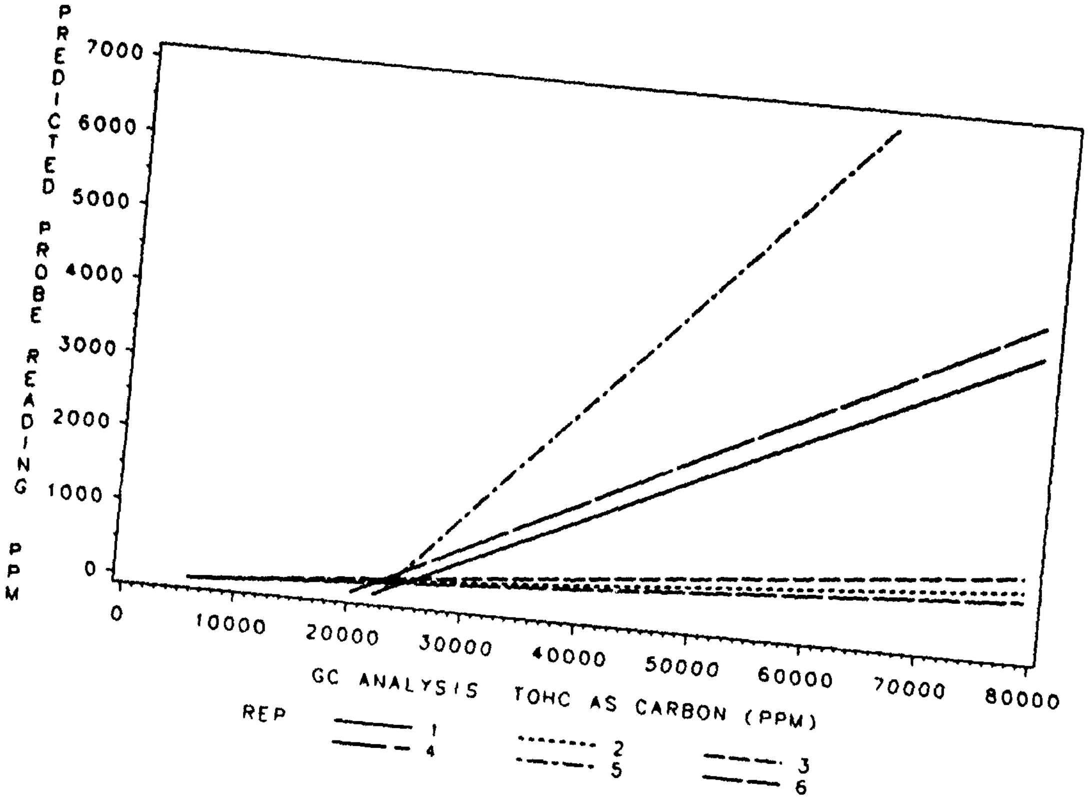


Figure C-56. Linear Regression of Device Readings and TOHC Values for Each of the USD Sensors Located at 5.5 Feet From the Source in Vapor-Phase Dry Sand Study.

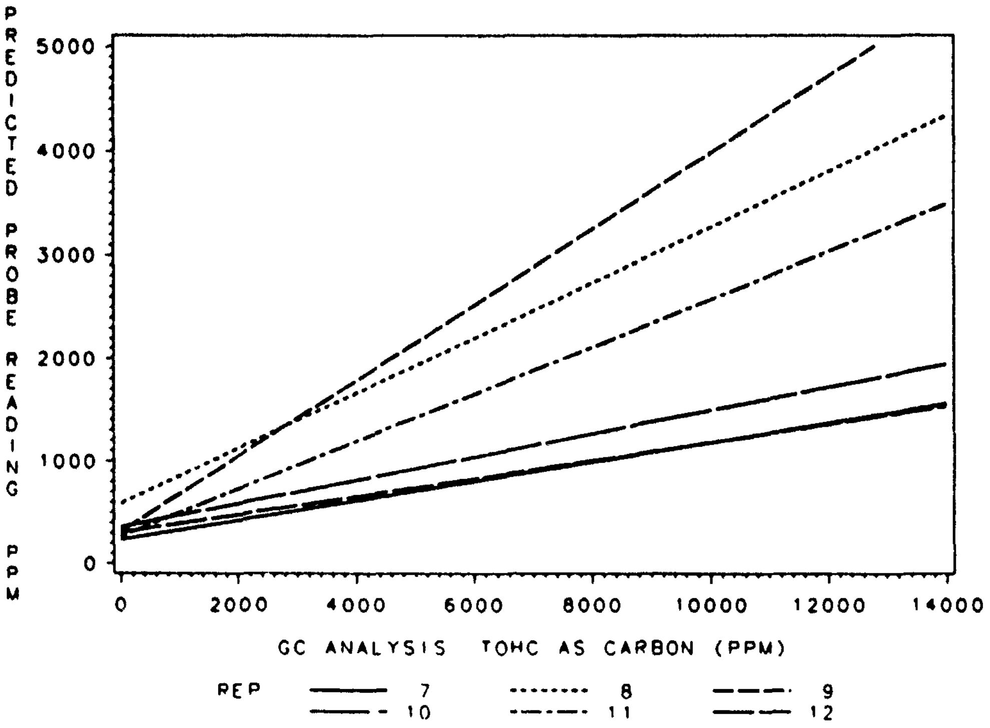


Figure C-57. Linear Regression of Device Readings and TOHC Values for Each of the USD Sensors Located at 3 Feet From the Source in Vapor-Phase Wet Sand Study.

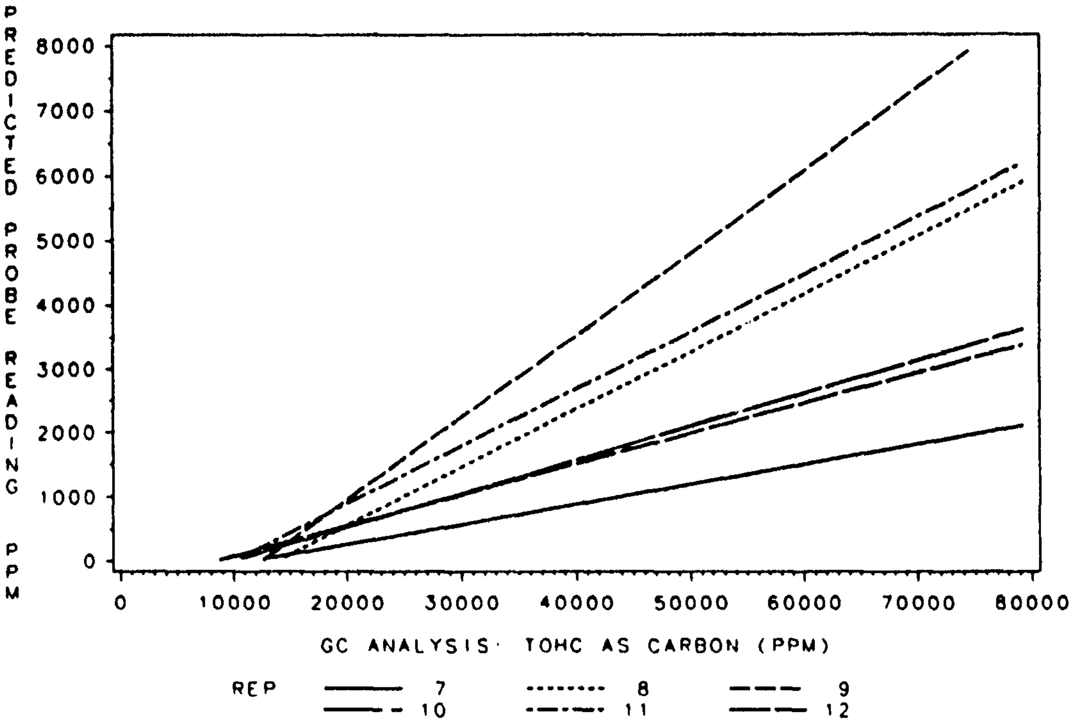


Figure C-58. Linear Regression of Device Readings and TOHC Values for Each of the USD Sensors Located at 5.5 Feet From the Source in Vapor-Phase Wet Sand Study.

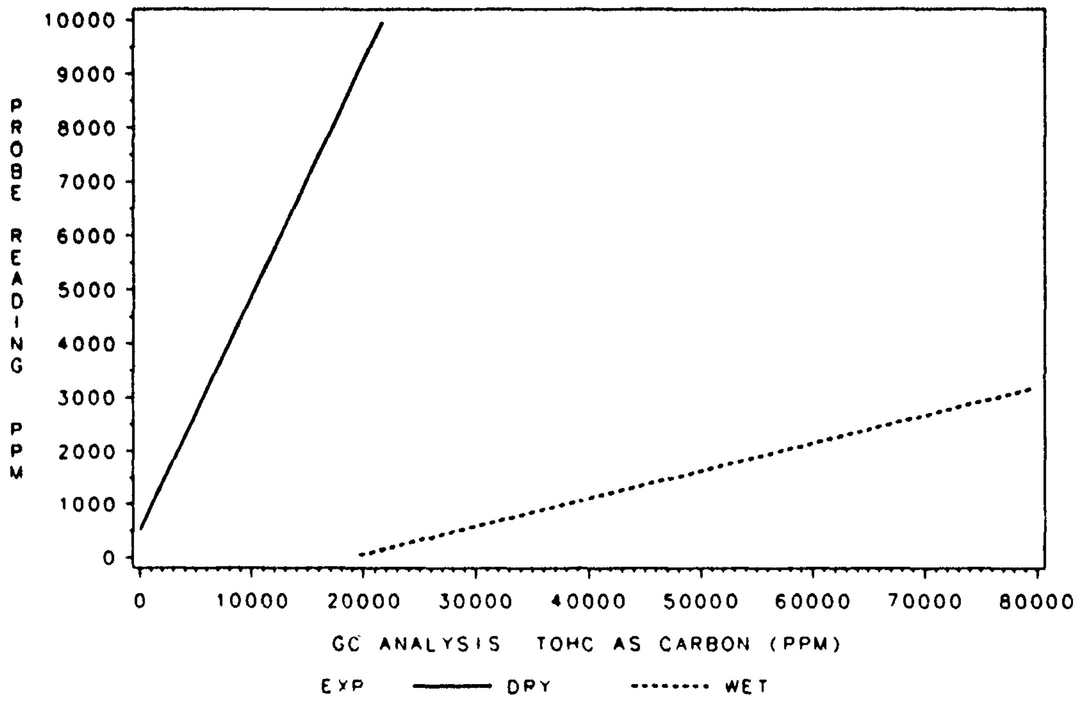


Figure C-59. Predicted Concentrations From Linear Regressions for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the USD Sensors 3 Feet From the Source of JP-4 for Dry and Wet Sand Experiments.

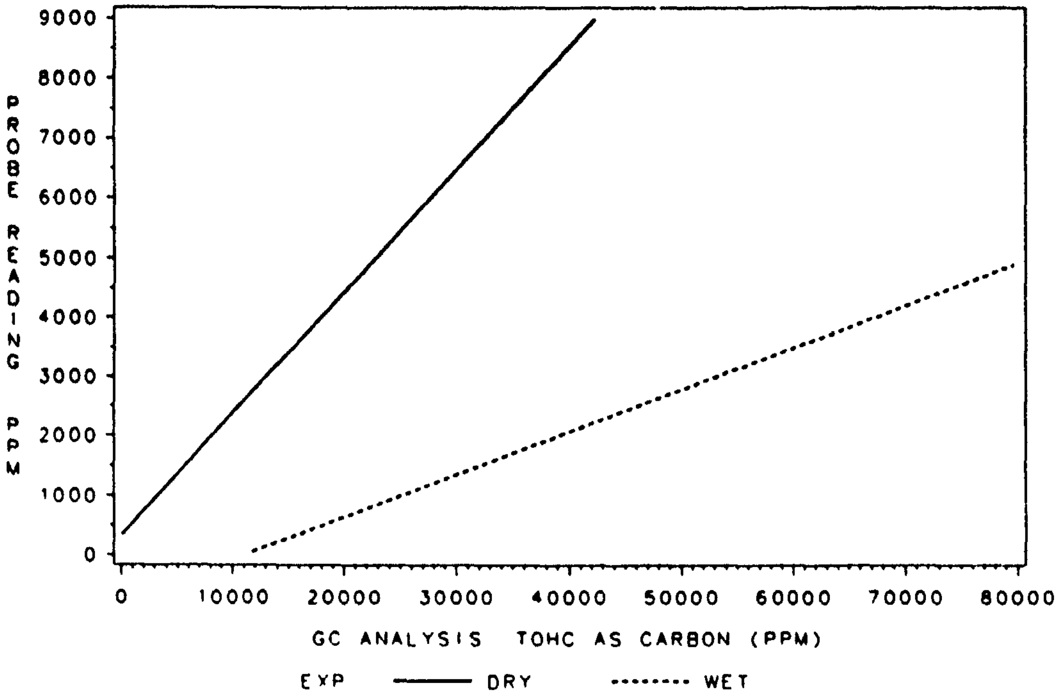


Figure C-60. Predicted Concentrations From Linear Regressions for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the USD Sensors 5.5 Feet From the Source of JP-4 for Dry and Wet Sand Experiments.

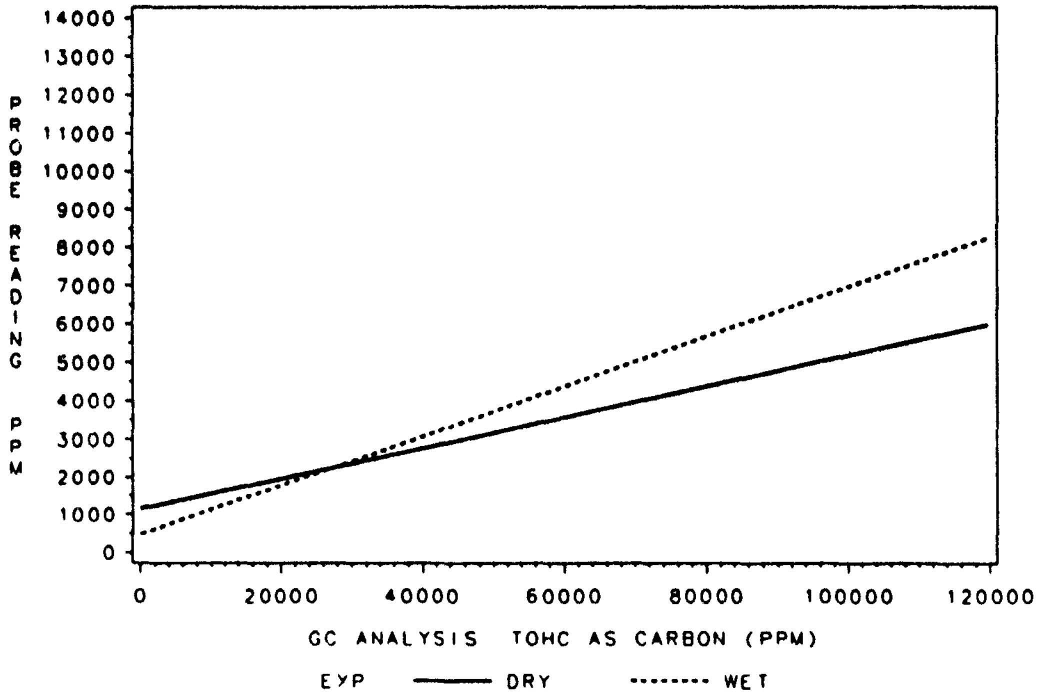
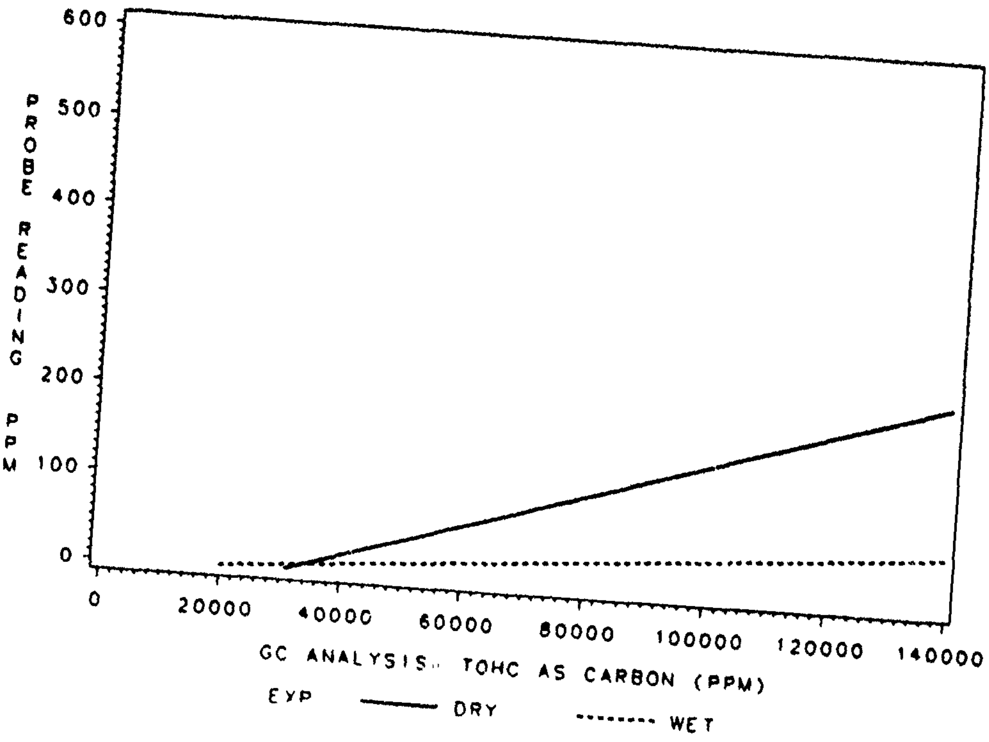


Figure C-61. Predicted Concentrations From Linear Regressions for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the AZI Sensor 5.5 Feet From the Source of JP-4 for Dry and Wet Sand Experiments.



Figurè C-62. Predicted Concentrations From Linear Regressions for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the RJ Sensors 3 Feet From the Source of JP-4 for Dry and Wet Sand Experiments.

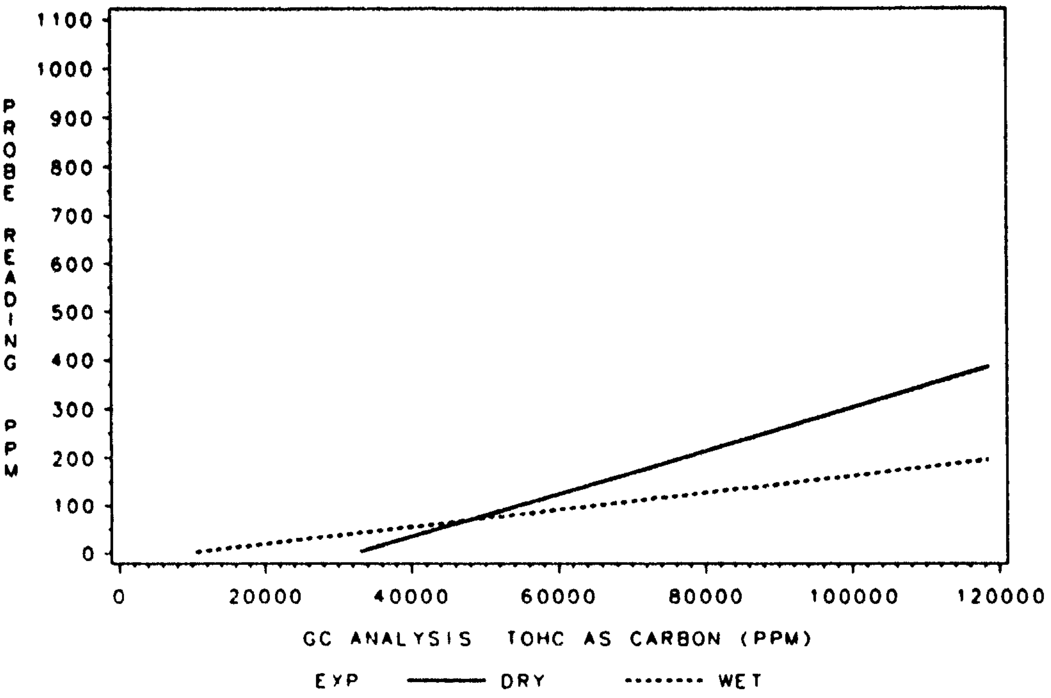


Figure C-63. Predicted Concentrations From Linear Regressions for the TOHC Concentrations Recorded From GC Analyses Versus Concentrations Recorded From the RJ Sensors 5.5 Feet From the Source of JP-4 for Dry and Wet Sand Experiments.

RESPONSE OF FCI: WELL B

VAPOR PHASE / FRESH JP-4 / DRY SAND

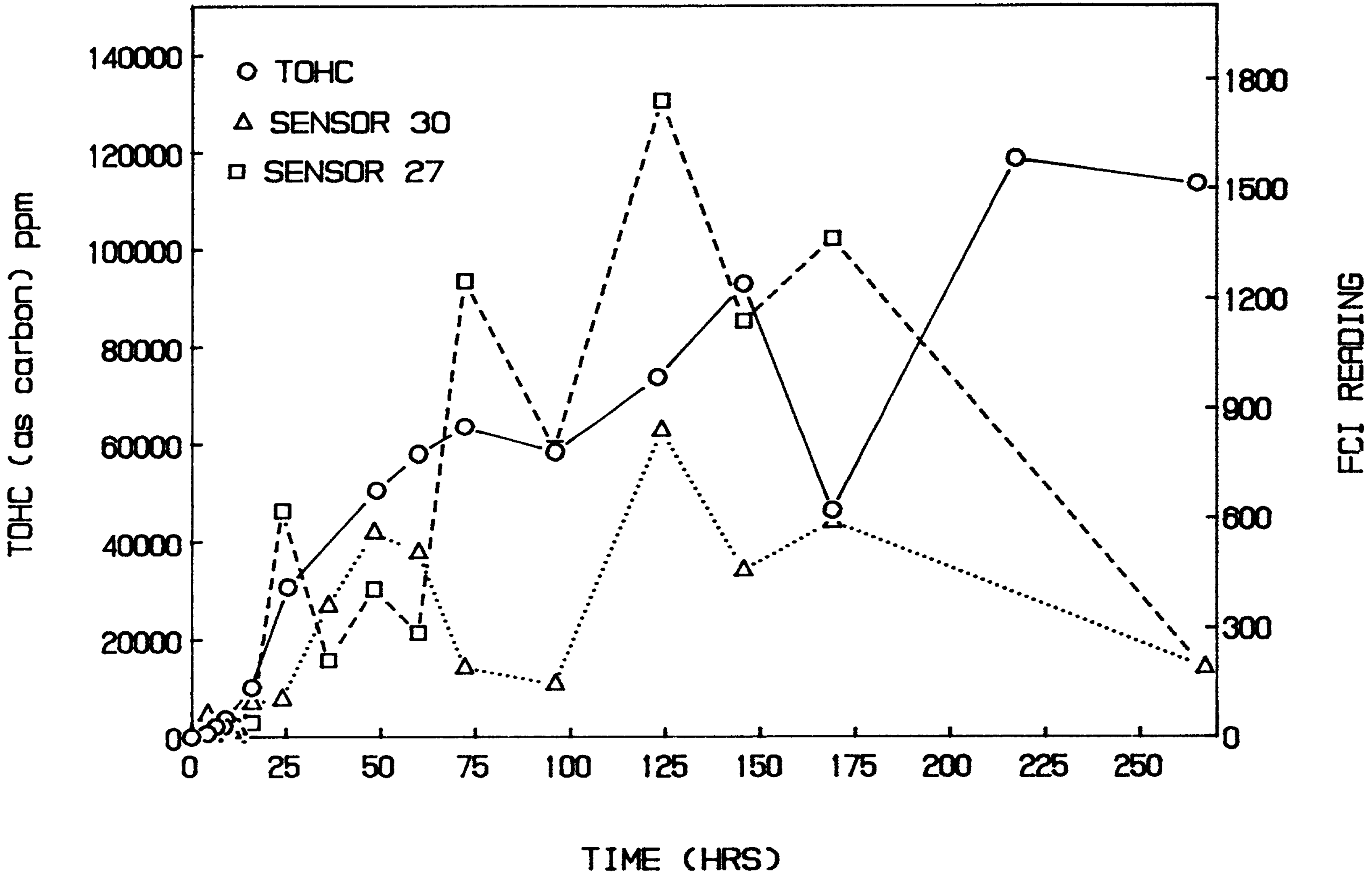


FIGURE C-G4

RESPONSE OF FCI: WELL C

VAPOR PHASE / FRESH JP-4 / DRY SAND

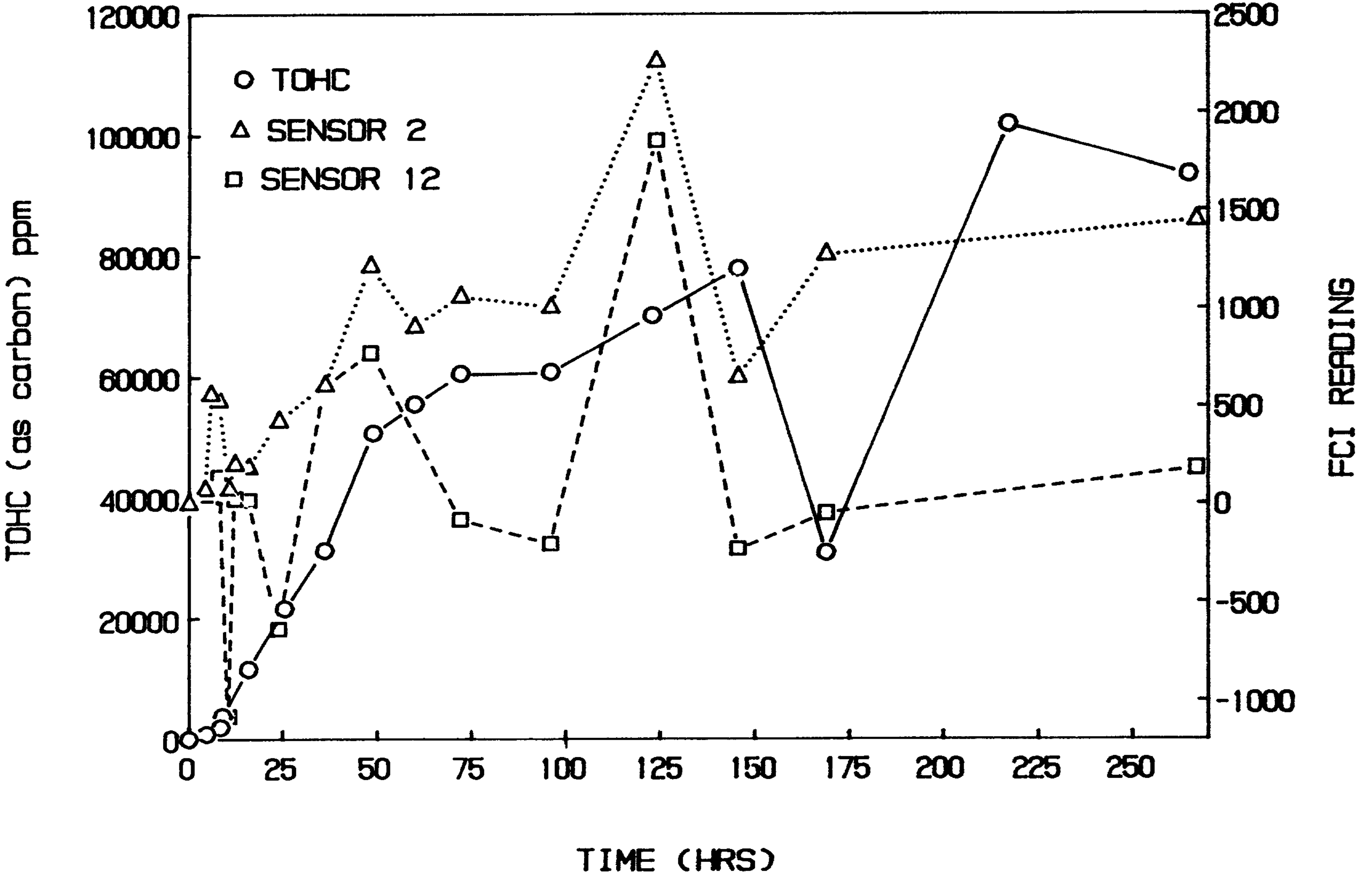


FIGURE C-65

RESPONSE OF FCI: WELL D

VAPOR PHASE / FRESH JP-4 / DRY SAND

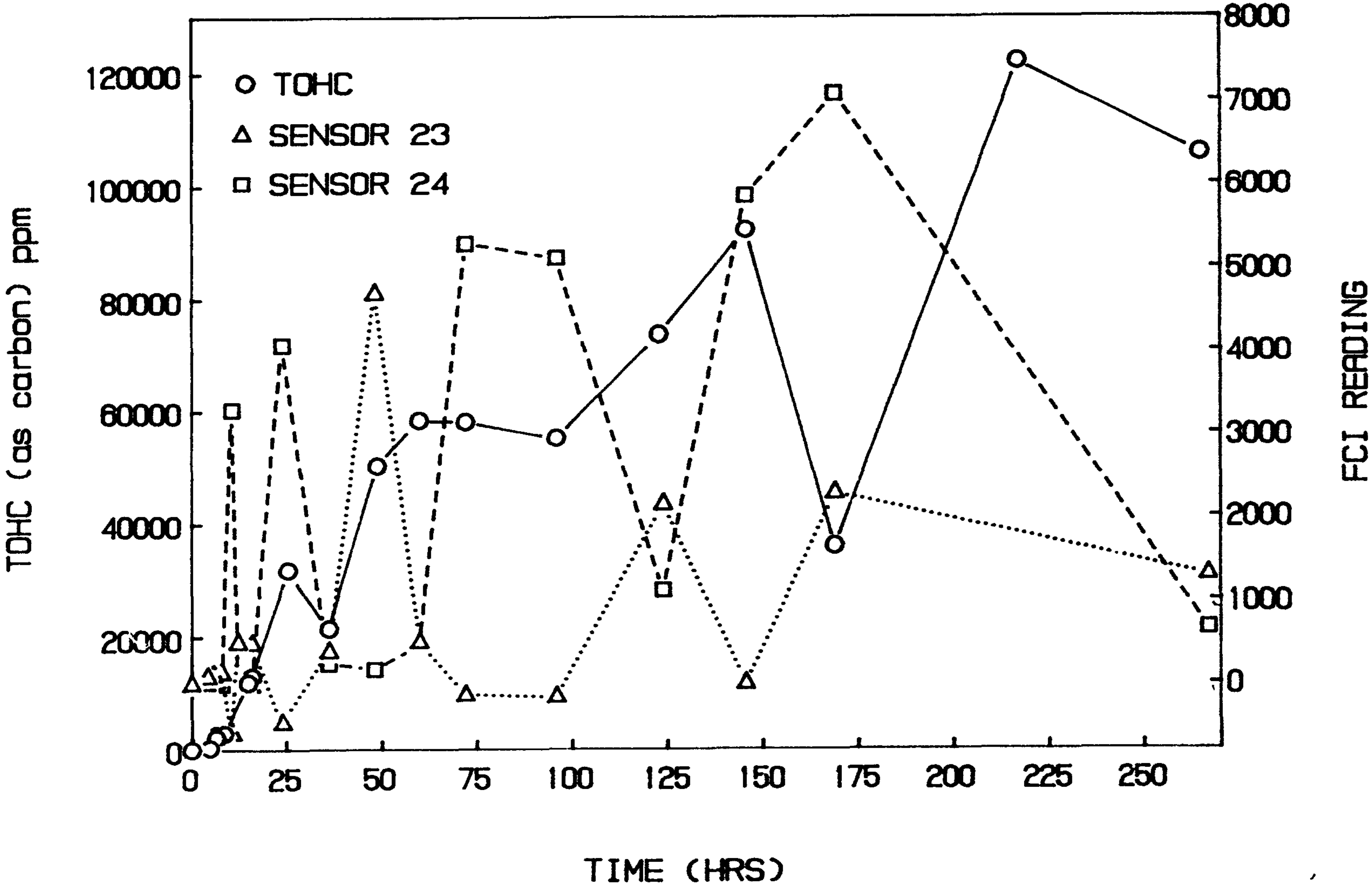
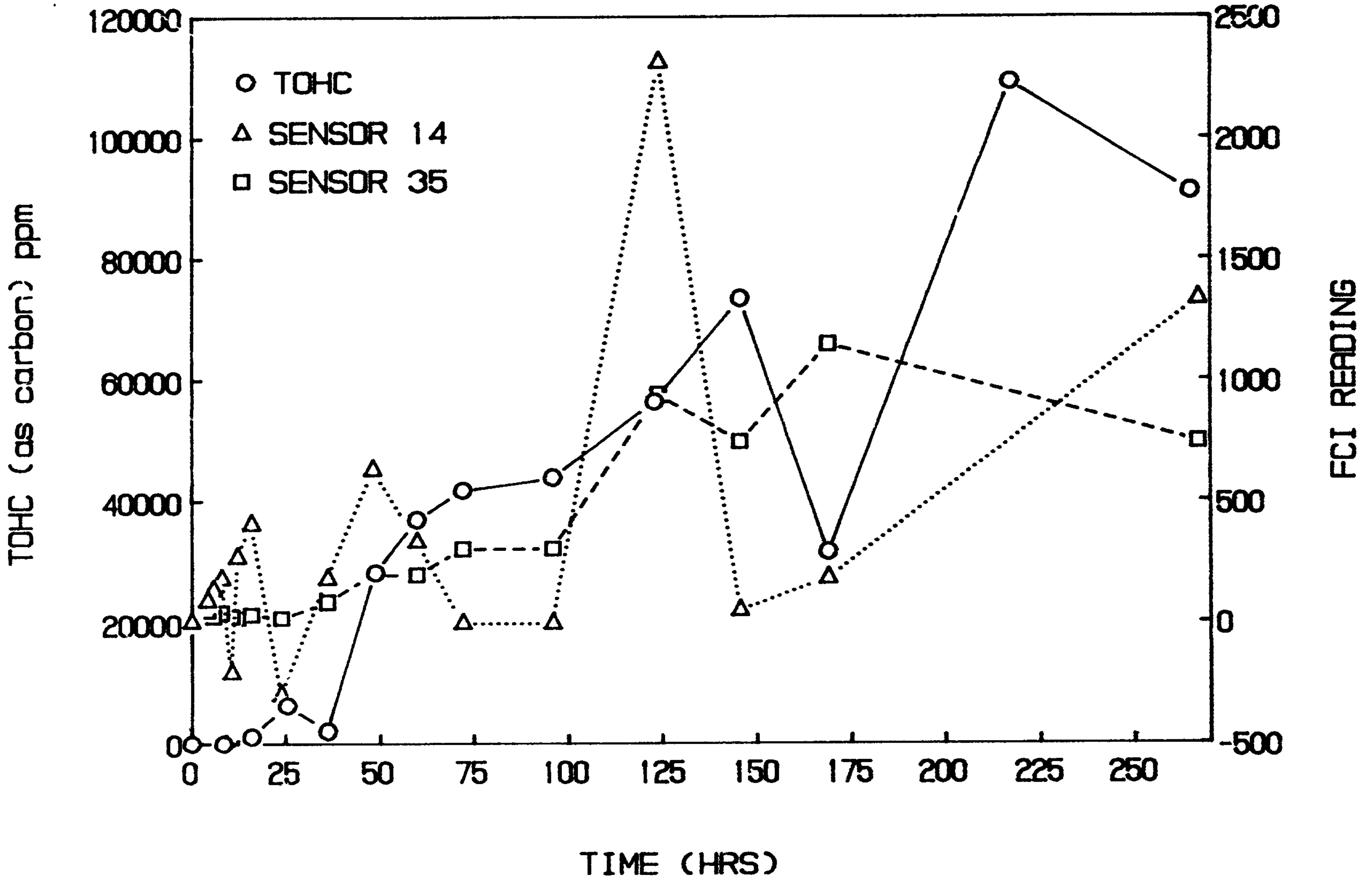


FIGURE C-66



RESPONSE OF FCI: WELL F

VAPOR PHASE / FRESH JP-4 / DRY SAND

FIGURE C-67

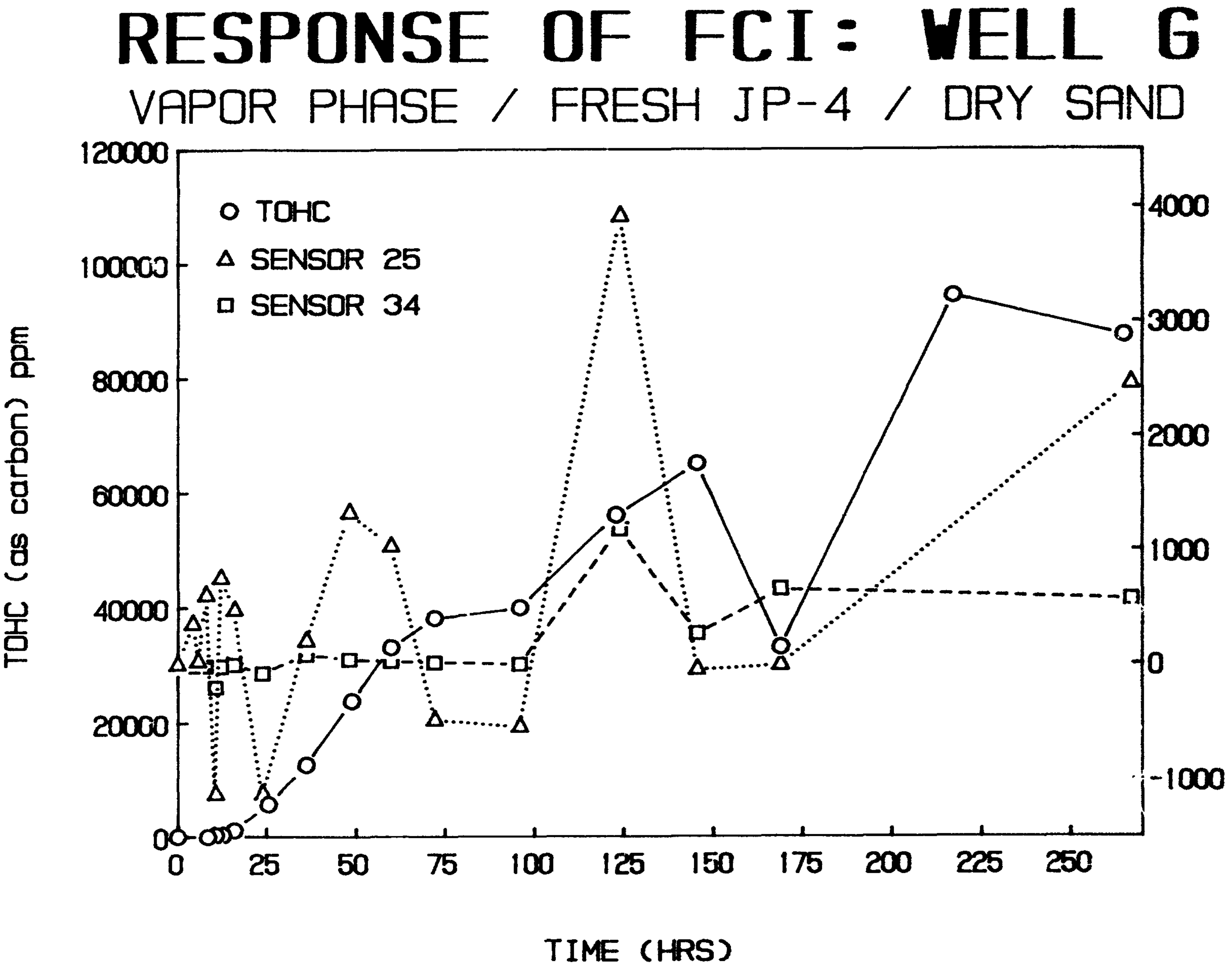

RESPONSE OF FCI: WELL G
VAPOR PHASE / FRESH JP-4 / DRY SAND
TOHC
SENSOR 25
SENSOR 34
TOHC (as carbon) ppm
0
20000
40000
60000
80000
100000
120000
FCI READING
-1000
0
1000
2000
3000
4000
TIME (HRS)
0
25
50
75
100
125
150
175
200
225
250

FIGURE C-68

RESPONSE OF FCI: WELL H

VAPOR PHASE / FRESH JP-4 / DRY SAND

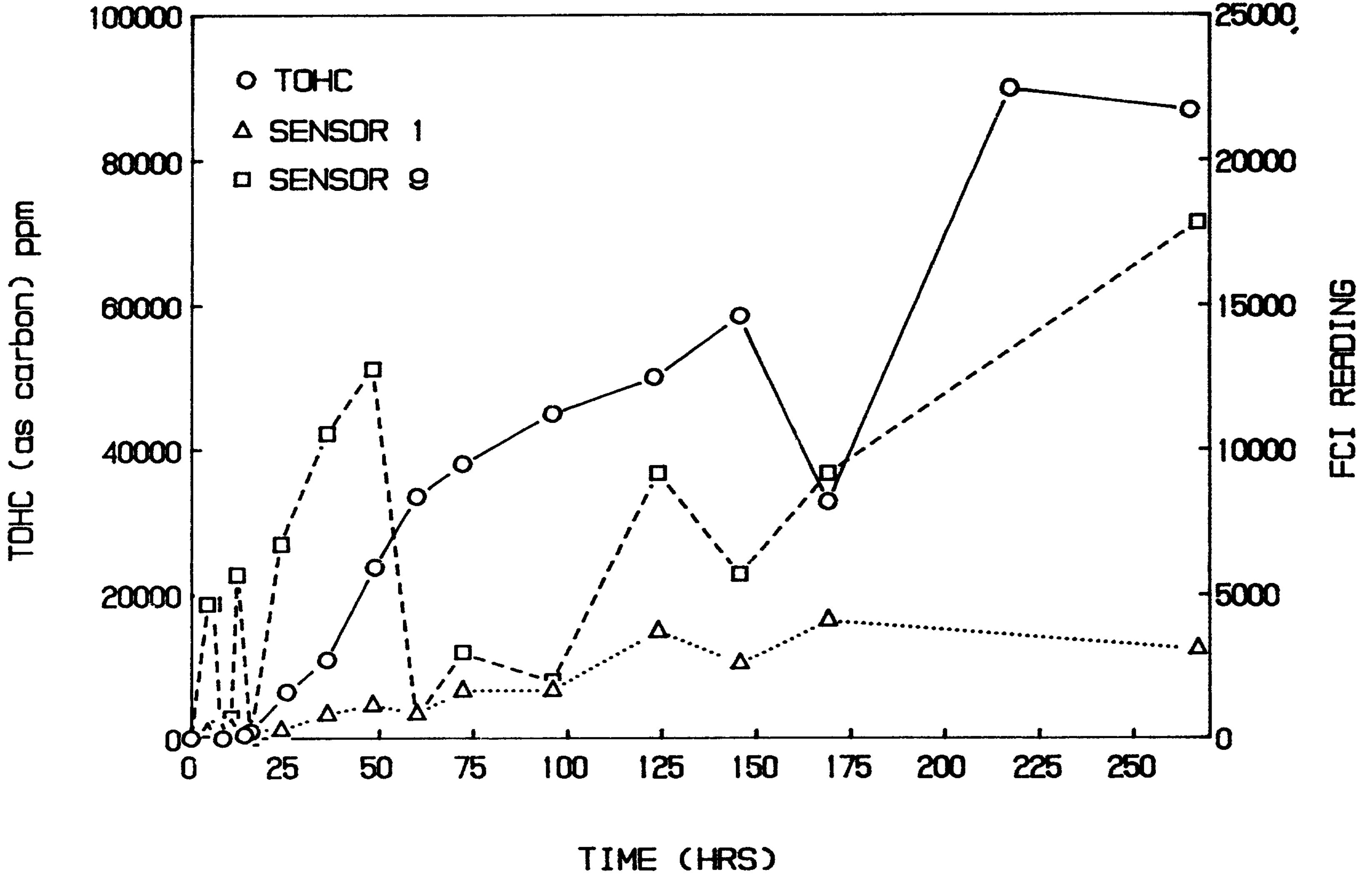
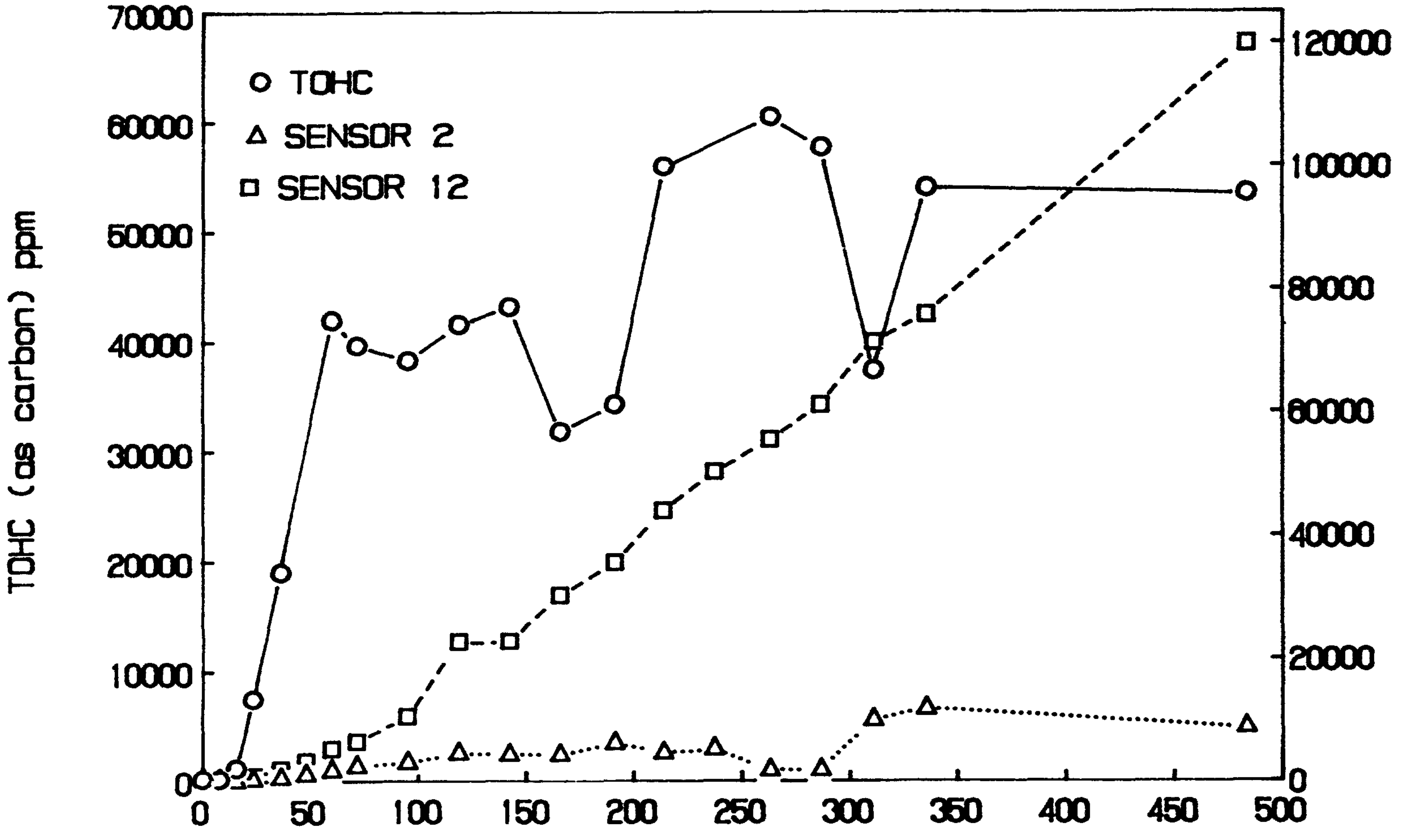


FIGURE C-69

RESPONSE OF FCI: WELL H

VAPOR PHASE / FRESH JP-4 / WET SAND



FIGURE

RESPONSE OF FCI: WELL H

VAPOR PHASE / AGED JP-4 / WET SAND

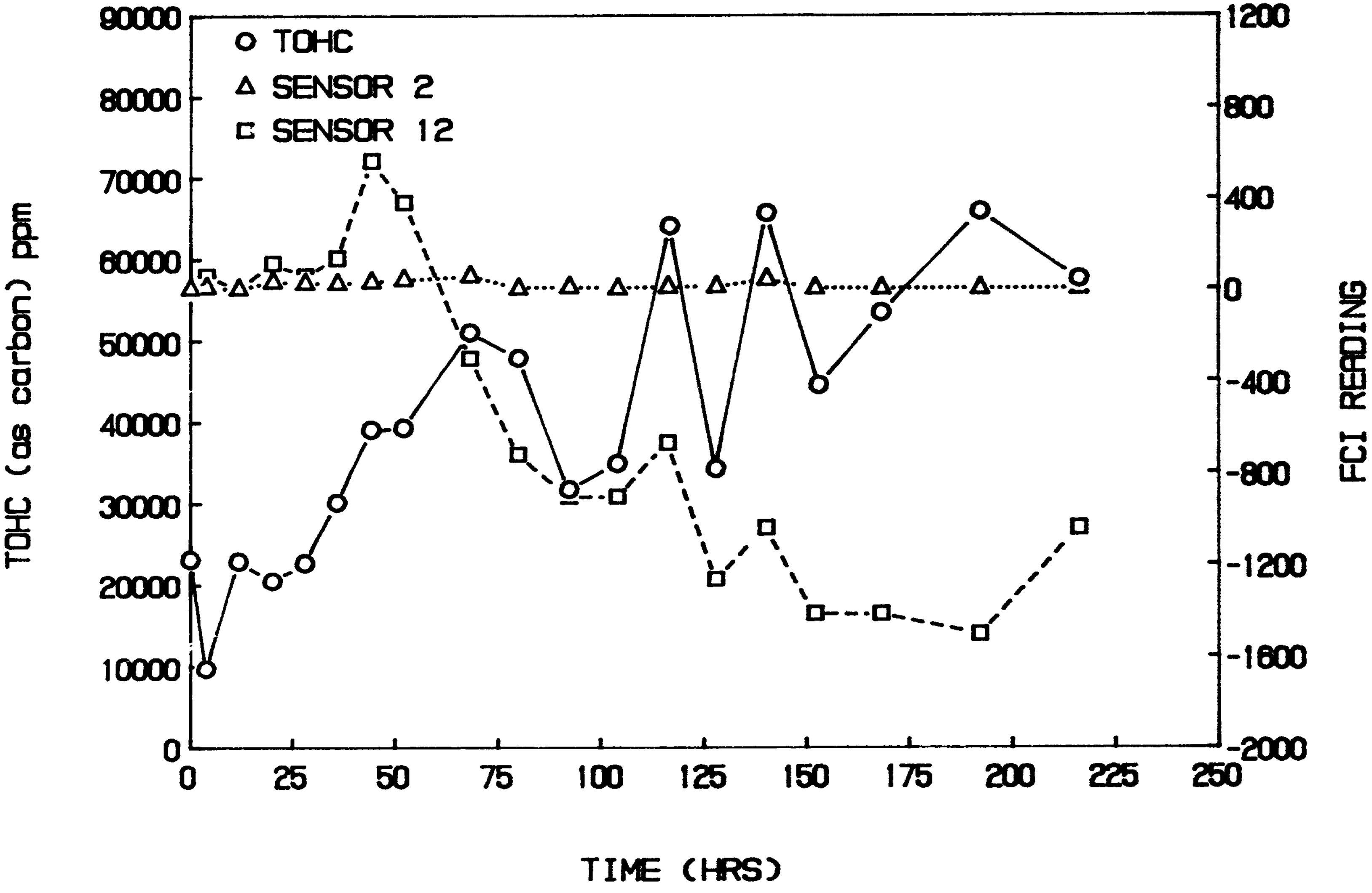


FIGURE C-71

APPENDIX D

RESULTS OF AGED JP-4/WET SAND TANK TEST

TABLE D-1. TEMPERATURE DATA FOR AGED JP-4 STUDY

TIME (hours)	ROOM TEMP (°C)	SAND TEMP 1 (°C)	SAND TEMP 2 (°C)
0.00	20	17	17
14.00	22	17	17
20.20	24	17	18
28.12	23	18	18
36.00	22	18	18
44.00	24	18	18
52.00	24	19	19
68.00	24	19	19
80.00	23	19	19
92.00	24	19	19
116.00	23	20	20
128.00	22	20	20
140.00	25	20	20
168.00	23	20	20
192.00	23	20	20
216.00	21	19	19

TABLE D-2. MOISTURE CONTENT DATA FOR WET SAND AGED JP-4 STUDIES

Sample depth (inches)	Time (hours)	% Moisture(a)
0-6	0	1.57
6-11	0	1.93
11-16	0	2.00
16-21	0	1.86
21-26	0	1.64
26-31	0	1.52
31-36	0	1.84
36-41	0	5.65
0-6	216	1.18
6-11	216	1.38
11-16	216	1.56
16-21	216	1.42
21-26	216	1.32
26-31	216	1.21
31-36	216	1.56
36-41	216	14.70

(a) %Moisture = [Sample wet wt. - Sample dry wt.)/Sample dry wt.] x 100.

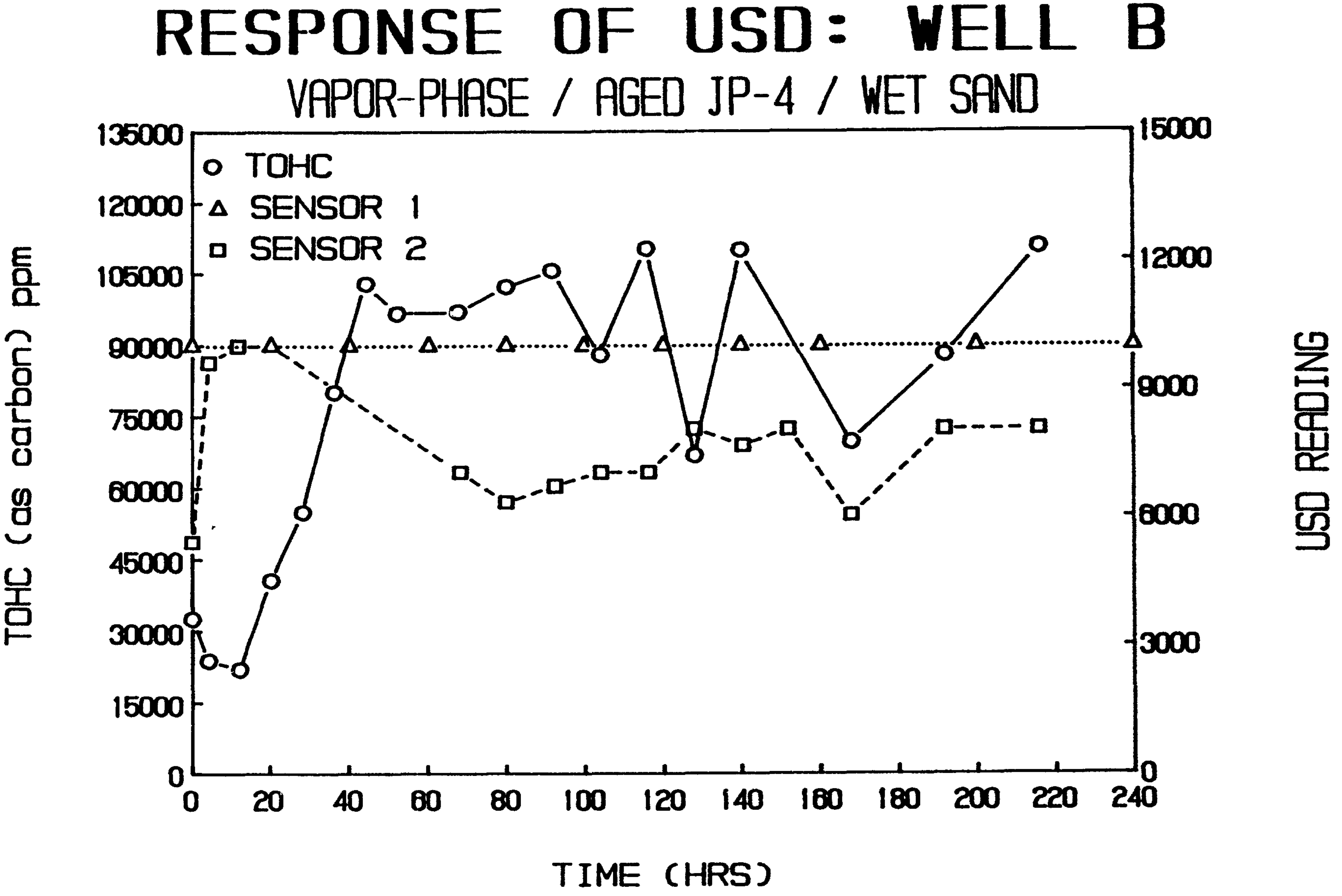

RESPONSE OF USD: WELL B
VAPOR-PHASE / AGED JP-4 / WET SAND
TOHC
SENSOR 1
SENSOR 2
TOHC (as carbon) ppm
135000
120000
105000
90000
75000
60000
45000
30000
15000
0
USD READING
15000
12000
9000
6000
3000
0
0
20
40
60
80
100
120
140
160
180
200
220
240
TIME (HRS)

FIGURE D-1

RESPONSE OF RJ: WELL B

VAPOR-PHASE/ AGED JP-4/ WET SAND

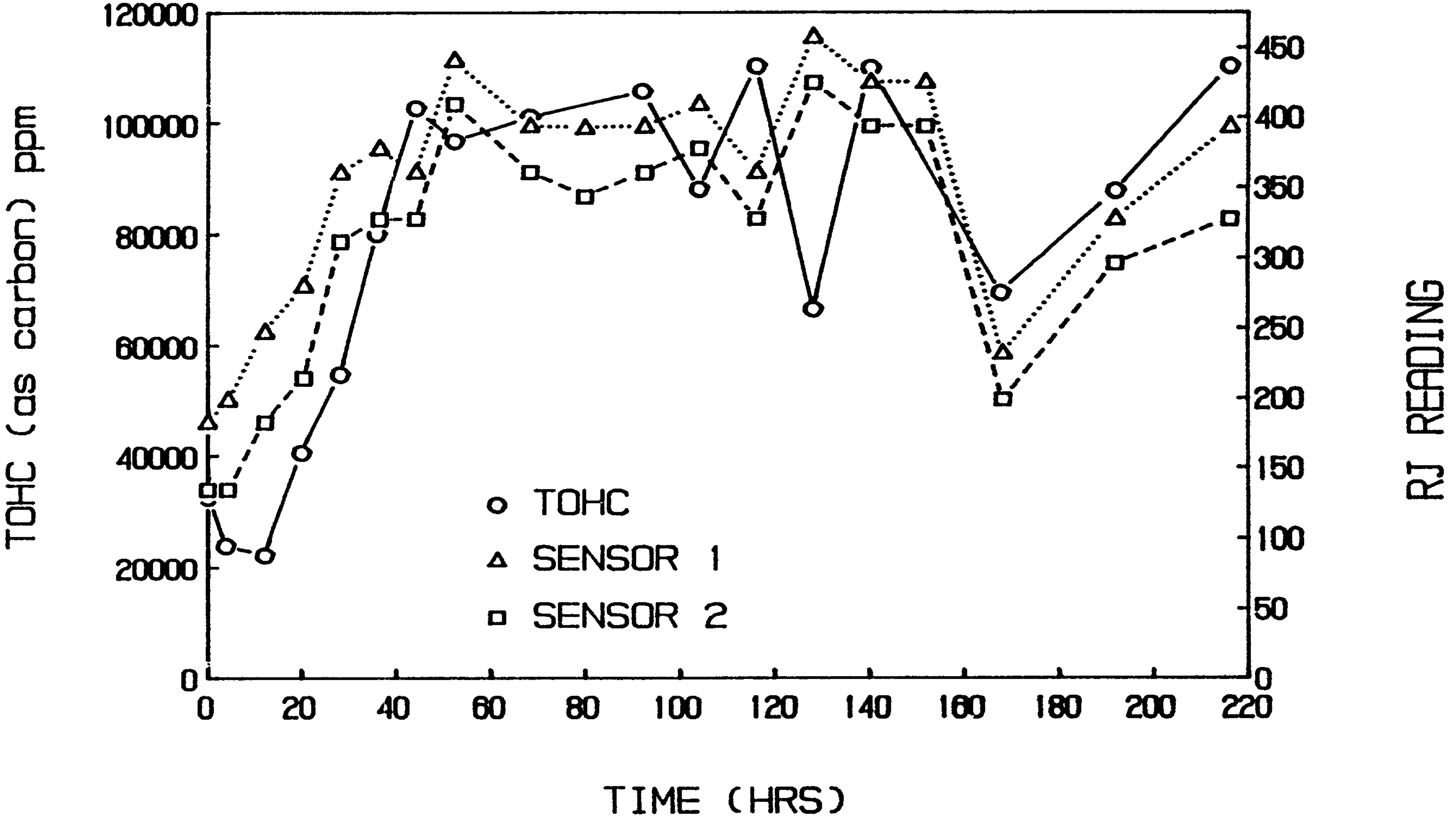


FIGURE D-2

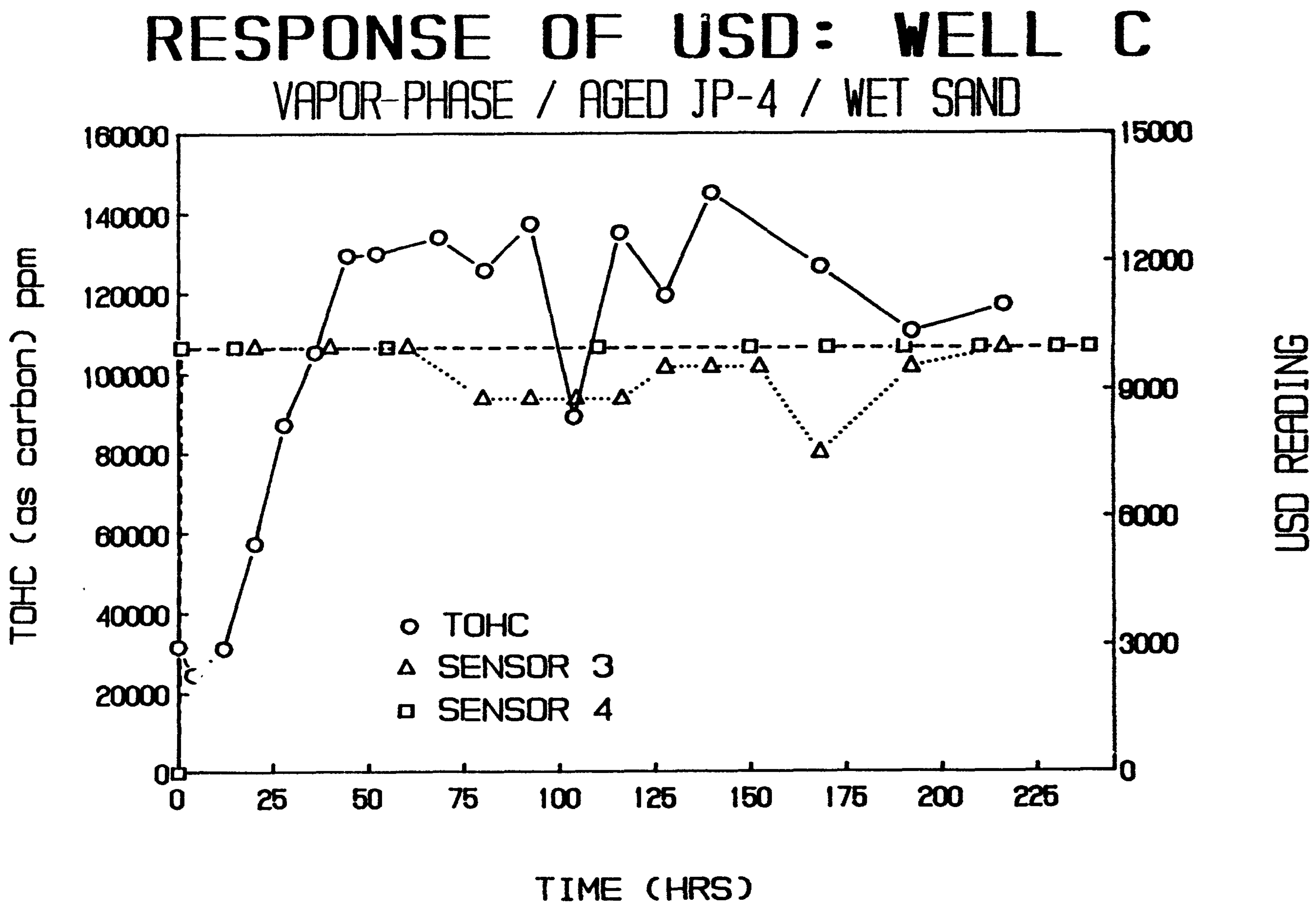

RESPONSE OF USD: WELL C
VAPOR-PHASE / AGED JP-4 / WET SAND
TOHC (as carbon) ppm
0
20000
40000
60000
80000
100000
120000
140000
160000
USD READING
0
3000
6000
9000
12000
15000
0
25
50
75
100
125
150
175
200
225
TIME (HRS)
○ TOHC
△ SENSOR 3
□ SENSOR 4

FIGURE D-3

RESPONSE OF RJ: WELL C

VAPOR-PHASE/ AGED JP-4/ WET SAND

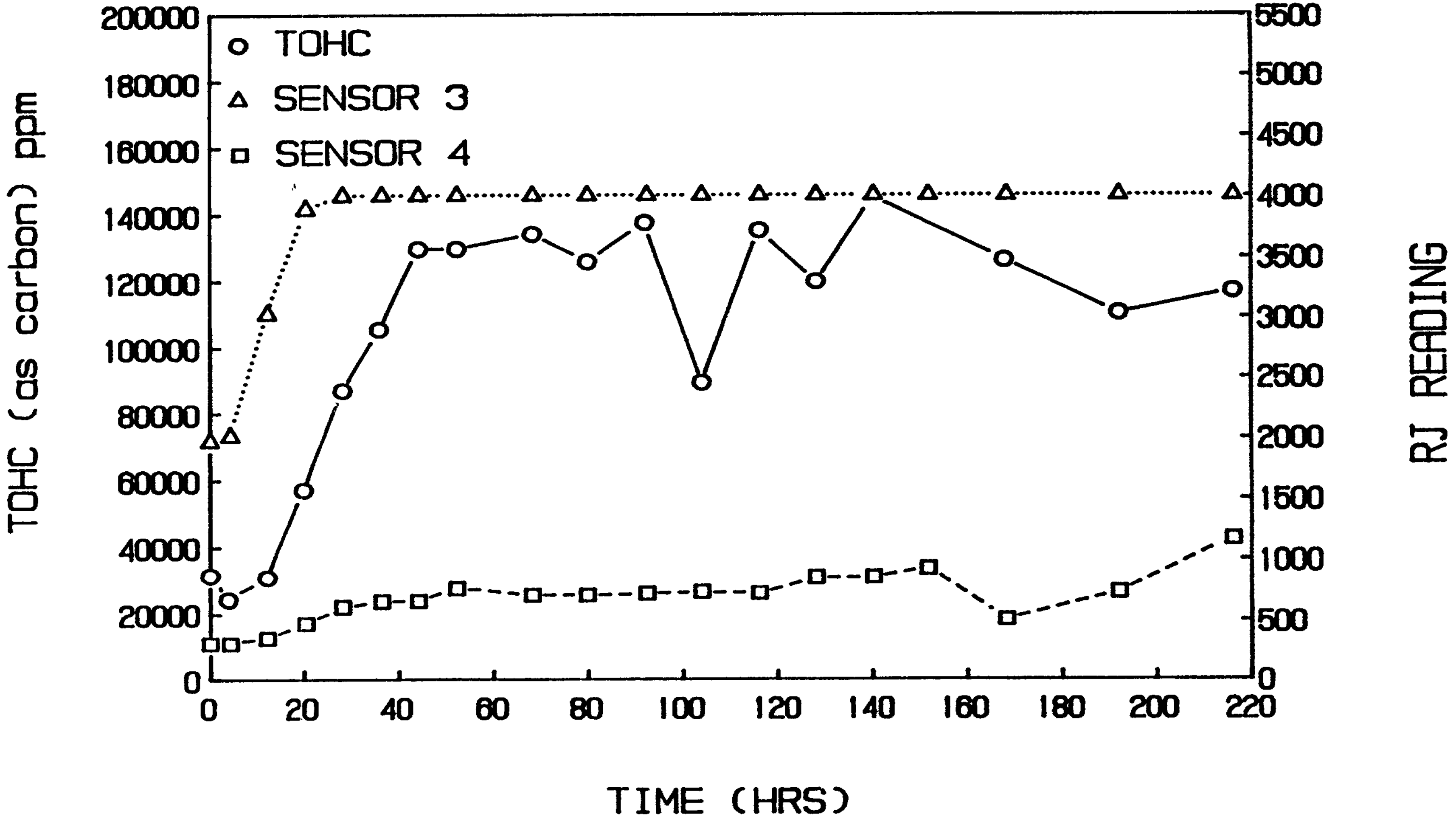


FIGURE D-4

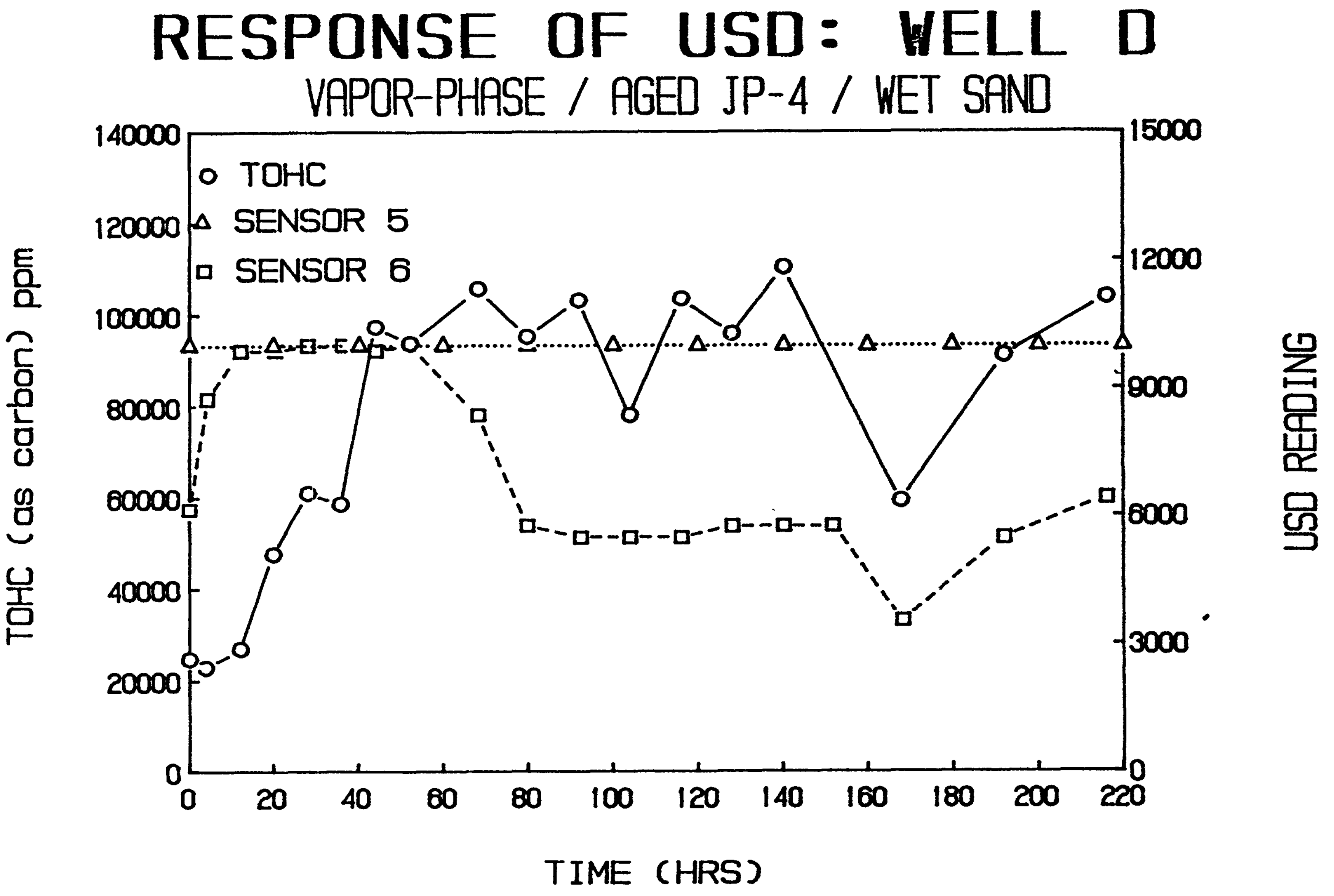

RESPONSE OF USD: WELL D
VAPOR-PHASE / AGED JP-4 / WET SAND
TOHC
SENSOR 5
SENSOR 6
TOHC (as carbon) ppm
140000
120000
100000
80000
60000
40000
20000
0
USD READING
15000
12000
9000
6000
3000
0
TIME (HRS)
0
20
40
60
80
100
120
140
160
180
200
220

FIGURE D-5

RESPONSE OF RJ: WELL D

VAPOR-PHASE/ AGED JP-4/ WET SAND

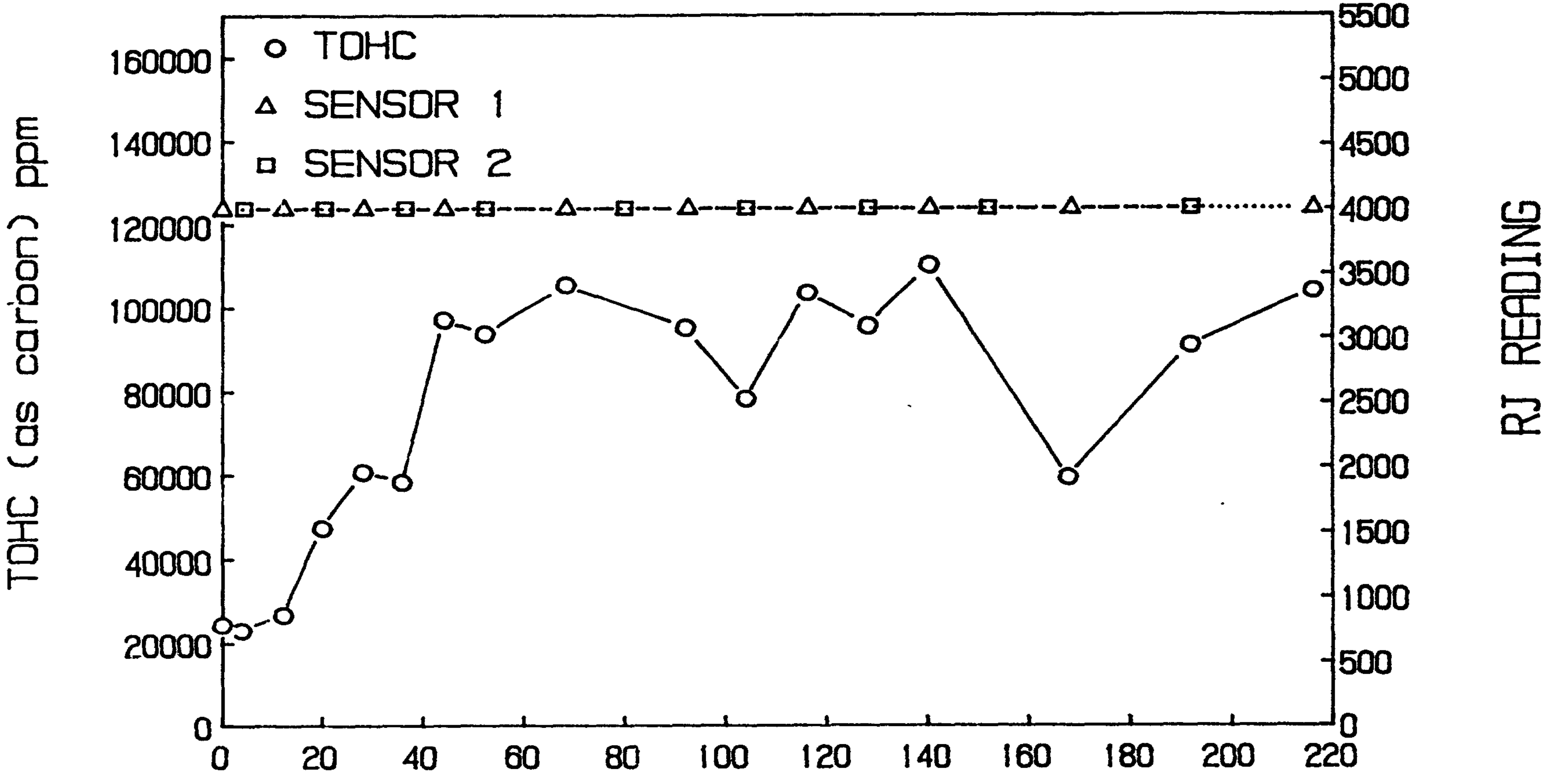


FIGURE D-6

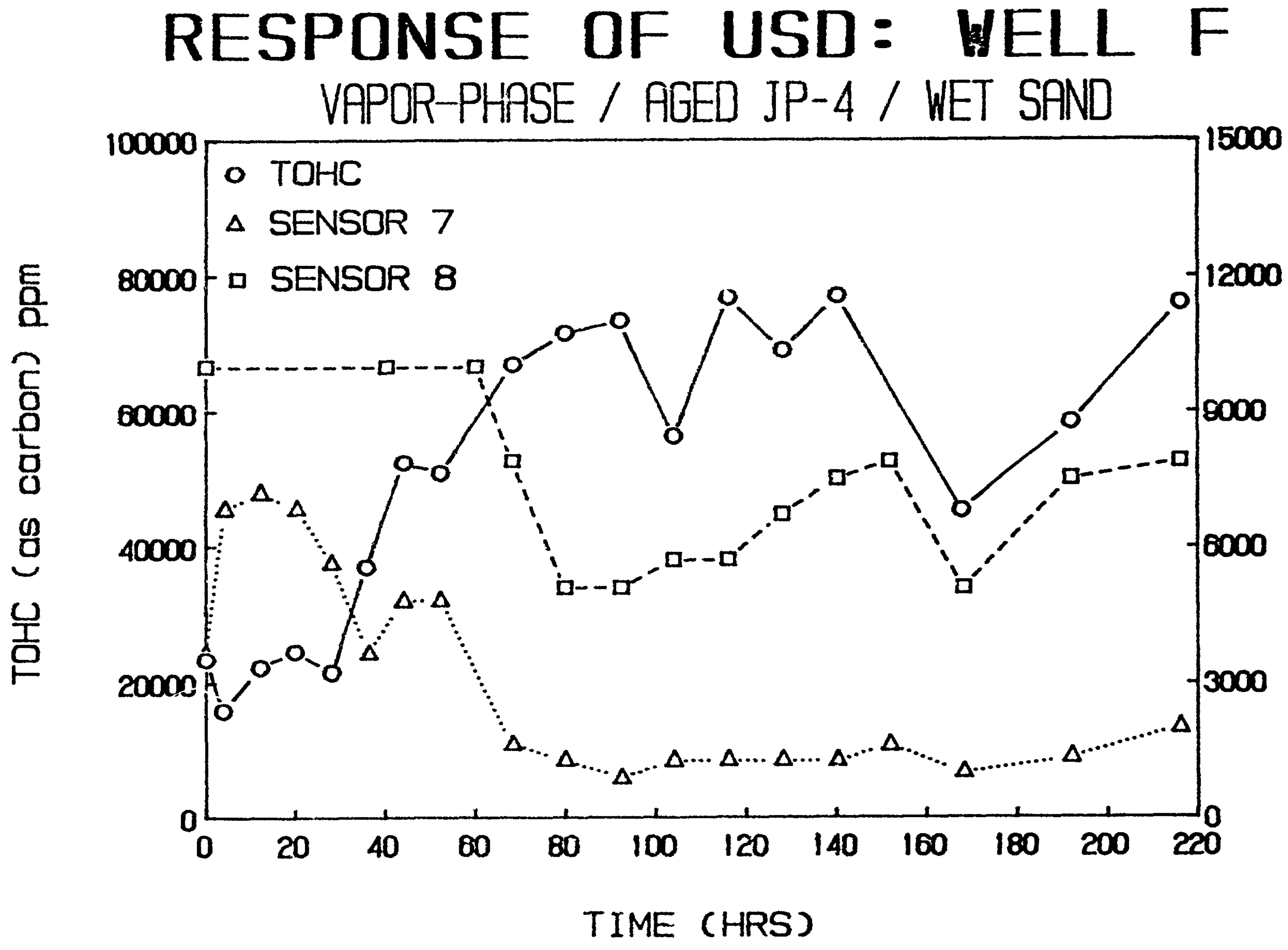

RESPONSE OF USD: WELL F
VAPOR-PHASE / AGED JP-4 / WET SAND
TOHC
SENSOR 7
SENSOR 8
TOHC (as carbon) ppm
100000
80000
60000
40000
20000
0
USD READING
15000
12000
9000
6000
3000
0
0
20
40
60
80
100
120
140
160
180
200
220
TIME (HRS)

FIGURE D-7

RESPONSE OF RJ: WELL F

VAPOR-PHASE/ AGED JP-4/ WET SAND

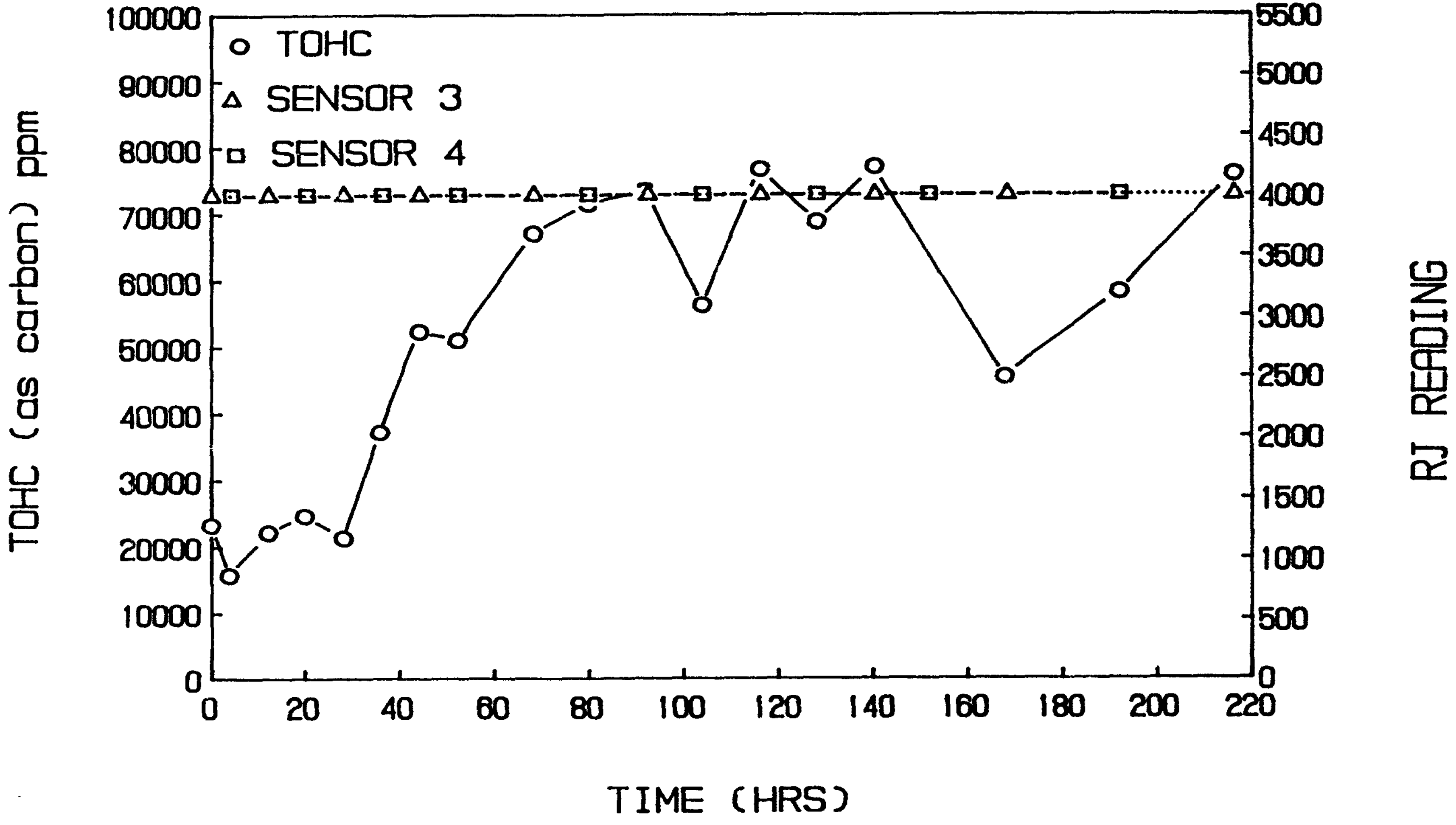


FIGURE D-8

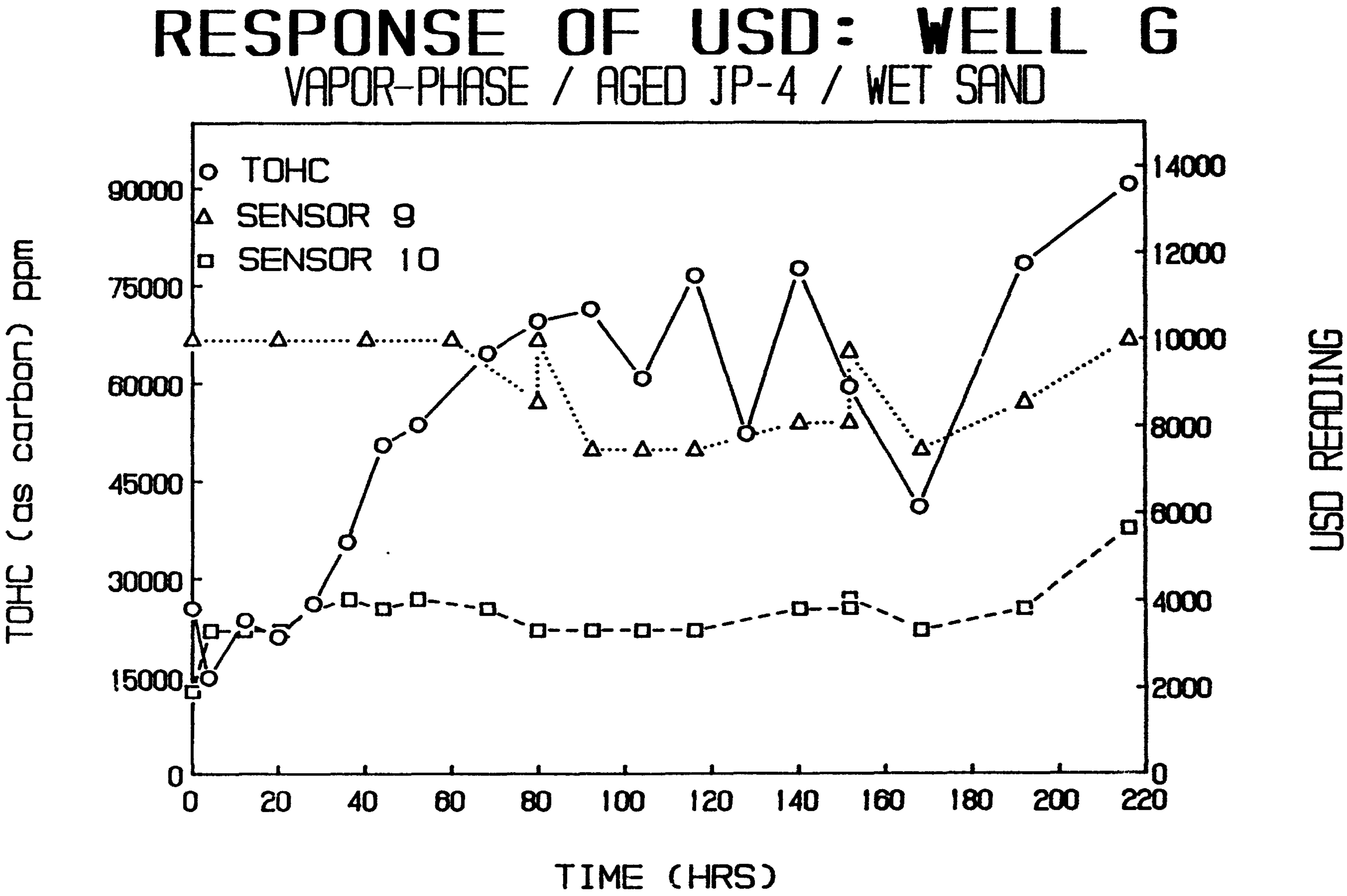

RESPONSE OF USD: WELL G
VAPOR-PHASE / AGED JP-4 / WET SAND
TOHC
SENSOR 9
SENSOR 10
TOHC (as carbon) ppm
0
15000
30000
45000
60000
75000
90000
USD READING
0
2000
4000
6000
8000
10000
12000
14000
TIME (HRS)
0
20
40
60
80
100
120
140
160
180
200
220

FIGURE D-9

RESPONSE OF RJ: WELL G

VAPOR-PHASE/ AGED JP-4/ WET SAND

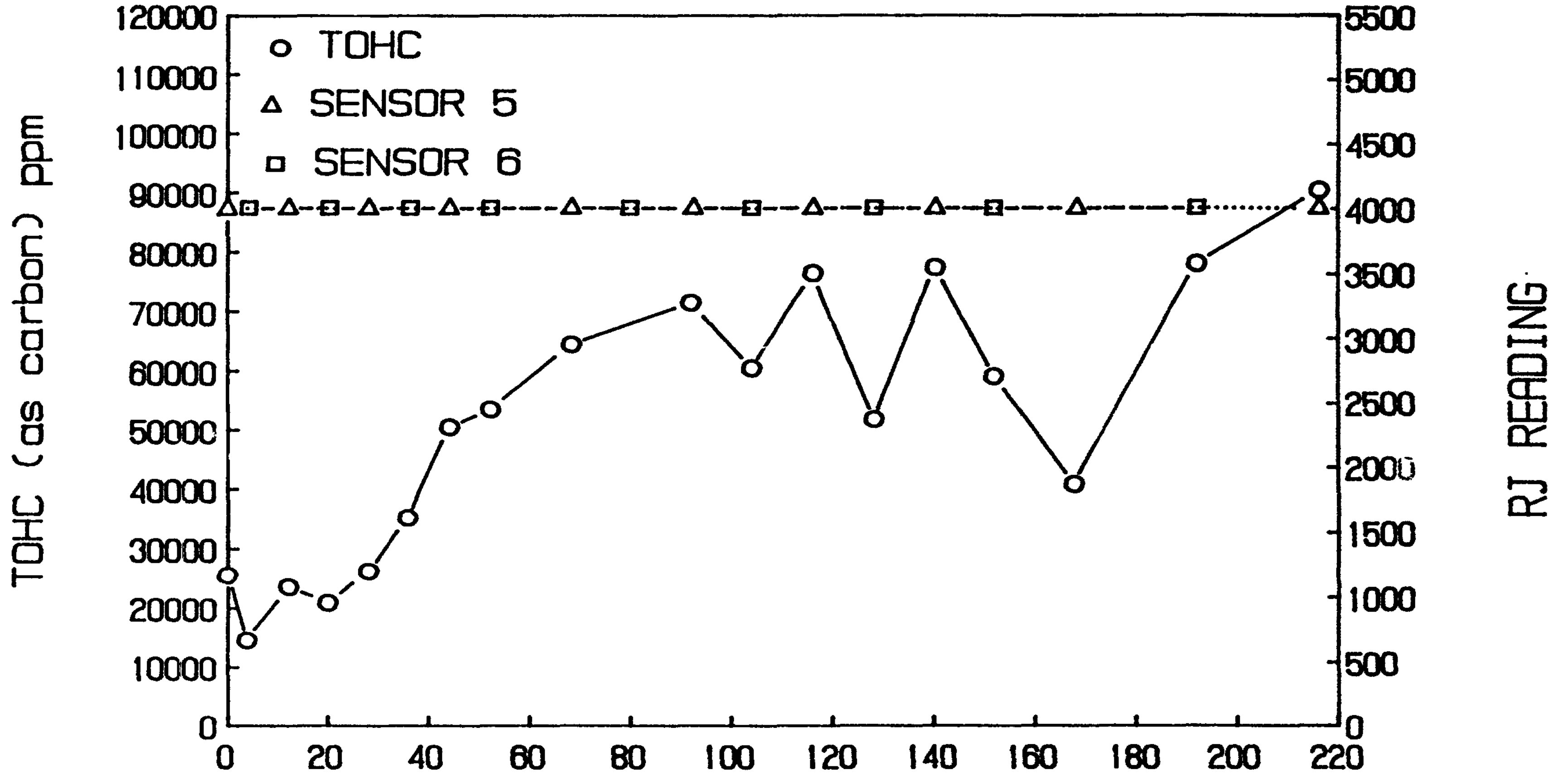


FIGURE D-10

RESPONSE OF USD: WELL H

VAPOR-PHASE/ AGED JP-4/ WET SAND

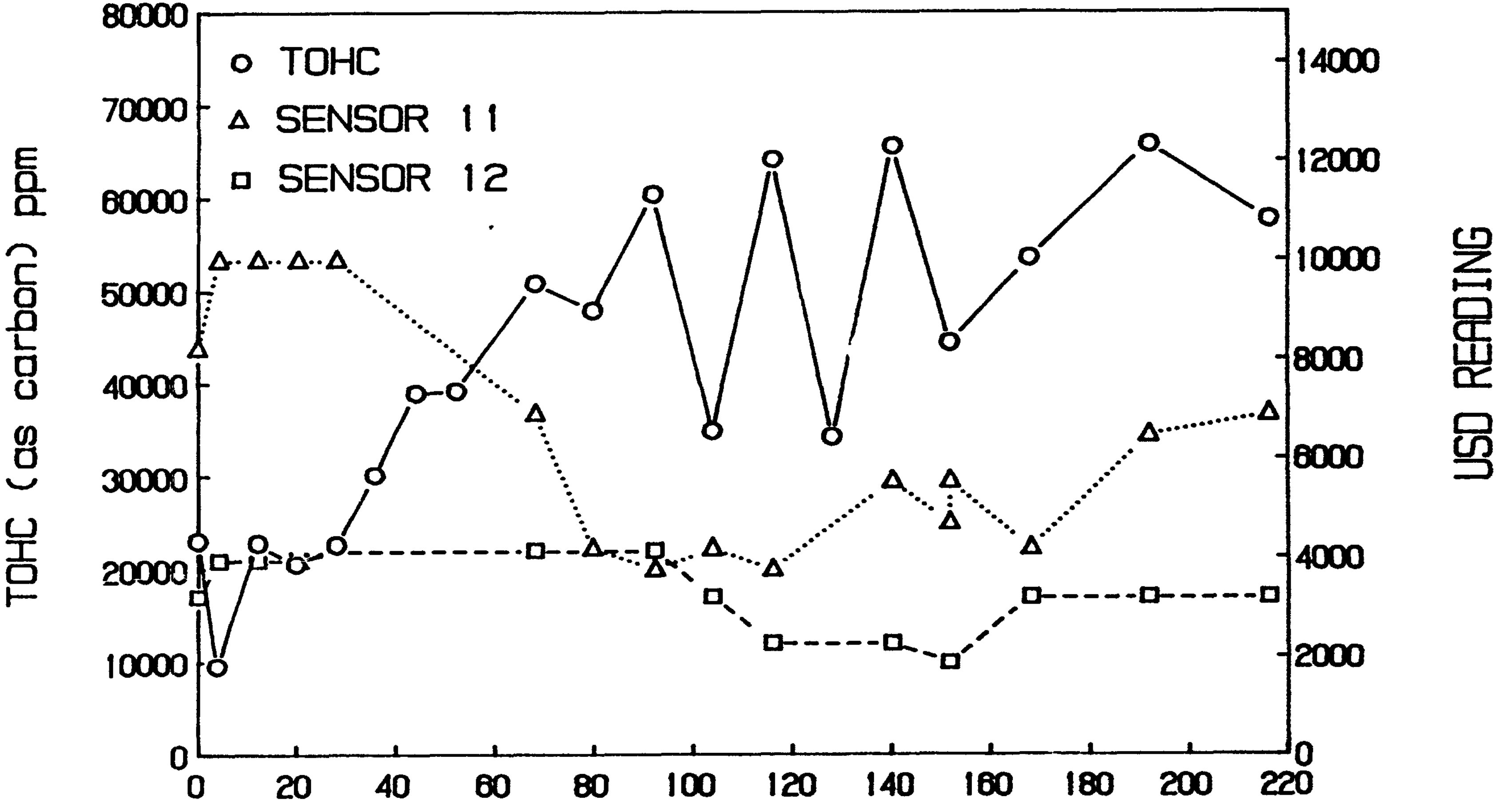
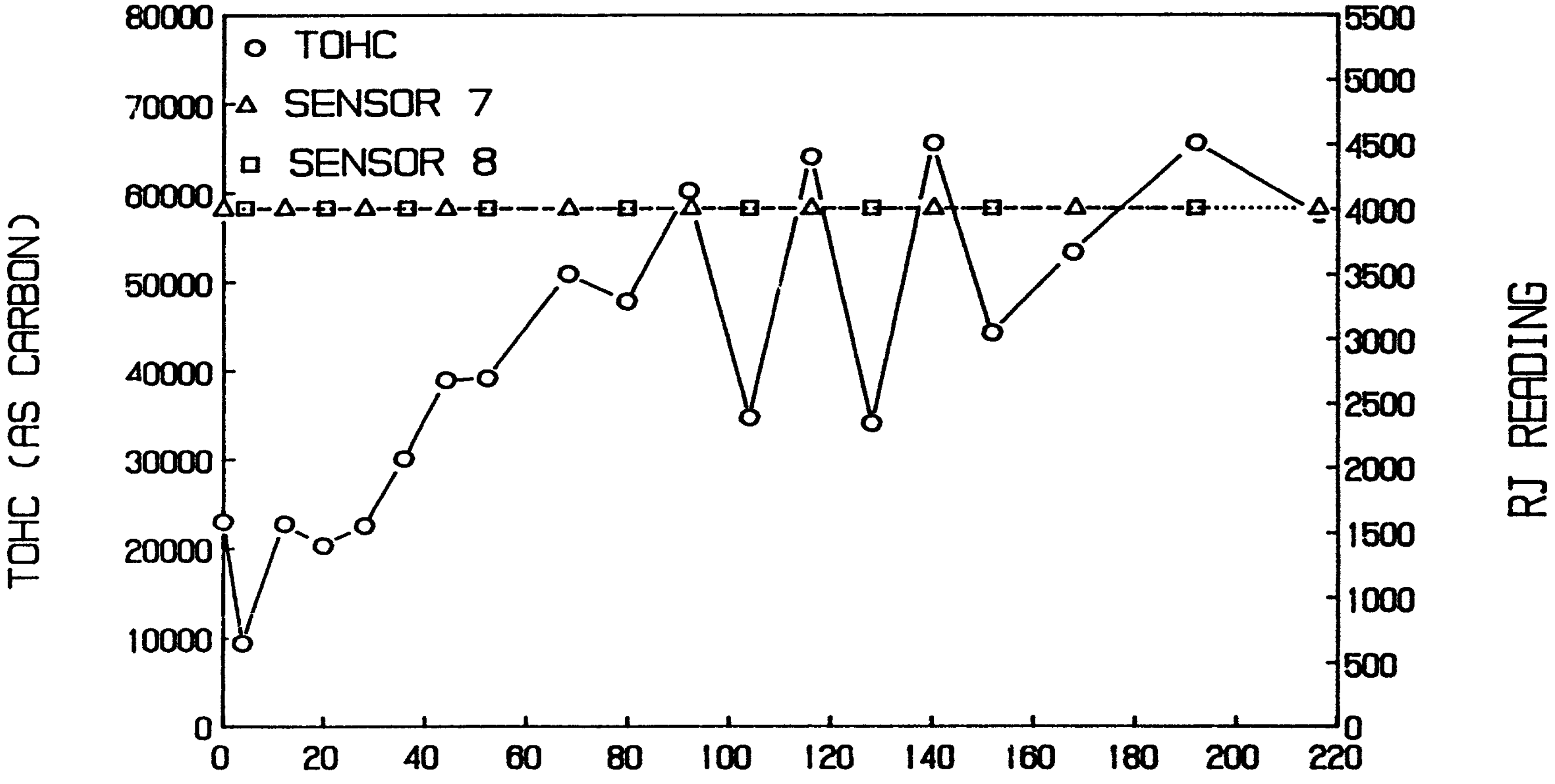


FIGURE D-11

RESPONSE OF RJ: WELL H

VAPOR-PHASE/ AGED JP-4/ WET SAND



TIME (HRS)

FIGURE D-12

RESPONSE OF AZI: WELL K

VAPOR-PHASE / AGED JP-4 / WET SAND

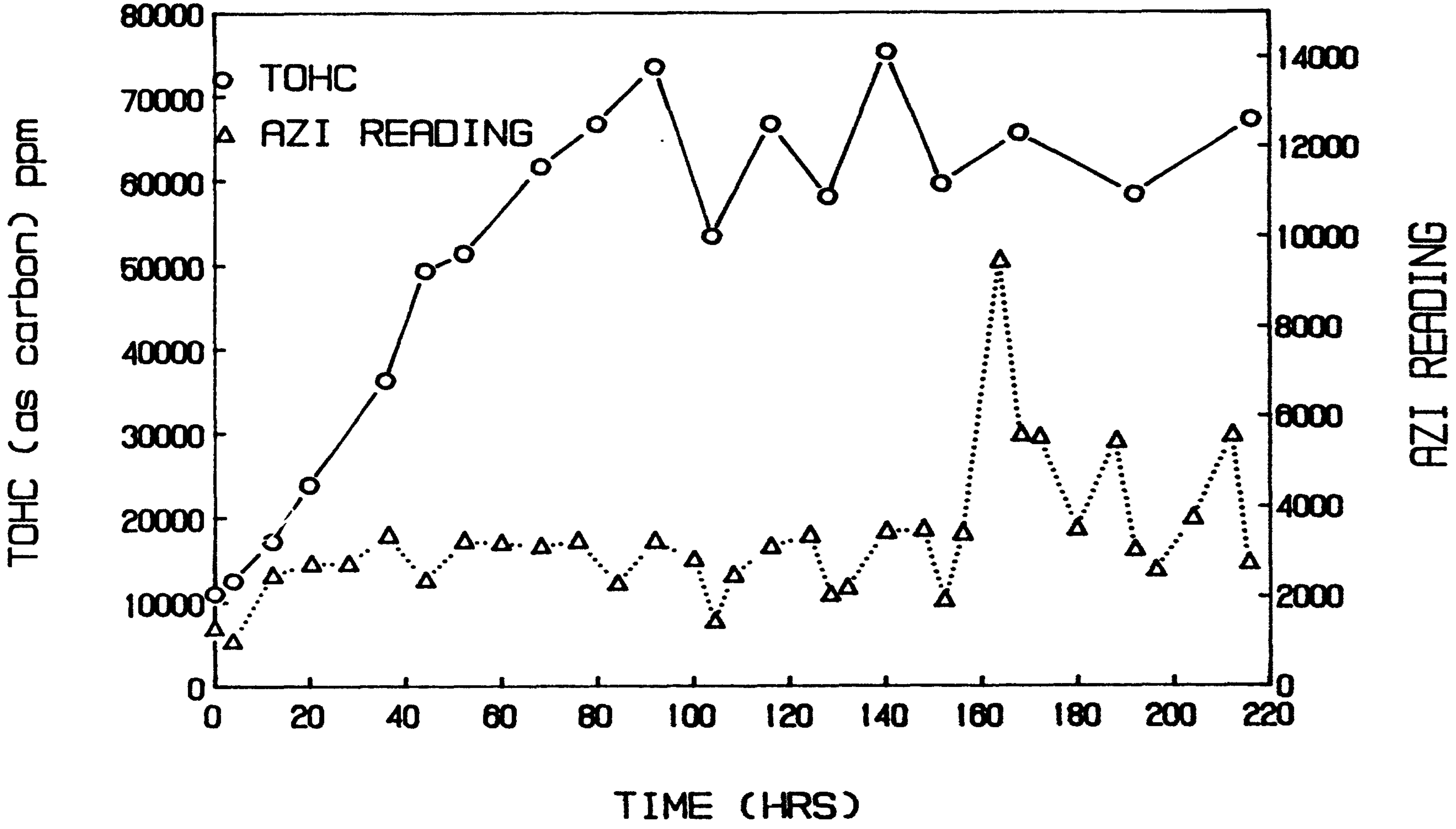


FIGURE D-13

APPENDIX E

RESULTS OF LIQUID-PHASE TANK TEST

TABLE E-1. LIQUID-PHASE TANK TEST RESULTS

DEVICE	WELL IDENTIFICATION CODE	THICKNESS OF FUEL LAYER (inches)	TIME (HRS)	COMMENTS
Leak-X	C	0.25	27.5	Alarm activated; probe placed back in well, but did not alarm
Leak-X	C	1.625	35.08	Alarming; probe removed
TCI	E	1.125	75.33	No alarms
TCI	E	5.75	96.83	No alarms
TCI	B	1.50	120.3	No alarms
TCI	E	9.875	120.3	Both probes alarming
TCI	J	3.5	120.3	No alarms
TCI	B	4.0	139.8	Both probes alarming
TCI	J	7.5	139.8	Both probes alarming
Leak-X	A	0.75	287.8	Alarming; probe removed
In-Situ	L	<0.06	287.8	Alarming
Leak-X	N	0.75	287.8	Alarming; probe removed
Leak-X	I	1.5	312.80	No alarm
Leak-X	I	1.5	313.05	Alarming; probe removed
In-Situ	P	0.25	331.3	Alarming
Leak-X	G	0.25	355.3	Alarming; probe removed
Leak-X	H	0.375	379.3	Alarming; probe removed
TCI	0	0.375	379.3	No alarm
TCI	0	0.875	403.3	No alarm
TCI	0	2.25	427.3	Both probes alarming

TABLE E-2. TEMPERATURE DATA FOR LIQUID-PHASE TEST

TIME (hours)	ROOM TEMP (°C)	SAND TEMP* (°C)	SAND TEMP** (°C)
0.00	23	19	20
24.00	24	19	20
36.00	24	19	20
48.00	23	19	20
60.00	21	19	20
72.00	20	19	20
96.33	21	19	20
121.08	24	19	19
143.58	22	19	19
190.30	23	19	19
219.80	23	19	19
235.30	24	18	19
264.80	24	18	19
288.30	25	19	20
379.30	21	19	19
455.80	21	19	19
481.60	23	18	19
499.30	21	19	19
529.30	21	18	19
573.30	22	20	20

* At 2 ft radius.

** At 4 ft radius.

LOADING HISTORY OF JP-4 WITH TIME FOR LIQUID-PHASE TANK TEST

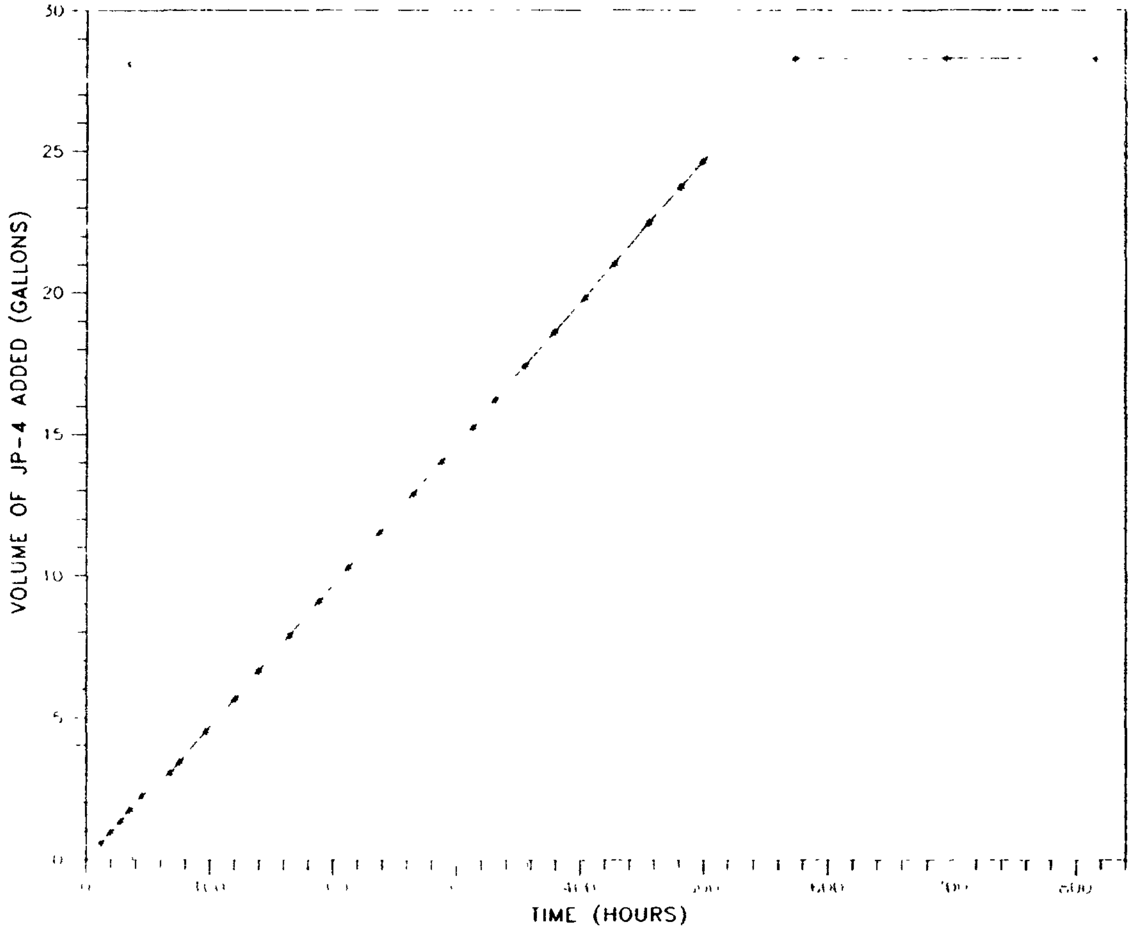


FIGURE E-1

VARIATION OF HYDROCARBON LAYER THICKNESS WITH TIME IN WELLS A THROUGH G 3 FEET FROM SOURCE

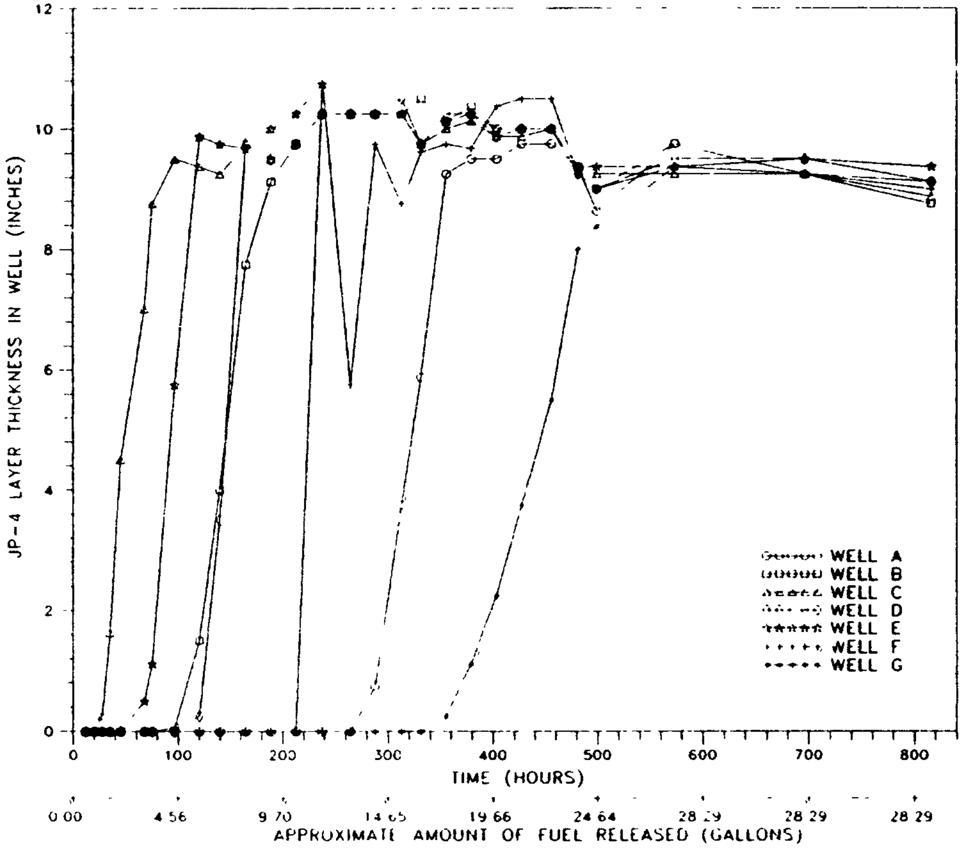


FIGURE E-2

VARIATION OF HYDROCARBON LAYER THICKNESS WITH TIME IN WELLS H THROUGH Q 5.5 FEET FROM SOURCE

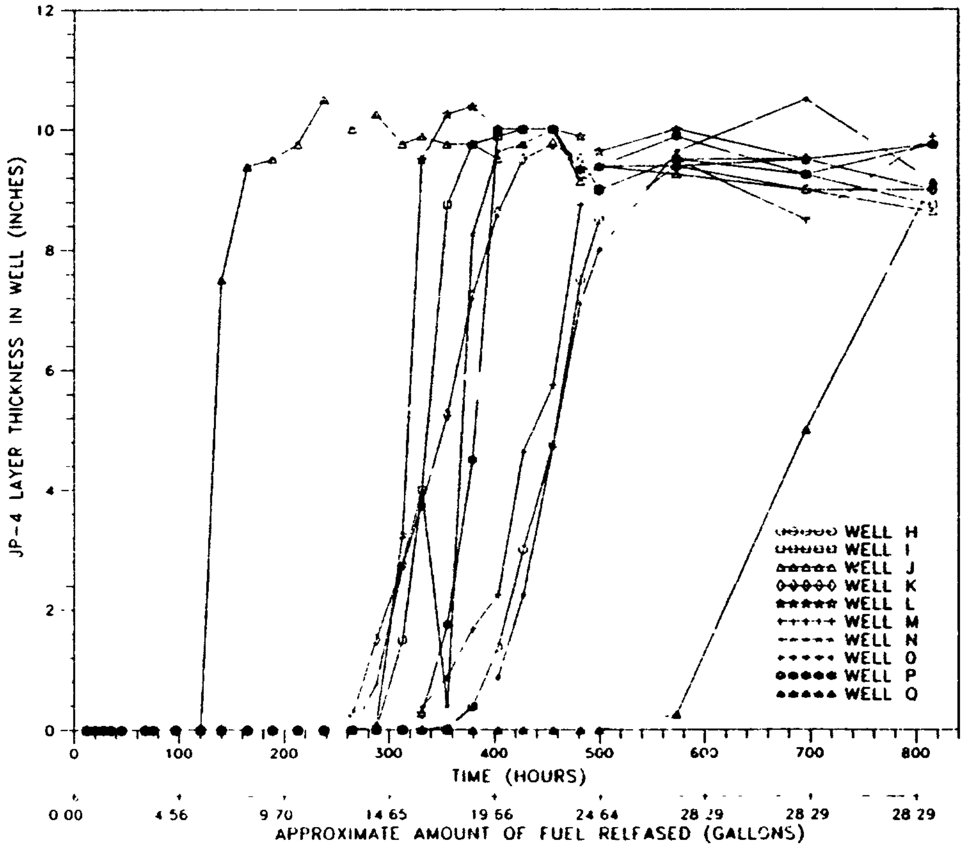


FIGURE E-3

APPENDIX F

ACCURACY AND RESPONSE TIME DATA FOR LIQUID-PHASE DEVICES

TABLE F-1. DATA FOR ESTIMATION OF LIQUID VOLUME AND DEPTH RELATIONSHIP

Initial Depth (vernier reading) = 2.154 in

Final Vernier Reading (in)	Depth of Water Column (in)	Volume Dispensed (mL)
2.041	0.113	20
1.76	0.394	70
1.501	0.653	120
1.212	0.942	170
0.931	1.223	220
0.657	1.497	270
0.369	1.785	320

Calculations:

Regression Output

Constant	0
Std Err of Y est	0.006882
R Squared	0.999868
No. of Observations	7
Degree of Freedom	6
X Coefficient(s)	0.005555
Std Err of Coef.	0.000013

Floating Liquid

Height (in)	Calculated Volume (mL)
0.125	22.50225
0.25	45.00450
1	180.0180

TABLE F-2. JP-4 LAYER THICKNESS VS. RESPONSE TIME DATA FOR IN-SITU DEVICE

PROBE NUMBER	THICKNESS JP-4 (inches)	RESPONSE TIME (minutes)	AVERAGE TEMPERATURE (Celcius)
1	1/4	0.83	21.8
2	1/4	0.83	22.5
3	1/4	0.75	21.8
4	1/4	0.75	22.0
5	1/4	0.83	22.0
1	1/8	0.92	20.0
2	1/8	0.45	20.2
3	1/8	0.92	19.9
4	1/8	0.67	20.0
5	1/8	0.70	20.0
1	1/16	1.28	21.5
2	1/16	1.10	19.4
3	1/16	0.58	21.5
4	1/16	0.82	21.5
5	1/16	0.73	21.8
1	1/32	1.20	21.0
2	1/32	0.50	21.5
3	1/32	0.93	21.0
4	1/32	0.92	21.3
5	1/32	0.65	21.2
1	1/64	0.98	21.5
2	1/64	0.70	22.5
3	1/64	0.72	22.0
4	1/64	0.65	22.5
5	1/64	1.03	21.5

TABLE F-3. JP-4 LAYER THICKNESS VS. RESPONSE TIME DATA FOR TCI DEVICE

PROBE NUMBER	THICKNESS JP-4 (inches)	RESPONSE TIME (minutes)	AVERAGE TEMPERATURE (Celcius)
1	1/4	161.00	22.3
2	1/4	141.83	22.4
3	1/4	149.17	22.8
4	1/4	159.97	22.0
5	1/4	156.13	20.5
1	1/8	48.23	20.9
2	1/8	160.22	20.7
3	1/8	252.28	21.0
4	1/8	203.25	21.0
5	1/8	131.20	20.9
1	1/16	160.10	22.2
2	1/16	144.05	21.3
3	1/16	181.92	20.8
4	1/16	149.03	22.0
5	1/16	153.50	21.8
1	1/32	169.47	21.0
2	1/32	194.27	21.0
3	1/32	182.92	21.0
4	1/32	187.33	21.3
5	1/32	188.37	21.0

TABLE F-4. JP-4 LAYER THICKNESS VS. RESPONSE TIME DATA FOR LEAK-X DEVICE

PROBE NUMBER	THICKNESS JP-4 (inches)	RESPONSE TIME (minutes)	AVERAGE TEMPERATURE (Celcius)
1	1/8	No response*	21.6
2	1/8	No response*	21.4
3	1/8	No response*	21.6
4	1/8	No response*	21.8
5	1/8	No response*	21.4
1	1/4	No response*	22.1
2	1/4	No response*	22.1
3	1/4	No response*	22.4
4	1/4	No response*	22.3
5	1/4	No response*	22.4
1	0.348	Immediate†	22.2
2	0.462	Immediate†	21.3
3	0.325	Immediate†	20.8
4	0.340	Immediate†	22.0
5	0.391	Immediate†	21.8

* = No reponse for 24 hours.

† = Thickness of JP-4 layer was increased until the alarm was activated.

TABLE F-5. ACCURACY ESTIMATES FOR LIQUID-PHASE DEVICES

DEVICE	THICKNESS JP-4 (INCHES)	ACCURACY
In-Situ	1/4	100
In-Situ	1/8	100
In-Situ	1/16	100
In Situ	1/32	100
In-Situ	1/64	100
TCI	1/4	100
TCI	1/8	100
TCI	1/16	100
TCI	1/32	100
Leak-X	1/4	0
Leak-X	1/8	0

TABLE F-6. PRECISION ANALYSIS FOR IN SITU, INC., AND TCI

Device	JP-4 Layer Thickness (inches)	T_{SD} (minutes)	T_{AV} (minutes)	Precision (percent)
In Situ, Inc.	1/4	0.0392	0.798	4.91
In Situ, Inc.	1/8	0.422	0.932	45.28
In Situ, Inc.	1/16	0.254	0.902	28.16
In Situ, Inc.	1/32	0.243	0.84	28.93
In Situ, Inc.	1/64	0.167	0.816	20.47
TCI	1/4	7.21	153.62	4.69
TCI	1/8	68.85	159.04	43.29
TCI	1/16	13.2	157.72	8.37
TCI	1/32	8.33	184.47	4.52

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APPENDIX G

BACKGROUND INTERFERENCE DATA FOR VAPOR-PHASE DEVICES

TABLE G-1. EFFECTS OF CARBON DIOXIDE (CO_2) ON VAPOR-PHASE DEVICES

PROBE	BKGROUND CO_2 (ppm)	BKGROUND READ-OUT	CO_2 (ppm)	FINAL PROBE READ-OUT	CO_2 (ppm)	FINAL PROBE READ-OUT	CO_2 (ppm)	FINAL PROBE READ-OUT	CO_2 (ppm)	FINAL PROBE READ-OUT
USD #3	500	48	1,000	63	2,000	72	9,000	92	22,000	17
USD #4	500	147	1,000	171	2,000	189	9,000	201	22,000	87
RJ #4	500	0	1,000	0	2,000	0	9,000	0	22,000	0
RJ #5	500	0	1,000	0	2,000	0	9,000	0	22,000	0
AZI	500	32	1,000	36	2,000	36	9,000	36	22,000	28
FCI (ppm)	500	0	1,000	323	2,000	653	9,000	11,678	22,000	11,842
(volt)		9.82		9.6		9.51		8.73		8.39
TCI	500	No alarm	1,000	No alarm	2,000	No alarm	9,000	No alarm	22,000	No alarm
In Situ	500	No alarm	1,000	No alarm	2,000	No alarm	9,000	No alarm	22,000	No alarm

TABLE G-2. EFFECTS OF CARBON MONOXIDE (CO) ON VAPOR-PHASE DEVICES

PROBE	BKGROUND CO (ppm)	BKGROUND READ-OUT	CO (ppm)	FINAL PROBE READ-OUT	CO (ppm)	FINAL PROBE READ-OUT	CO (ppm)	FINAL PROBE READ-OUT
USD #3	0	63	500	234	1,400	302	9,900	349
USD #4	0	164	500	532	1,400	708	9,900	819
RJ #4	0	0	500	0	1,400	0	9,900	0
RJ #5	0	0	500	0	1,400	0	9,900	0
AZI	0	32	500	44	1,400	72	9,900	313
FCI (ppm)	0	0	500	4	1,400	8	9,900	215
(volt)		8.17		8.15		8.2		8.02
TCI	0	No alarm	500	No alarm	1,400	No alarm	9,900	No alarm
In Situ	0	No alarm	500	No alarm	1,400	No alarm	9,900	No alarm

TABLE G-3. EFFECTS OF HYDROGEN SULFIDE (H_2S) ON VAPOR-PHASE DEVICES

PROBE	BKGROUND H_2S (ppm)	BKGROUND READ-OUT	H_2S (ppm)	FINAL PROBE READ-OUT	H_2S (ppm)	FINAL PROBE READ-OUT	H_2S (ppm)	FINAL PROBE READ-OUT
USD #3	0	63	450	2,921	900	9,621	6,660	9,999
USD #4	0	75	450	9,999	900	9,999	6,660	1,314
RJ #4	0	0	450	0	900	0	6,660	0
RJ #5	0	0	450	0	900	0	6,660	0
AZI	0	78	450	2,102	900	6,502	6,660	6,502
FCI (ppm)	0	0	450	91	900	749	6,660	18,947
(volt)		4.15		4.1		4.01		3.53
TCI	0	No alarm	450	No alarm	900	No alarm	6,660	No alarm
In Situ	0	No alarm	450	No alarm	900	No alarm	6,660	No alarm

TABLE G-4. EFFECTS OF METHANE (CH_4) ON VAPOR-PHASE DEVICES

PROBE	BKGROUND CH_4 (ppm)	BKGROUND READ-OUT	CH_4 (ppm)	FINAL PROBE READ-OUT	CH_4 (ppm)	FINAL PROBE READ-OUT	CH_4 (ppm)	FINAL PROBE READ-OUT
USD #3	77	8	565	26	2,249	45	9,804	100
USD #4	77	63	565	99	2,249	142	9,804	158
RJ #4	77	0	565	0	2,249	0	9,804	0
RJ #5	77	0	565	0	2,249	0	9,804	0
AZI	77	32	565	32	2,249	44	9,804	72
FCI (ppm)	77	0	565	21	2,249	32	9,804	1
(volt)		6.88		6.92		6.93		6.87
TCI	77	No alarm	565	No alarm	2,249	No alarm	9,804	No alarm
In Situ	77	No alarm	565	No alarm	2,249	No alarm	9,804	No alarm

TABLE G-5. EFFECTS OF TRICHLOROETHYLENE (TCE) ON VAPOR-PHASE DEVICES

PROBE	BKGROUND TCE (ppm)	BKGROUND READ-OUT	TCE (ppm)	FINAL PROBE READ-OUT	TCE (ppm)	FINAL PROBE READ-OUT	TCE (ppm)	FINAL PROBE READ-OUT
USD #3	0	30	250	159	600	256	1,500	729
USD #4	0	63	250	282	600	518	1,500	1,258
RJ #4	0	0	250	0	600	0	1,500	37
RJ #5	0	0	250	0	600	0	1,500	0
AZI	0	32	250	182	600	1,742	1,500	6,502
FCI (ppm)	0	0	250	22	600	5	1,500	209,417
(volt)		6.7		6.74		6.72		4.23
TCI	0	No alarm	250	No alarm	600	No alarm	1,500	No alarm
In Situ	0	No alarm	250	No alarm	600	No alarm	1,500	No alarm

APPENDIX H

JP-4 VAPOR AND LIQUID DISTRIBUTION IN SAND TANKS

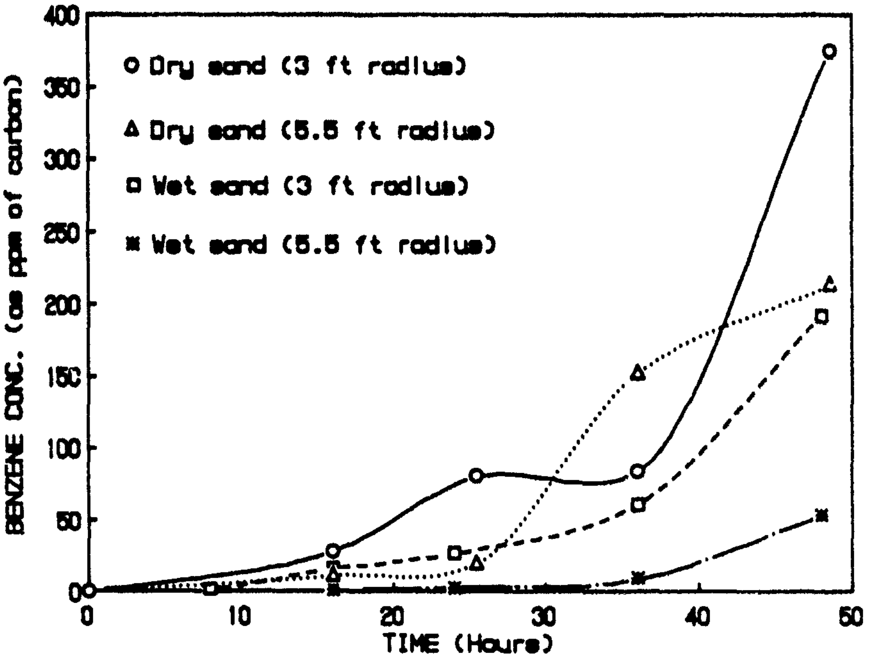


Figure H-1. Distribution of Benzene in Wells Located at 3 and 5.5 Feet From JP-6 Leak.

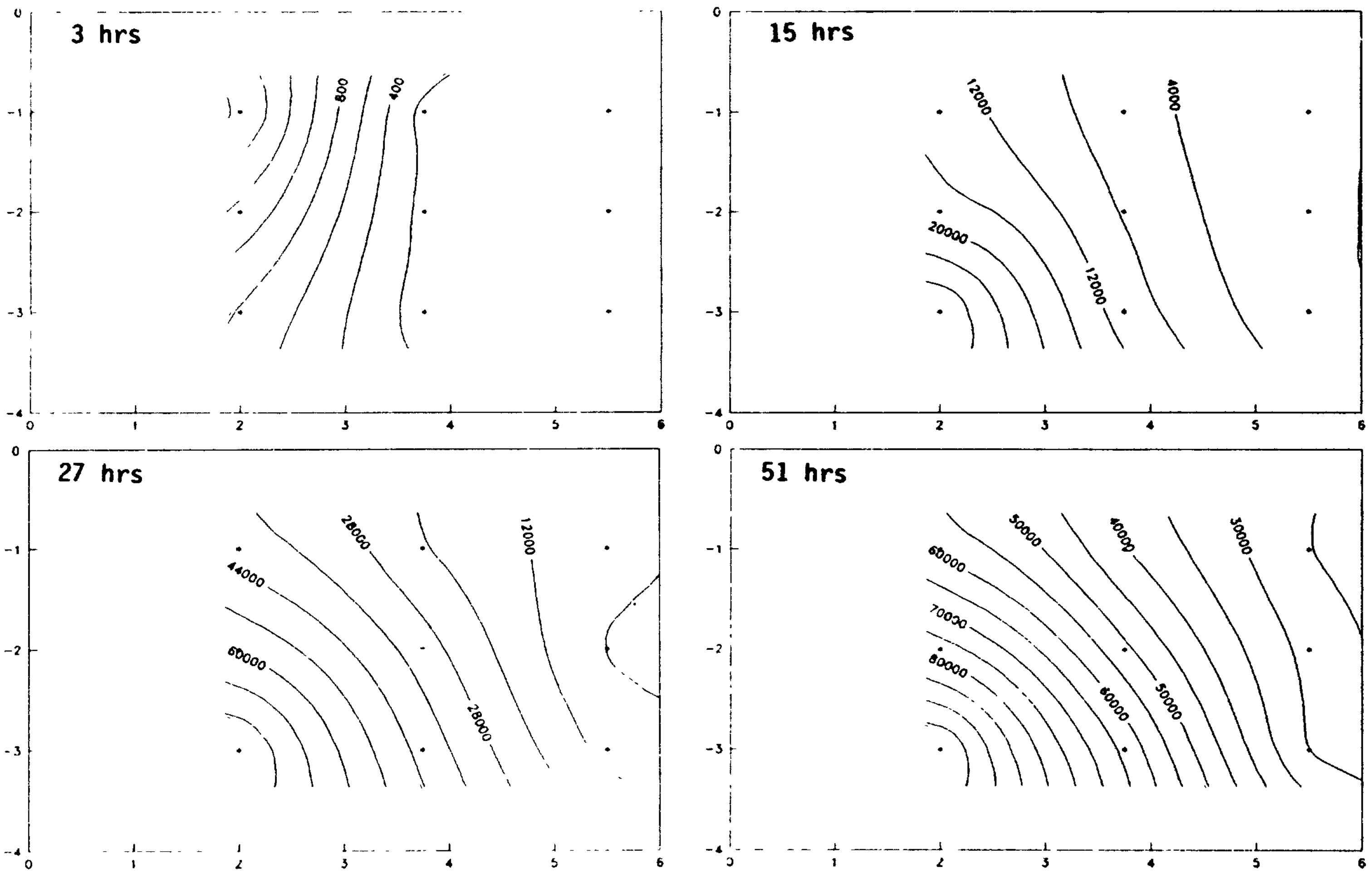


Figure H-2. Jet Fuel Vapor Concentration Isopleths (as ppm of Carbon) for Dry Sand at Different Times (Unit for Axes are in Feet).

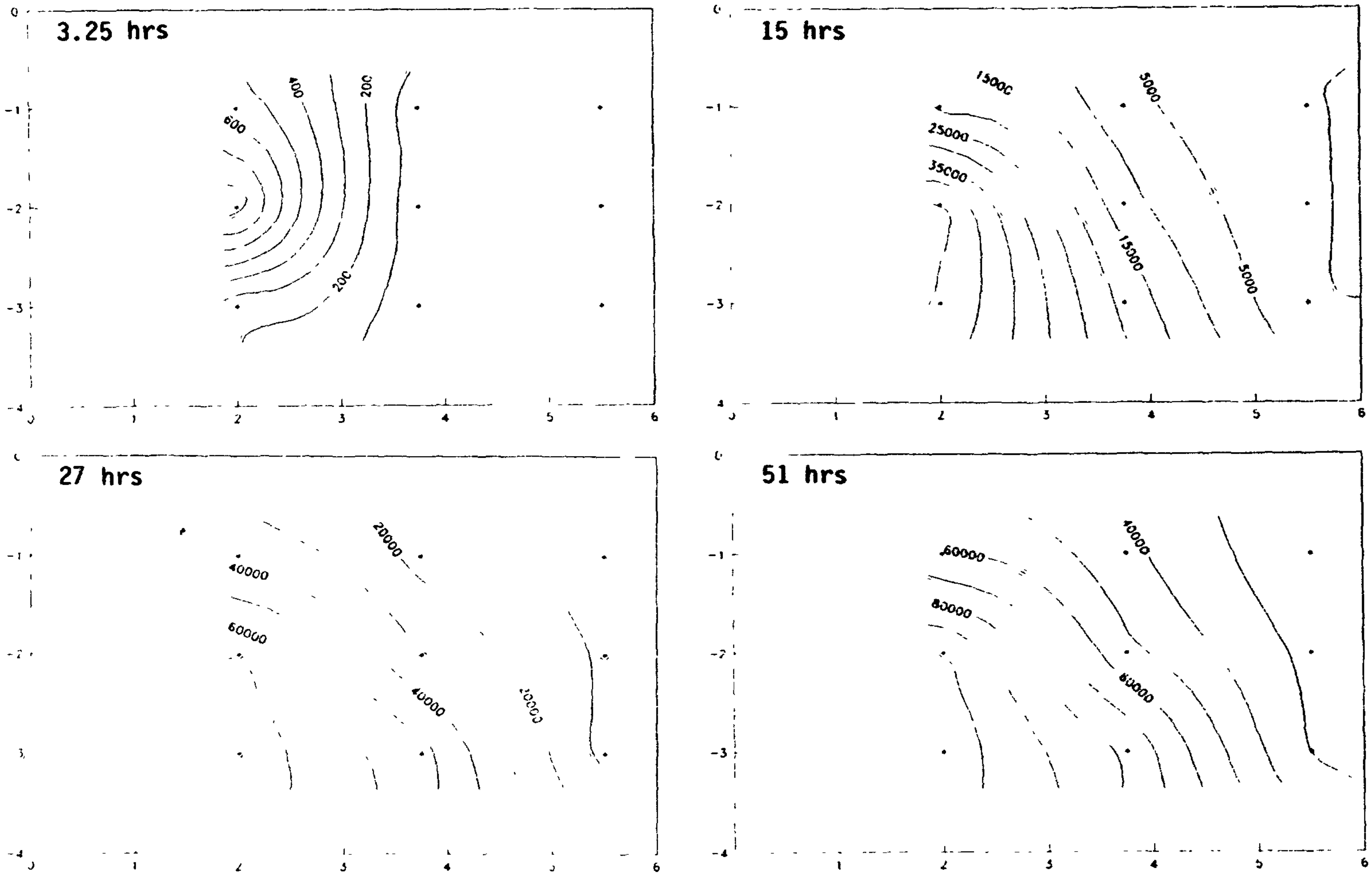
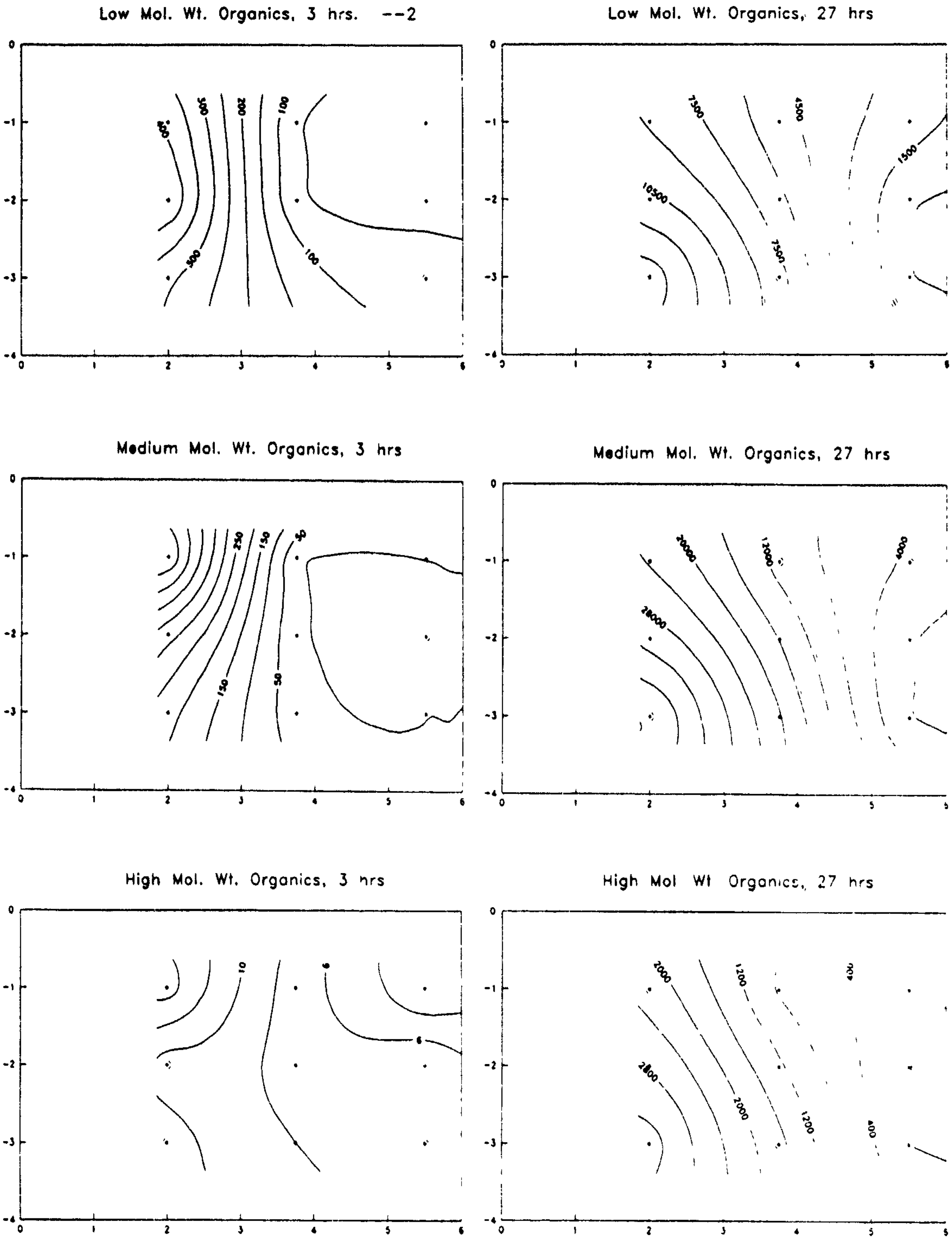


Figure H-3. Jet Fuel Vapor Concentration Isopleths (as ppm of Carbon) for Wet Sand at Different Times (Unit for Axes are in Feet).



Low Mol. Wt. Organics, 3 hrs. --2

Low Mol. Wt. Organics, 27 hrs

Medium Mol. Wt. Organics, 3 hrs

Medium Mol. Wt. Organics, 27 hrs

High Mol. Wt. Organics, 3 hrs

High Mol Wt Organics, 27 hrs

Figure H-4. Distribution of Different Molecular Weight Fractions (in ppm as Carbon) in Dry Sand.

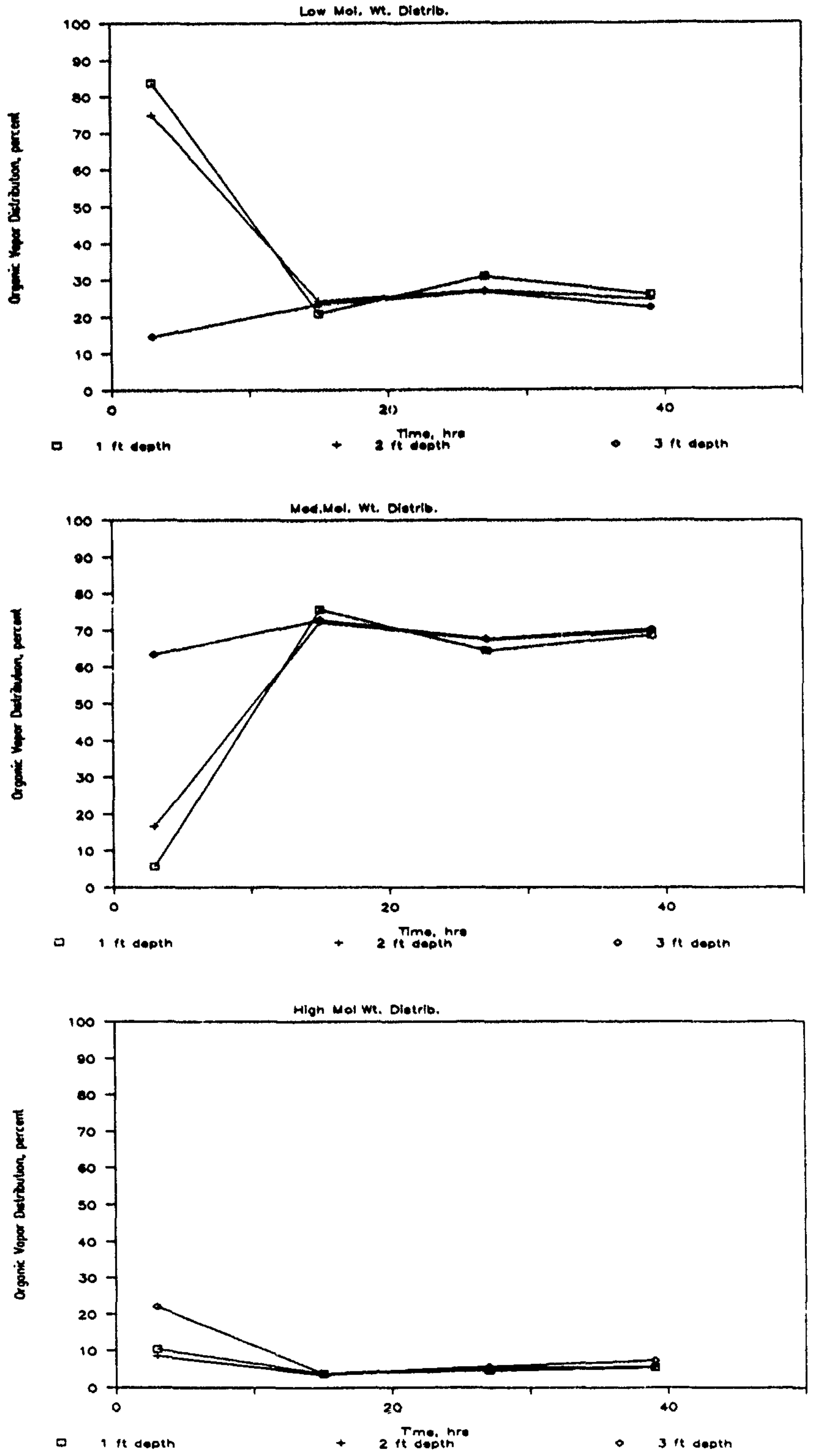


Figure H-5. Distribution of Percentages of Different Molecular Weight Fractions at 3.75 Feet Radius in Dry Sand.

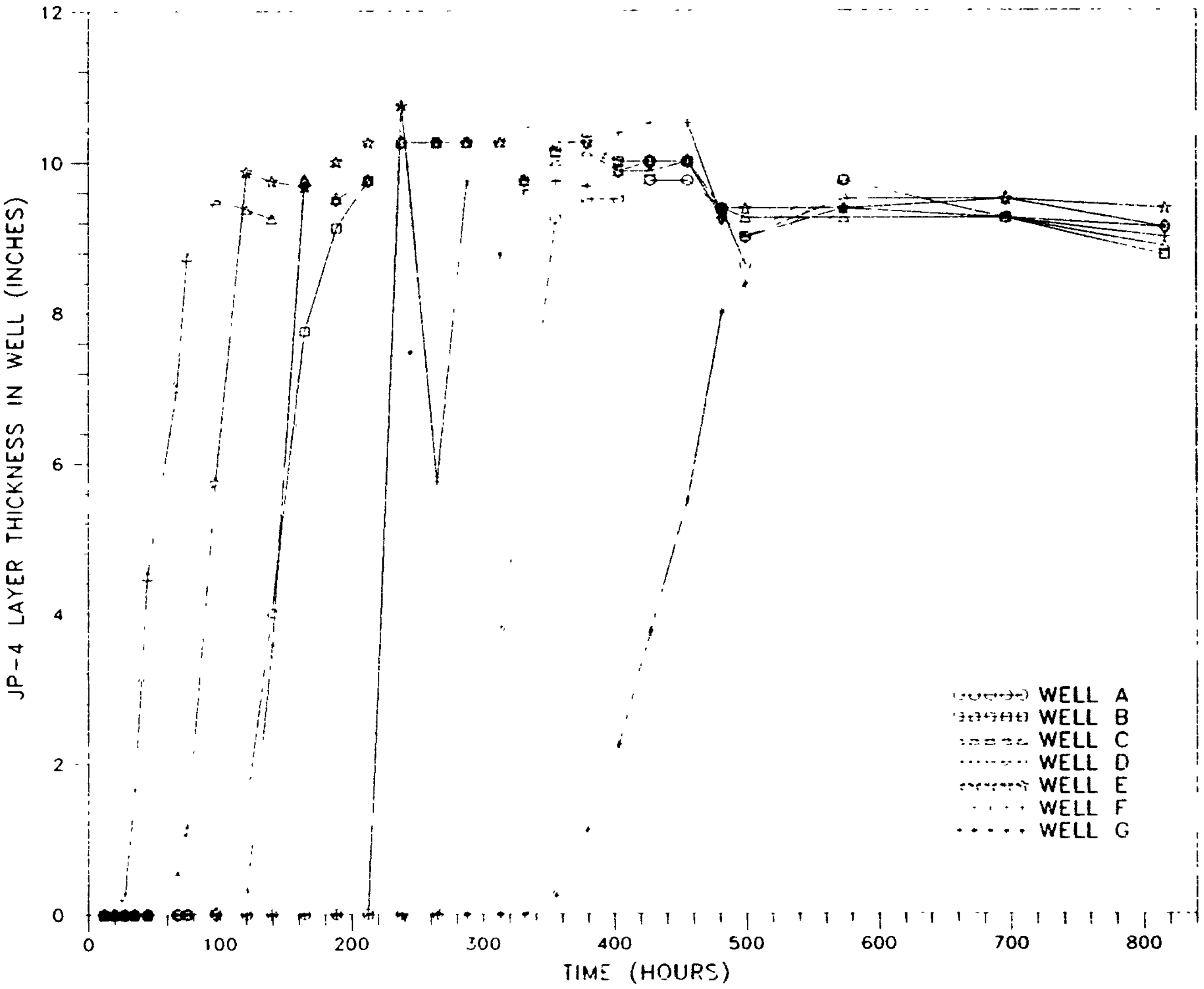


Figure H-6. Variation of Hydrocarbon Layer Thickness With Time in Wells A Through G, 3 Feet From Source.

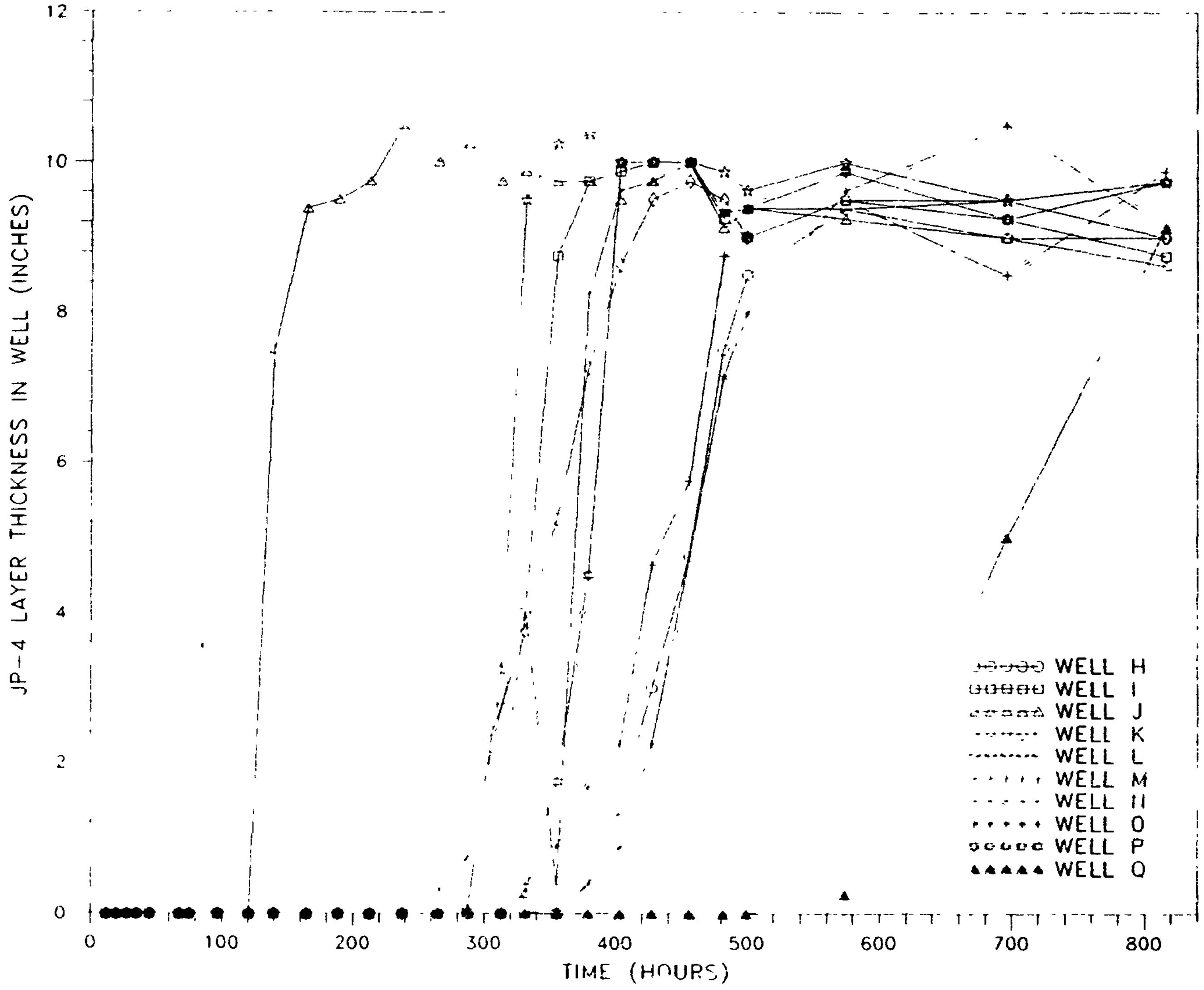


Figure H-7. Variation of Hydrocarbon Layer Thickness With Time in Wells H Through Q, 5.5 Feet From Source.

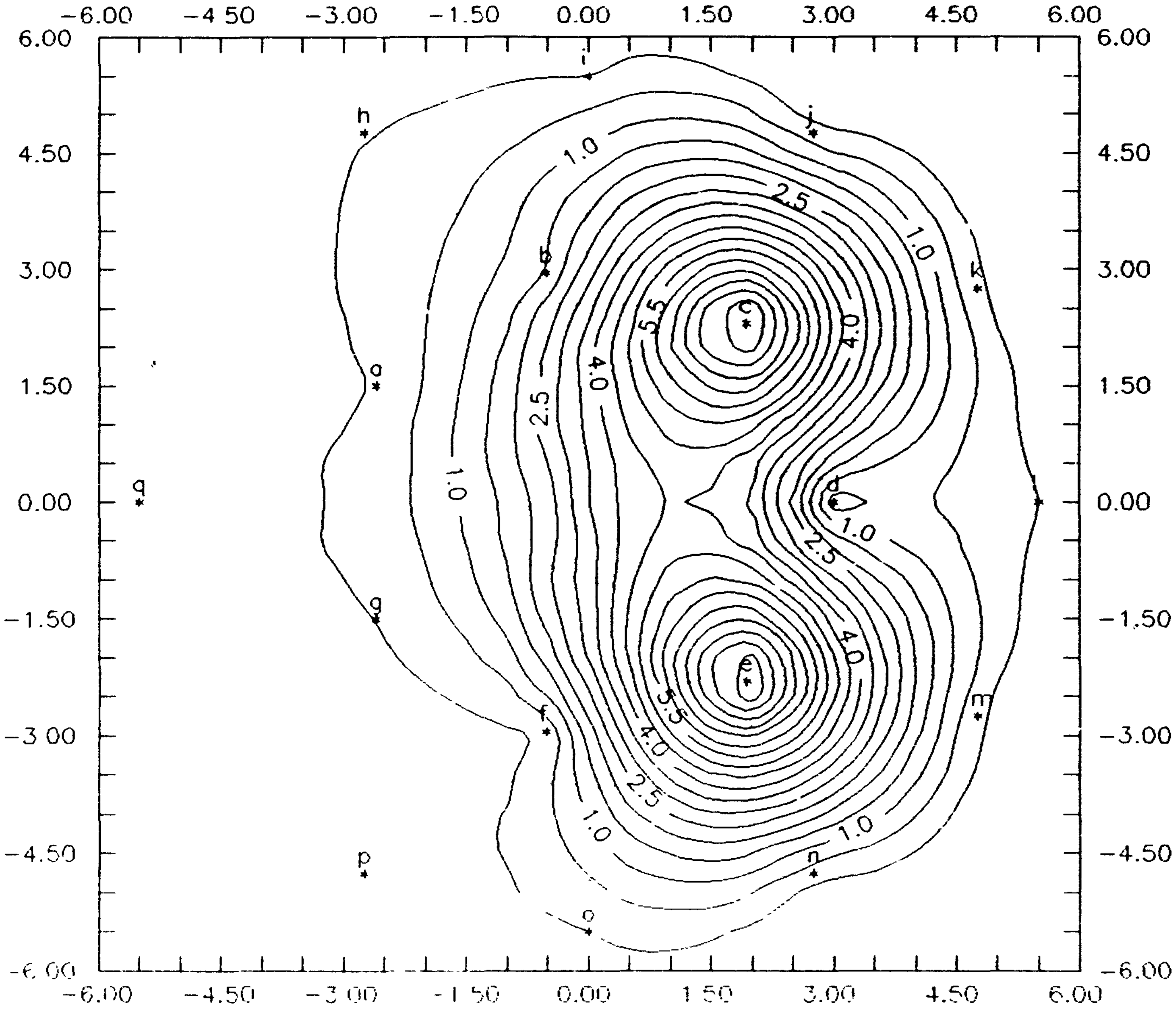


Figure H-8. JP-4 Distribution After 120.3 Hours.

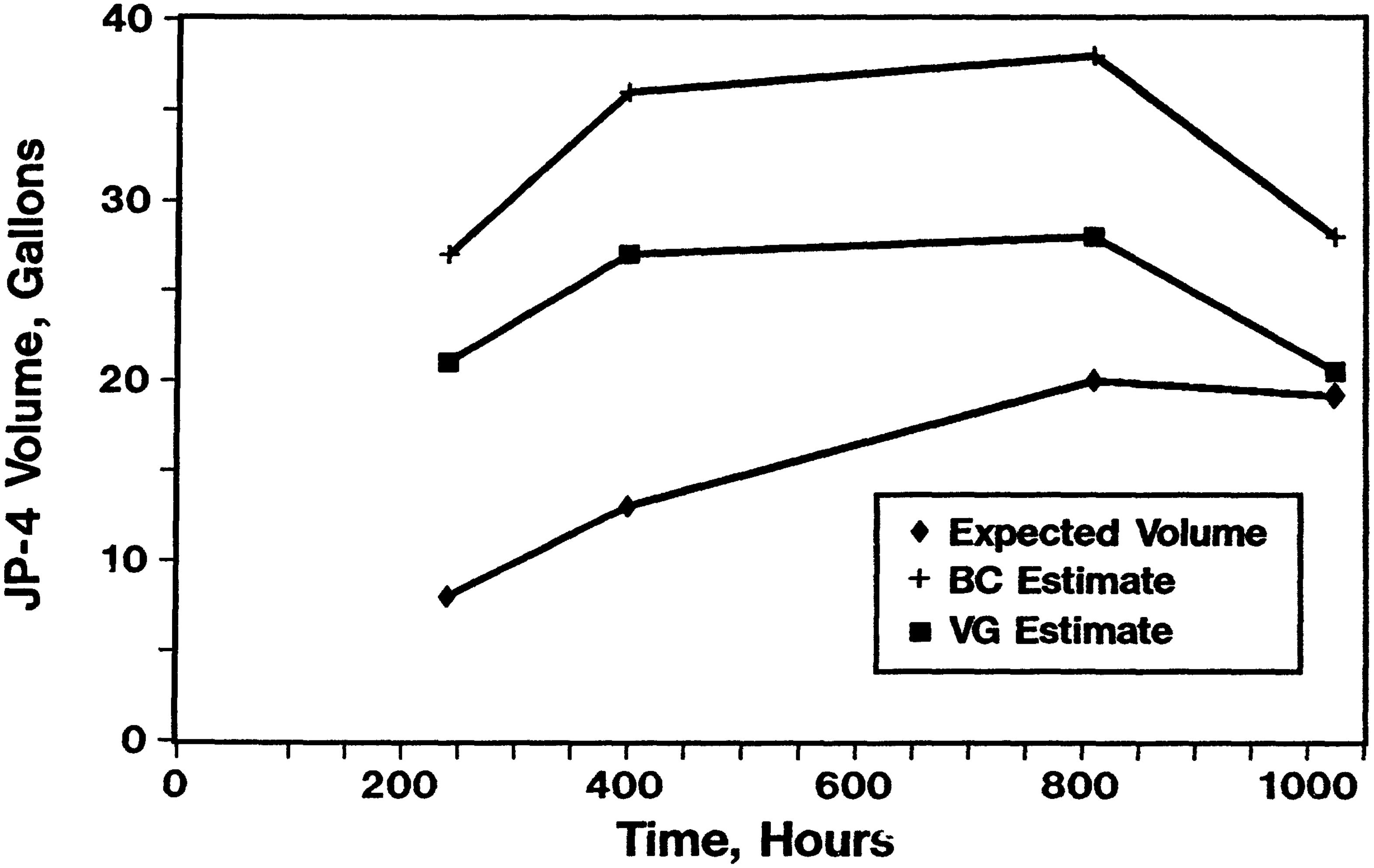


Figure H-9. Comparison of Expected and Calculated JP-4 Volumes.

APPENDIX I

JP-4 VAPOR DISTRIBUTION IN SAND AND SOIL COLUMNS

TABLE I-1. EXPERIMENTAL CONDITIONS FOR THE DRY SAND/JP-4 COLUMN

Condition	Value
Diameter	10.5 cm
Length	95.5 cm
Weight of Sand	13,175 g
% Moisture	0.005 ± 0.0001%
% Organic Carbon	0.008 ± 0.001%
Bulk Density	1.60 g/cm^3
Particle Density	2.50 ± 0.05 g/cm^3
Total Porosity	0.357
Air-Filled Porosity	0.357
Water-Filled Porosity	0

TABLE I-2. 50 PERCENT BREAKTHROUGH TIMES AND RETARDATION RATIOS FOR THE DRY SAND COLUMN

Component	Distance = 18.4 cm		Distance = 58.4 cm		Distance = 78.3 cm	
	Time, hrs, for 50% Breakthrough	Retardation Ratio	Time, hrs, for 50% Breakthrough	Retardation Ratio	Time, hrs, for 50% Breakthrough	Retardati Ratio
Butane	2	1.00	6	1.00	7	1.00
Pentane	2	1.00	7	1.17	7	1.00
Hexane	4	2.00	8	1.33	8	1.14
Benzene	3	1.50	10	1.67	8	1.14
Cyclohexane	2	1.00	10	1.67	10	1.43
2-Methylhexane	3	1.50	7	1.17	9	1.29
3-Methylhexane	2	1.00	10	1.67	10	1.43
Heptane	5	2.50	8	1.33	14	2.00
Methylcyclohexane	4	2.00	9	1.50	9	1.29
Toluene	5	2.50	13	2.17	17	2.43
2-Methylheptane	3	1.50	14	2.33	17	2.43
3-Methylheptane	3	1.50	18	3.00	18	2.57
Octane	5	2.50	18	3.00	18	2.57
Ethylbenzene	NC[a]	NC[a]	NC[a]	NC[a]	NC[a]	NC[a]
m-, p-Xylene	NC[a]	NC[a]	NC[a]	NC[a]	NC[a]	NC[a]

[a] Not computed because of analytical problems.

TABLE I-3. EXPERIMENTAL CONDITIONS FOR THE SOIL/JP-4 COLUMNS

Condition	Dry Soil	Wet Soil
Diameter	10.5 cm	10.4 cm
Length	95.8 cm	91.1 cm
Weight of Soil (Wet)	12,729 g	10,059 g
% Moisture (Dry Weight Basis)	0.07 ± 0.001%	26.0% ± 0.1%
% Organic Carbon (Dry Weight Basis)	2.09 ± 0.1%	4.15 ± 0.1%
Bulk Density (Dry Soil)	1.54 g/cm^3	1.029 g/cm^3
Particle Density	2.43 ± 0.005 g/cm^3	2.38 ± 0.02 g/cm^3
Total Porosity	0.373	0.558
Air-Filled Porosity	0.372	0.291
Water-Filled Porosity	0.001	0.267

TABLE I-4. 50 PERCENT BREAKTHROUGH TIMES AND RETARDATION RATIOS FOR THE DRY SOIL COLUMN

Component	Distance = 18.4 cm		Distance = 58.4 cm		Distance = 78.3 cm	
	Time, hrs, for 50% Breakthrough	Retardation Ratio	Time, hrs, for 50% Breakthrough	Retardation Ratio	Time, hrs, for 50% Breakthrough	Retardatio Ratio
Butane	3.5	1.00	16	1.00	27	1.0
Pentane	12	3.43	42	2.63	57	2.11
Hexane	25	7.1	>102	>6.38	>121	>4.48
Benzene	>50	>14.3	>150	>9.38	NA^a	NA^a
Cyclohexane	NC^b	NC^b	NC^b	NC^b	NC^b	NC^b
2-Methylhexane	NC^b	NC^b	NC^b	NC^b	NC^b	NC^b
3-Methylhexane	>48	>13.7	>121	>7.56	>150	>5.56
Heptane	>43	>12.3	>140	>8.75	>150	>5.56
Methylcyclohexane	>52	>14.9	>161	>10.1	NA^a	NA^a
Toluene	>106	>30.3	NA^a	NA^a	NA^a	NA^a
2-Methylheptane	>79	>22.6	NA^a	NA^a	NA^a	NA^a
3-Methylheptane	>71	>20.3	NA^a	NA^a	NA^a	NA^a
Octane	>89	>25.4	NA^a	NA^a	NA^a	NA^a
Ethylbenzene	NA^a	NA^a	NA^a	NA^a	NA^a	NA^a
m-, p-Xylene	NA^a	NA^a	NA^a	NA^a	NA^a	NA^a

[a] Not available because of very high retardation.

[b] Not computed because of analytical problems.

TABLE I-5. 50 PERCENT BREAKTHROUGH TIMES AND RETARDATION RATIOS FOR THE WET SOIL COLUMN

Component	Distance = 18.6 cm		Distance = 58.4 cm		Distance = 78.5 cm	
	Time, hrs, for 50% Breakthrough	Retardation Ratio	Time, hrs, for 50% Breakthrough	Retardation Ratio	Time, hrs, for 50% Breakthrough	Retardation Ratio
Butane	3	1.00	10	1.00	12	1.00
Pentane	4	1.33	13	2.30	19	1.58
Hexane	7	2.33	24	2.40	36	3.00
Benzene	>23	>7.67	>44	>4.40	>63	>5.25
Cyclohexane	11	3.67	44	4.40	44	3.67
2-Methylhexane	13	4.33	50	5.00	69	5.75
3-Methylhexane	9	3.00	43	4.30	70	5.83
Heptane	12	4.00	58	5.80	69	5.75
Methylcyclohexane	>16	>5.33	>67	>6.70	>100	>8.33
Toluene	>30	>10.0	>106	>10.6	>144	>12.0
2-Methylheptane	>20	>6.67	>108	>10.8	>190	>15.8
3-Methylheptane	>24	>8.00	>137	>13.7	>157	>13.1
Octane	>30	>10.0	>123	>12.3	>200	>16.7
Ethylbenzene	>50	>16.7	NA[a]	NA[a]	NA[a]	NA[a]
m-, p-Xylene	>58	>19.3	NA[a]	NA[a]	NA[a]	NA[a]

[a] Not available because of very high retardation.

TABLE I-6. COMPARISON OF DIFFUSION TIMES (HOURS) FOR 50 PERCENT BREAKTHROUGH AT SAMPLING PORT 5 AND BEST FIT RETARDATION FACTORS FOR DRY SAND, DRY SOIL, AND WET SOIL

Component	Dry Sand		Dry Soil		Wet Soil	
	Hrs for 50% Breakthrough	R	Hrs for 50% Breakthrough	R	Hrs for 50% Breakthrough	R
Butane	6	1.4	16	3.5	10	1.1
Pentane	7	1.2	42	8.9	13	1.1
Hexane	8	1.2	130	24.2	24	1.1
Benzene	10	1.9	>330	104	>44	10.1
Cyclohexane	10	1.4	NC[a]	NC[a]	44	1.9
2-Methylhexane	7	1.0	NC[a]	NC[a]	50	1.3
3-Methylhexane	10	1.5	>250	53.6	43	1.6
Heptane	8	1.4	>330	68.0	58	2.7
Methylcyclohexane	9	1.7	>310	74.6	>67	2.9
Toluene	13	2.7	>500	286	>106	11.4
2-Methylheptane	14	2.1	>500	182	>108	5.0
3-Methylheptane	18	2.4	>500	179	>137	5.3
Octane	18	2.5	>570	251	>123	11.0
Ethylbenzene	NC[a]	NC[a]	NA[b]	1893	NA[b]	18.4
m-, p-Xylene	NC[a]	NC[a]	NA[b]	1382	NA[b]	38.0

[a] Not computed because of analytical problems.

[b] Not available because of very high retardation.

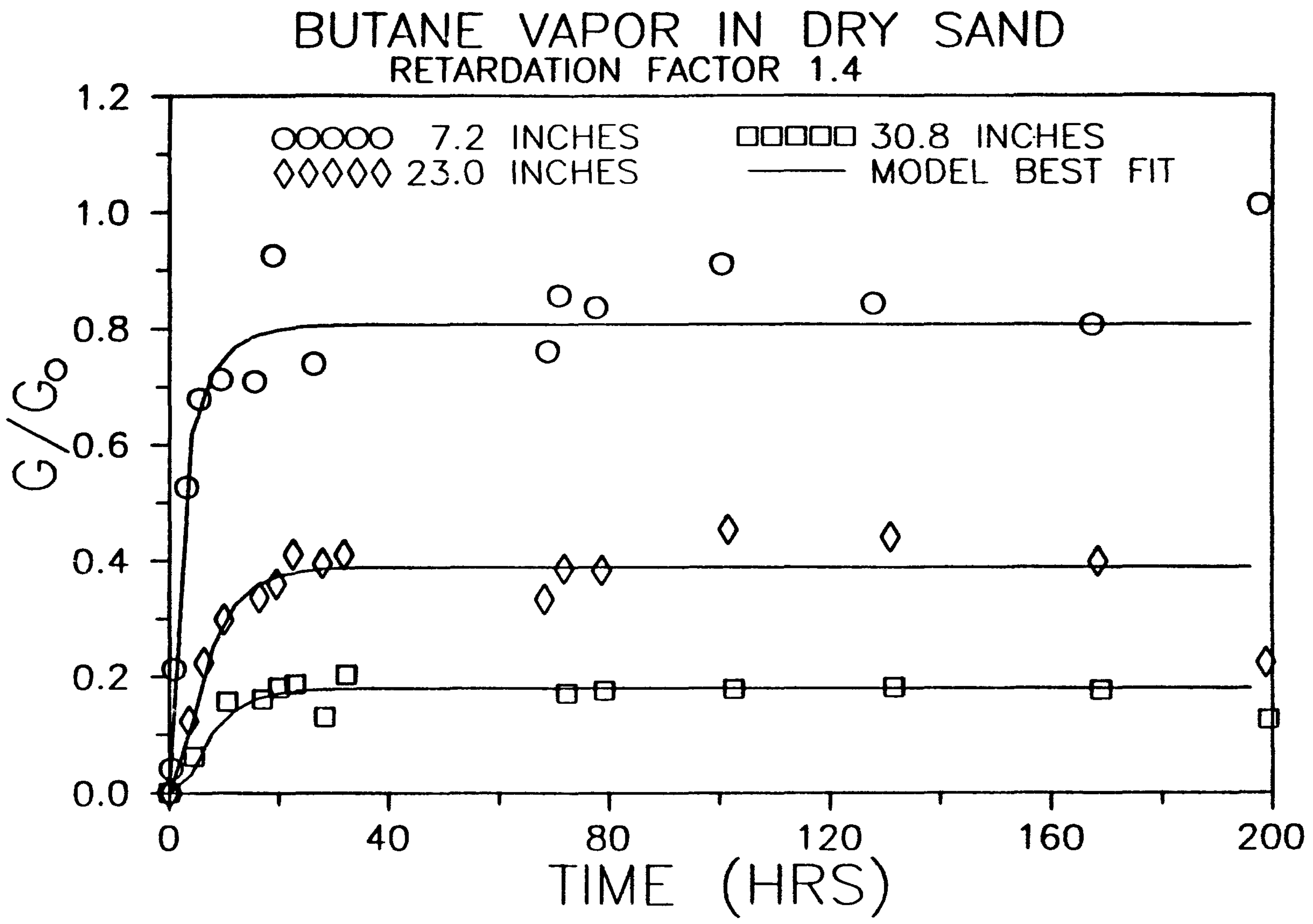


Figure I-1. Experimental and Computed Concentration Versus Time Profiles for Butane in Dry Sand.

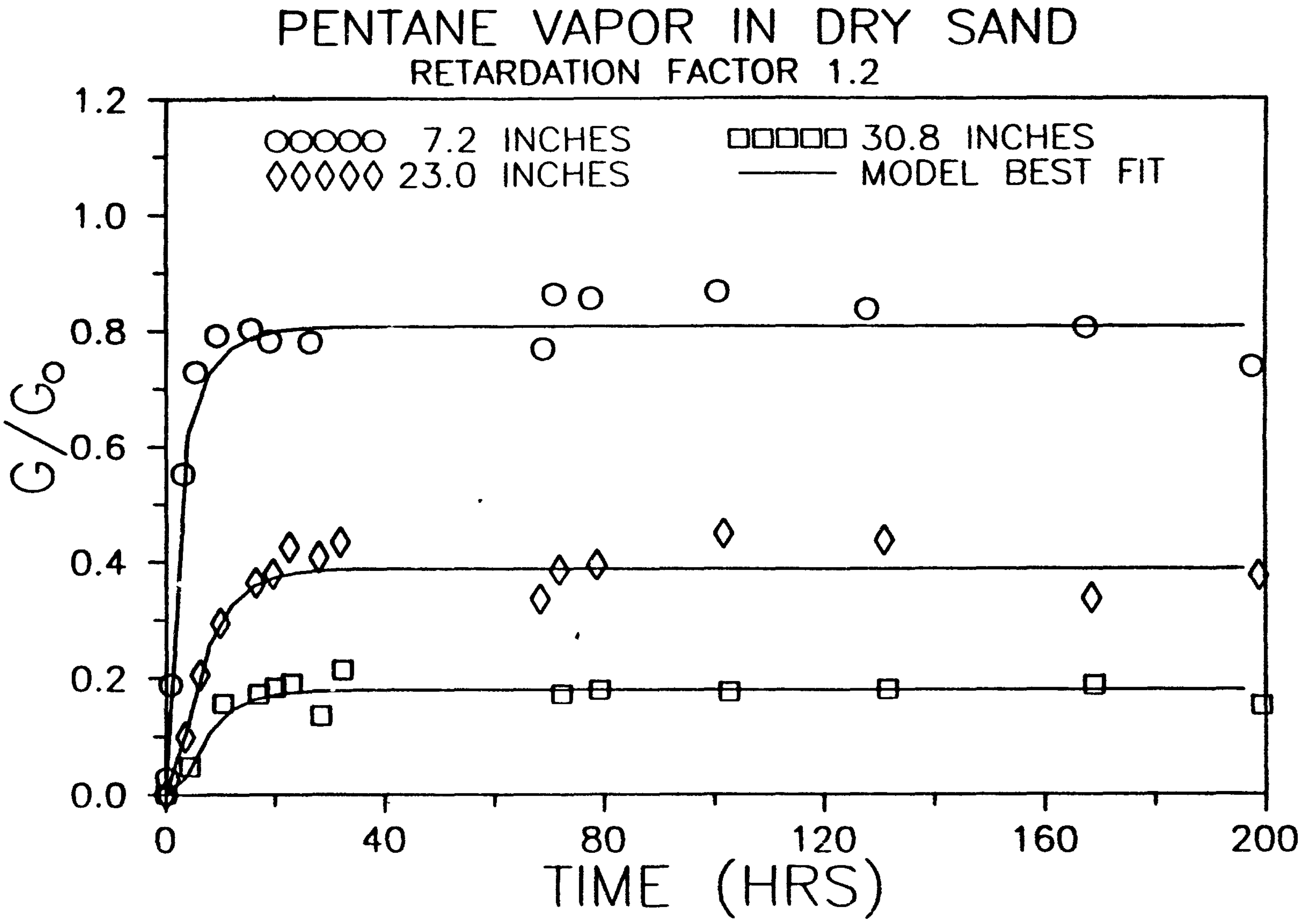


Figure I-2. Experimental and Computed Concentration Versus Time Profiles for Pentane in Dry Sand.

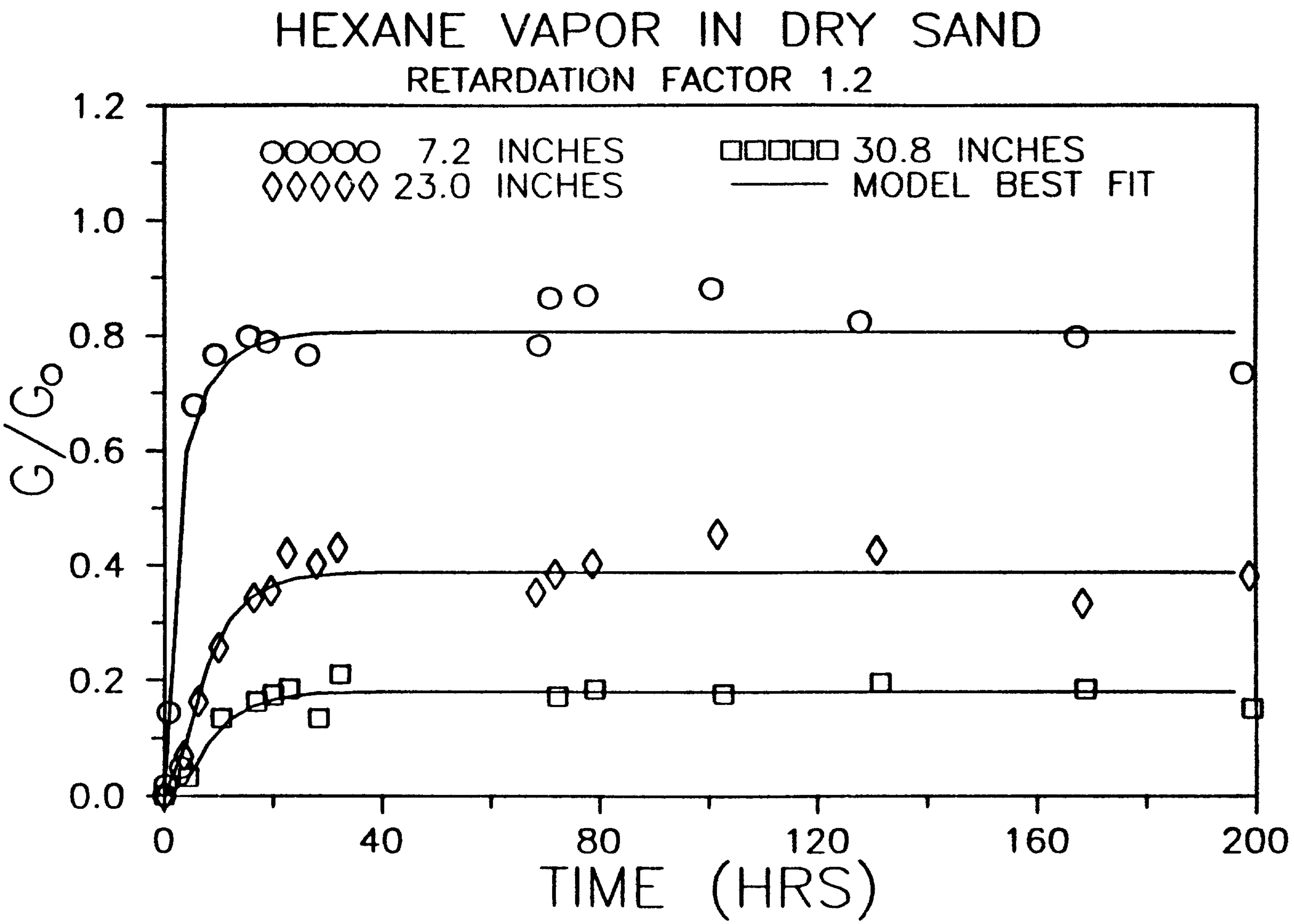


Figure I-3. Experimental and Computed Concentration Versus Time Profiles for Hexane in Dry Sand.

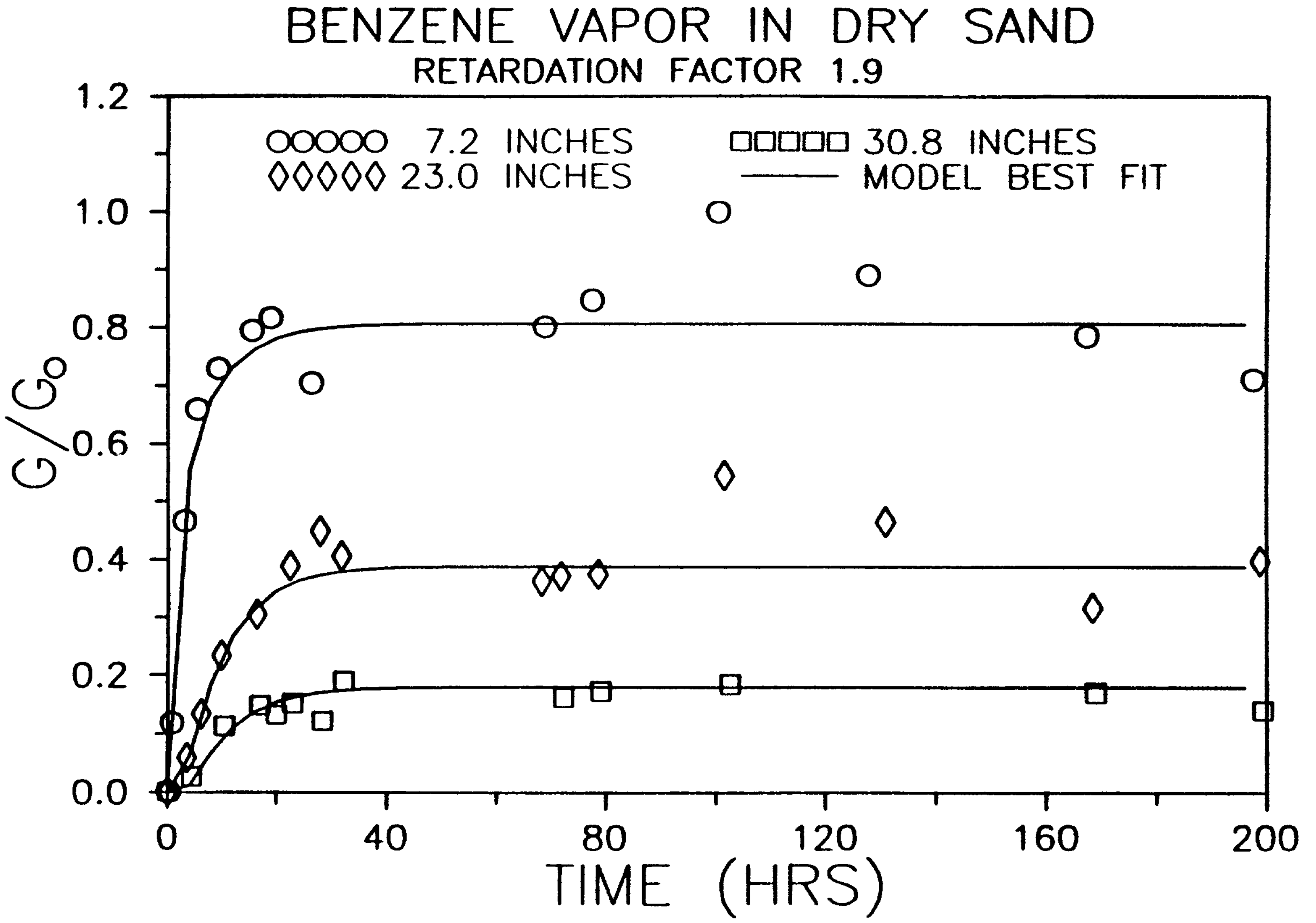


Figure I-4. Experimental and Computed Concentration Versus Time Profiles for Benzene in Dry Sand.

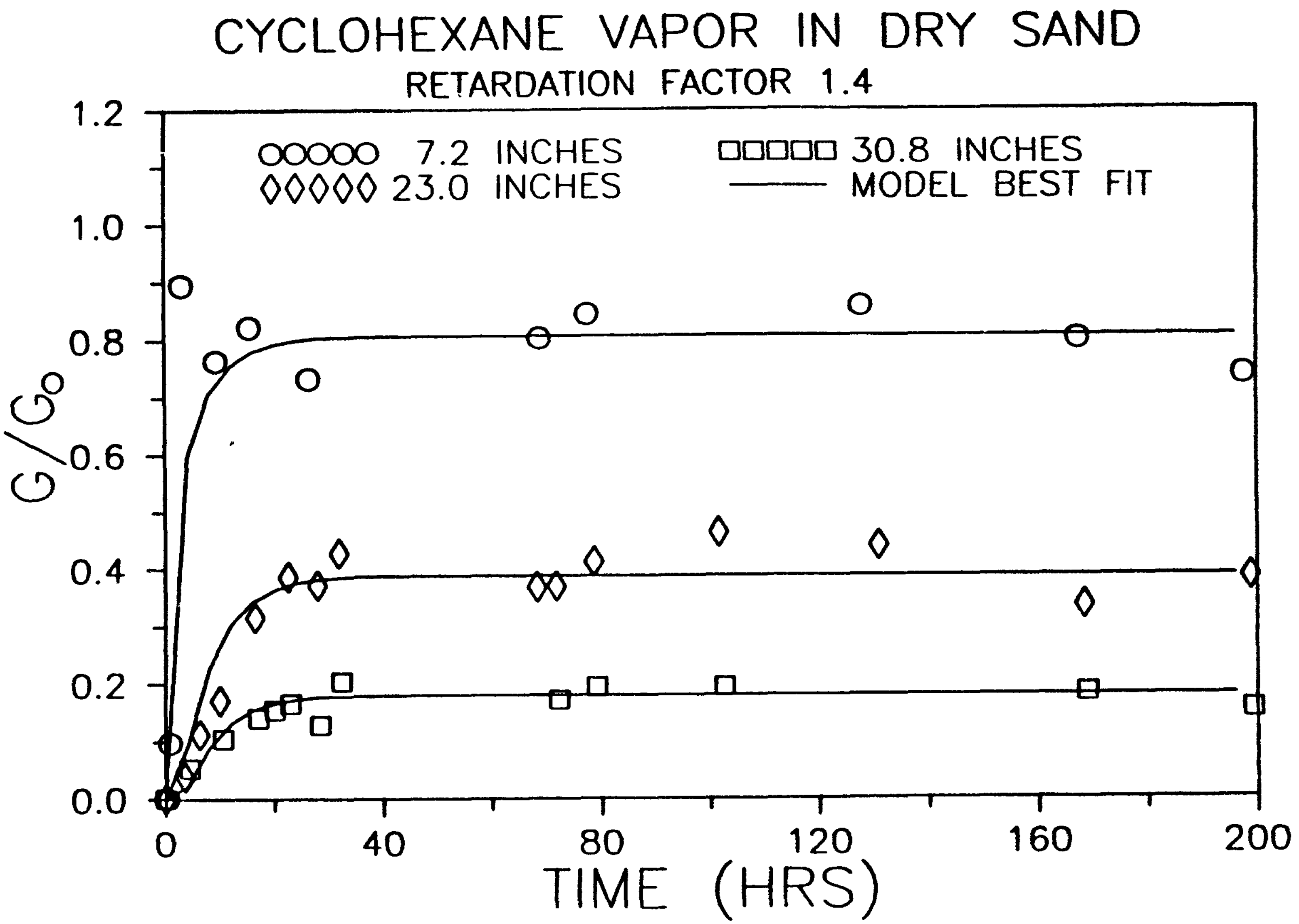


Figure I-5. Experimental and Computed Concentration Versus Time Profiles for Cyclohexane in Dry Sand.

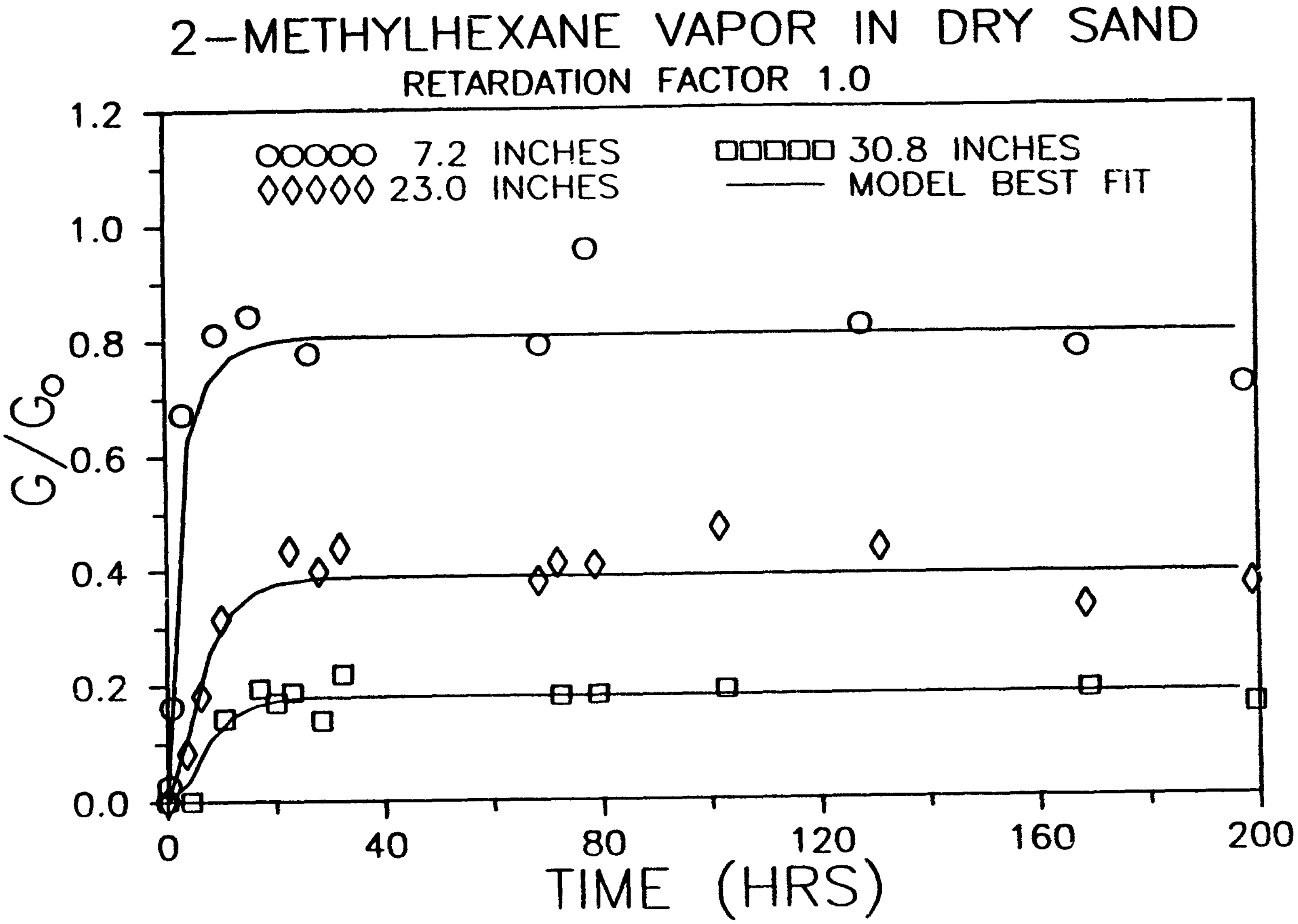


Figure I-6. Experimental and Computed Concentration Versus Time Profiles for 2-Methylhexane in Dry Sand.

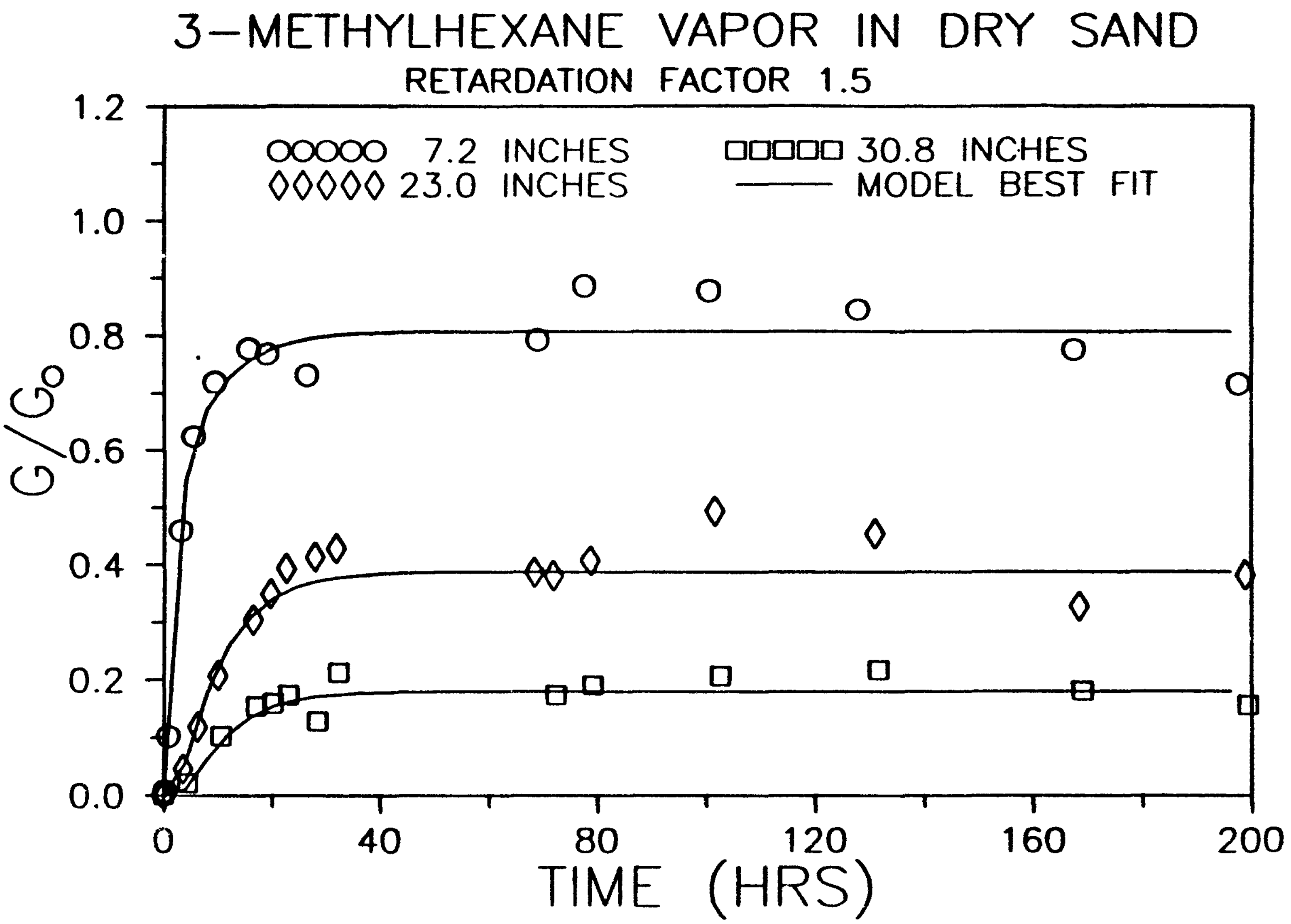


Figure I-7. Experimental and Computed Concentration Versus Time Profiles for 3-Methylhexane in Dry Sand.

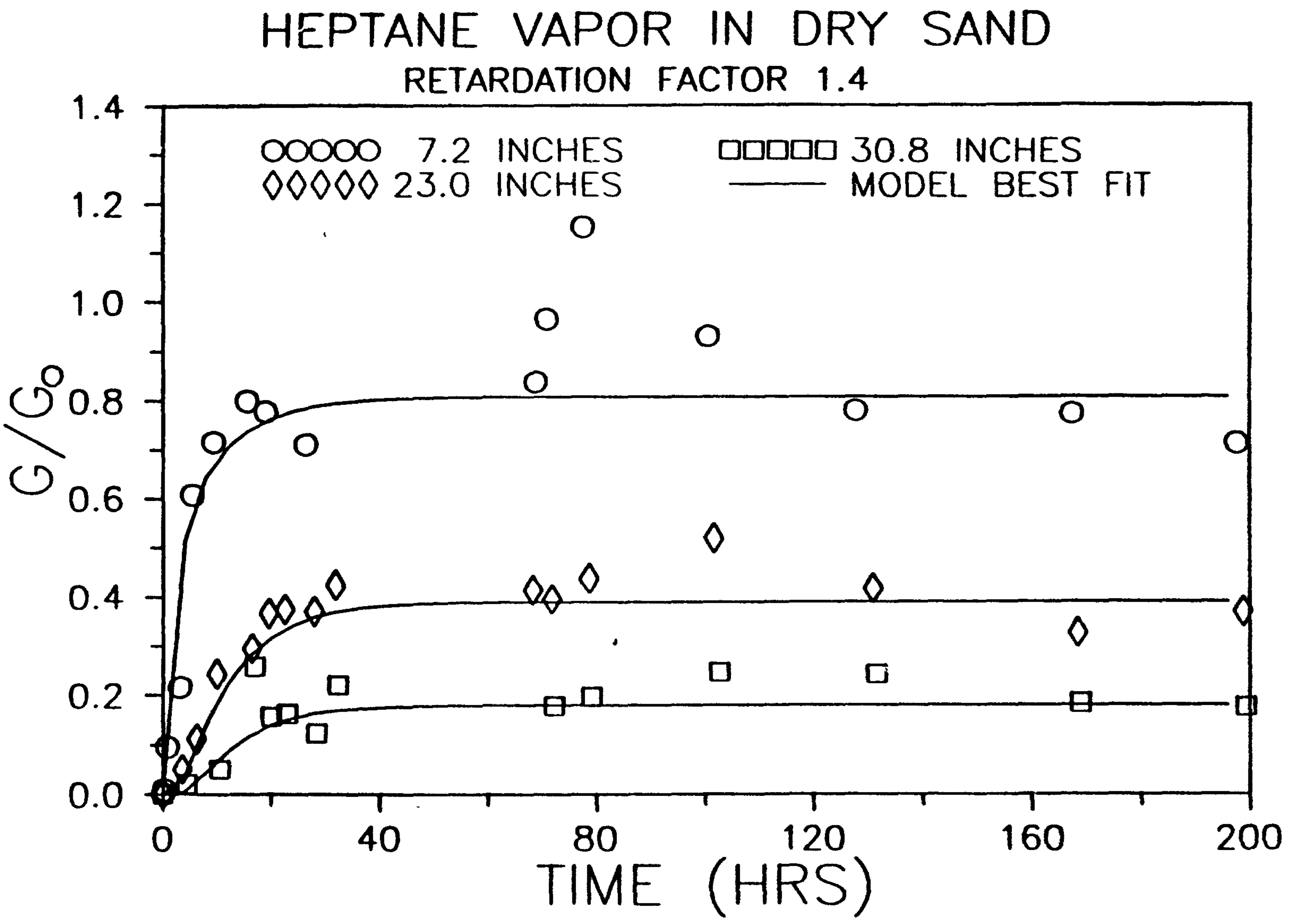


Figure I-8. Experimental and Computed Concentration Versus Time Profiles for Heptane in Dry Sand.

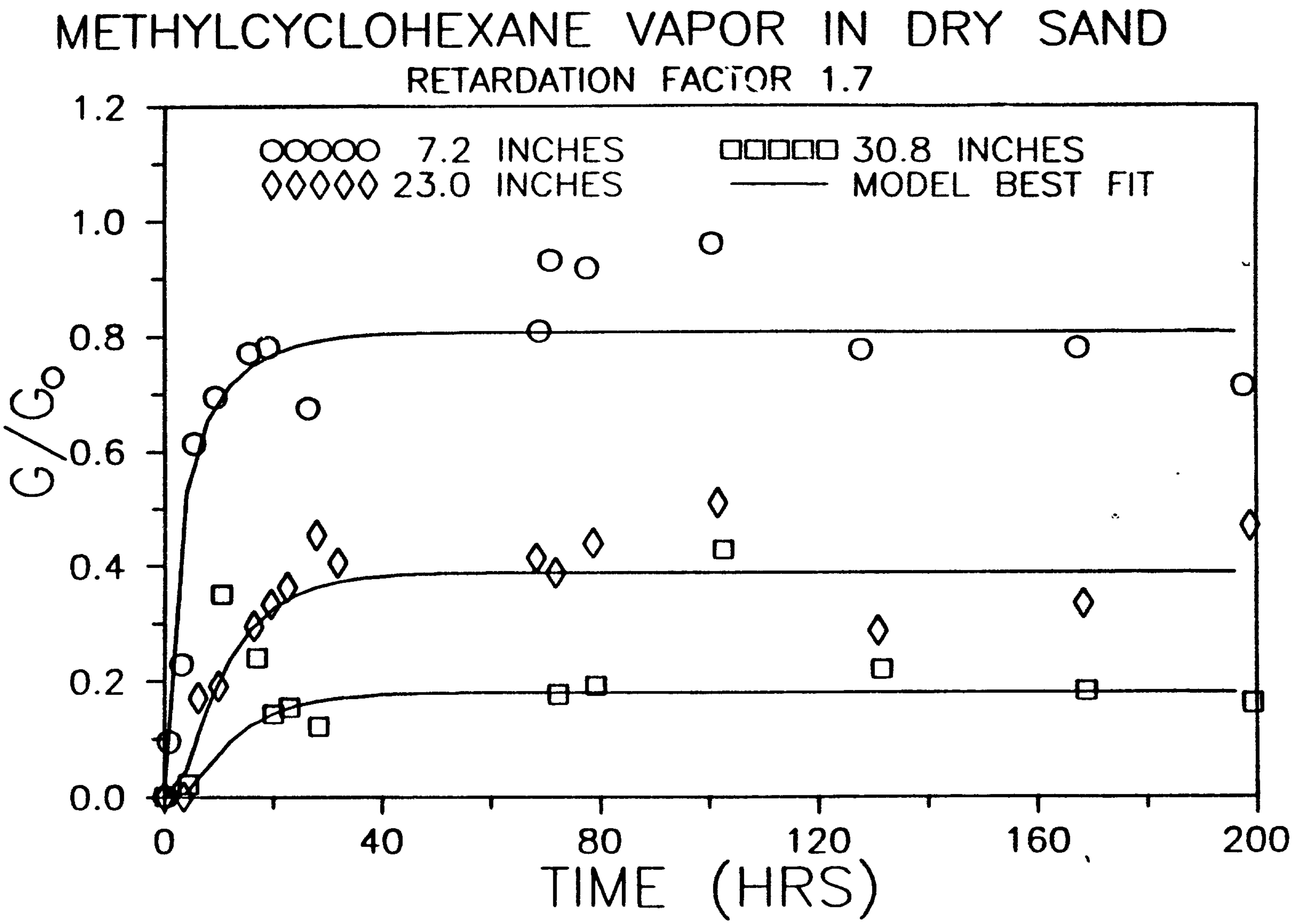


Figure I-9. Experimental and Computed Concentration Versus Time Profiles for Methylcyclohexane in Dry Sand.

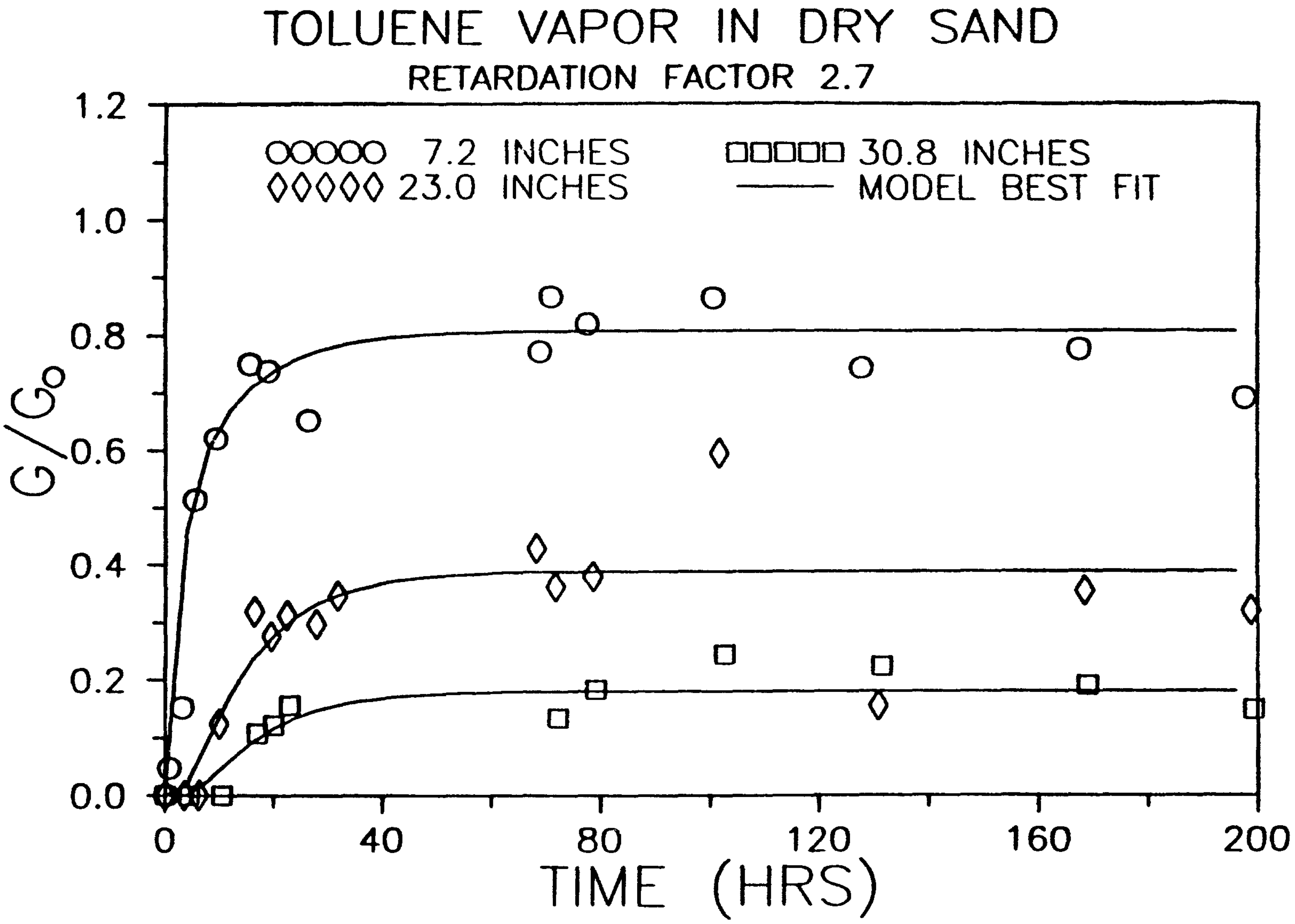


Figure I-10. Experimental and Computed Concentration Versus Time Profiles for Toluene in Dry Sand.

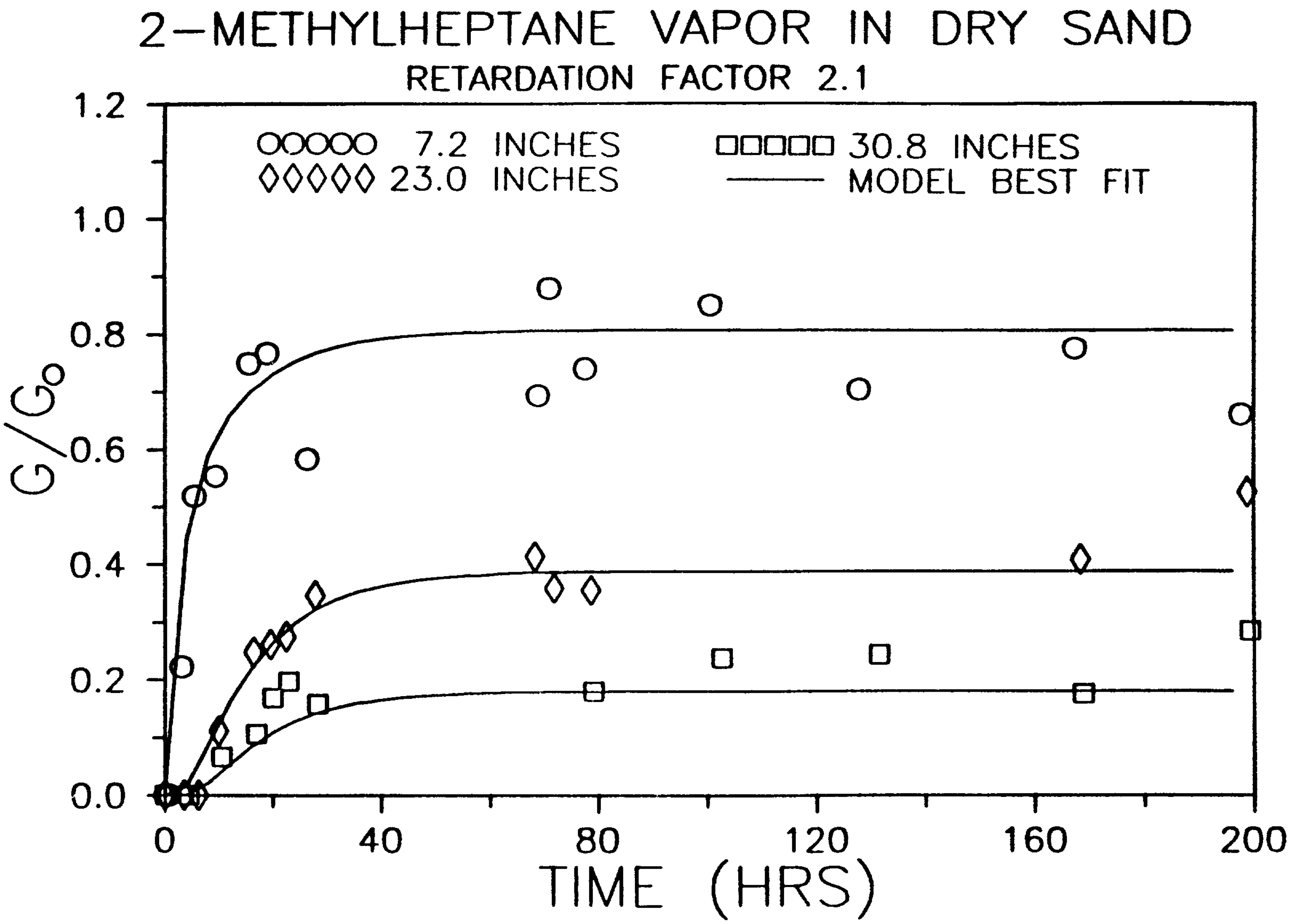


Figure I-11. Experimental and Computed Concentration Versus Time Profiles for 2-Methylheptane in Dry Sand.

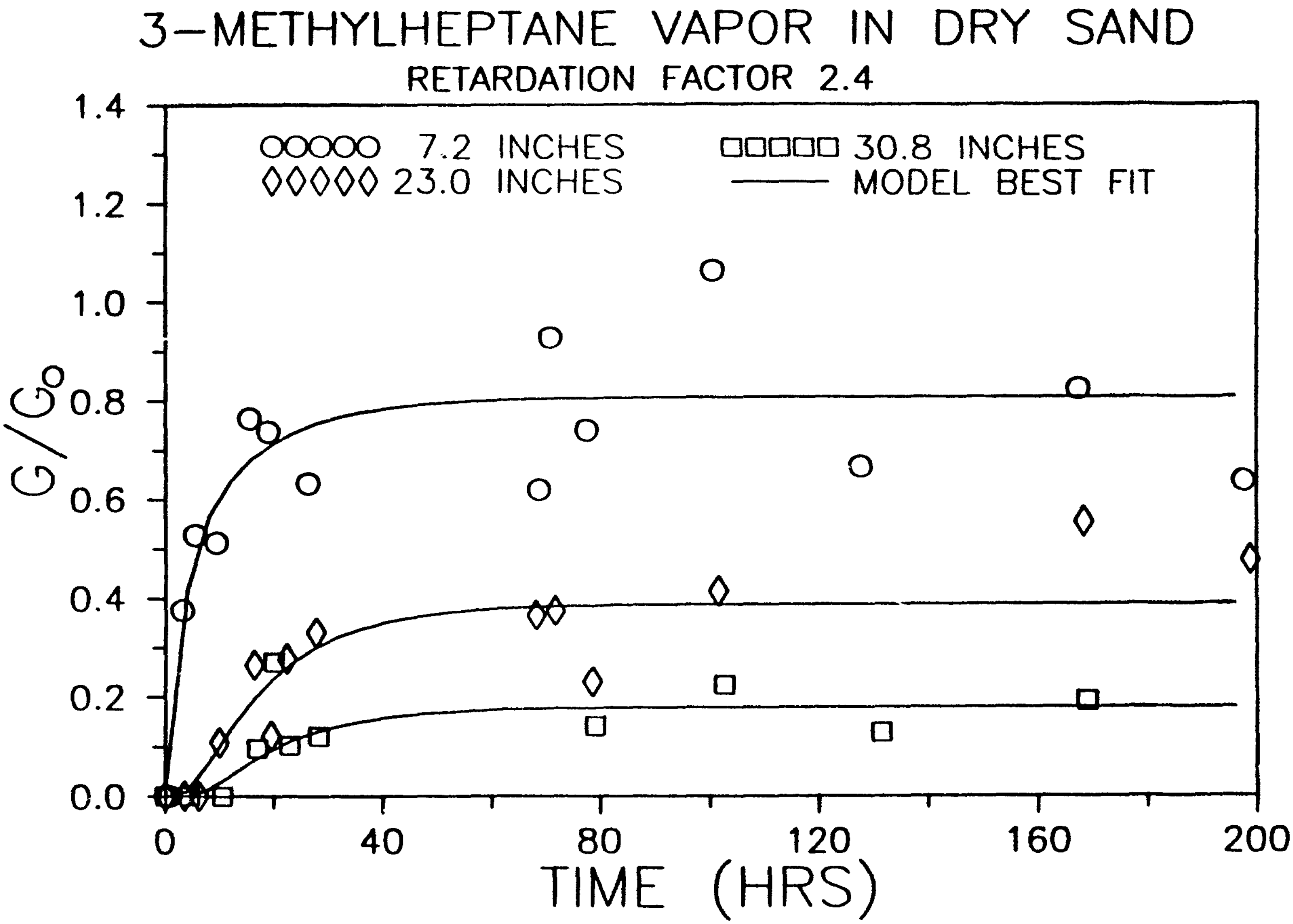


Figure I-12. Experimental and Computed Concentration Versus Time Profiles for 3-Methylheptane in Dry Sand.

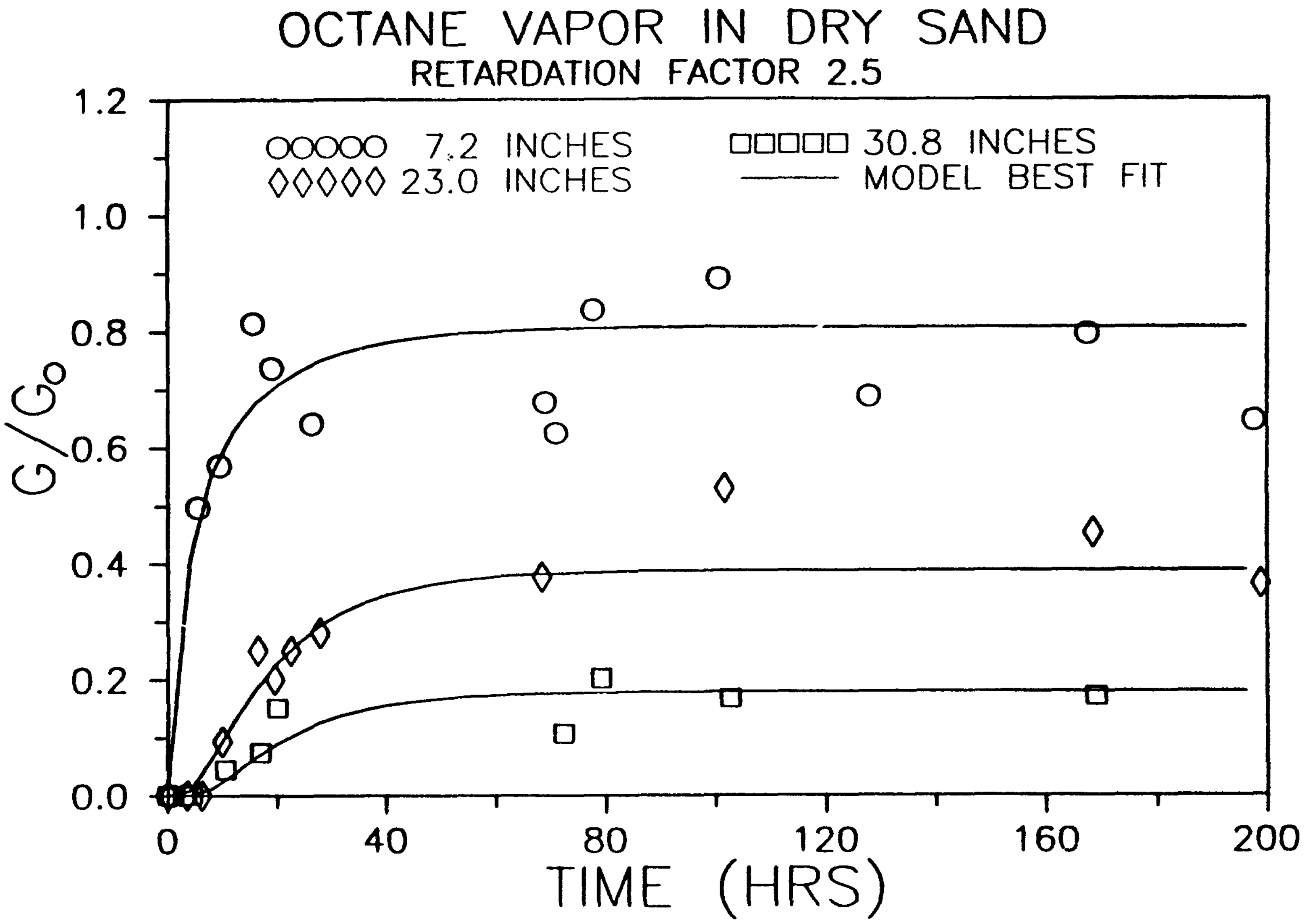


Figure I-13. Experimental and Computed Concentration Versus Time Profiles for Octane in Dry Sand.

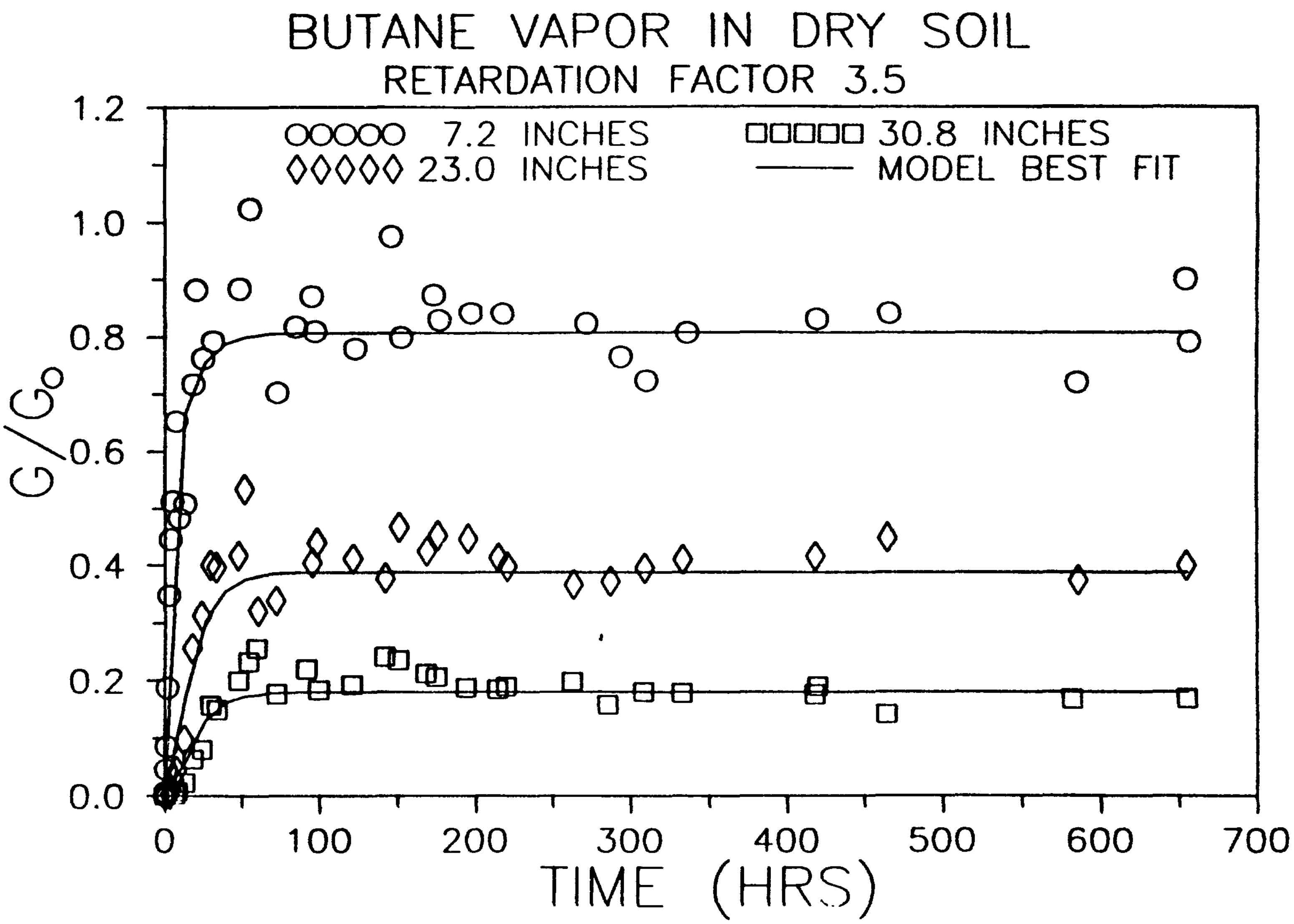


Figure I-14. Experimental and Computed Concentration Versus Time Profiles for Butane in Dry Soil.

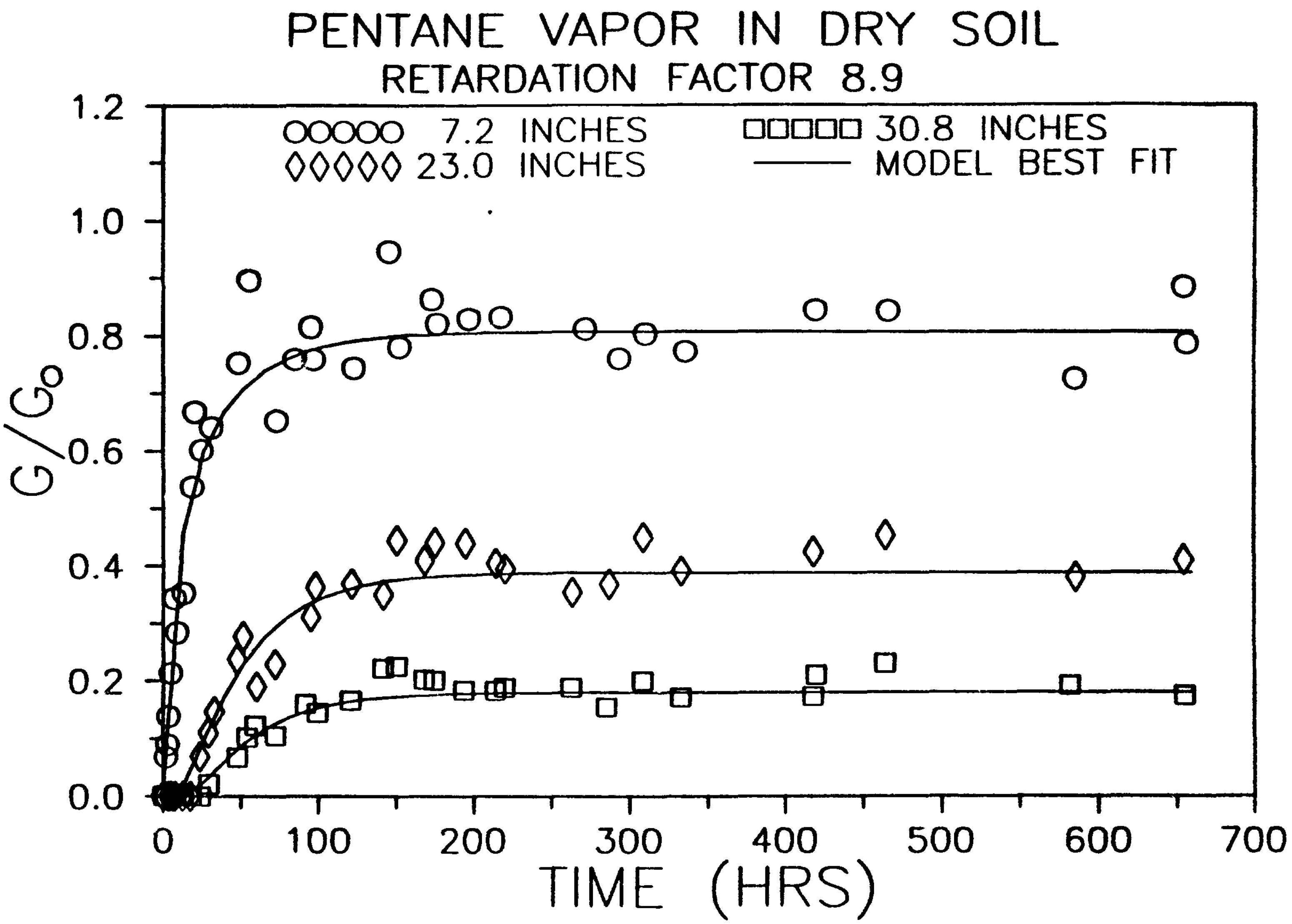


Figure I-15. Experimental and Computed Concentration Versus Time Profiles for Pentane in Dry Soil.

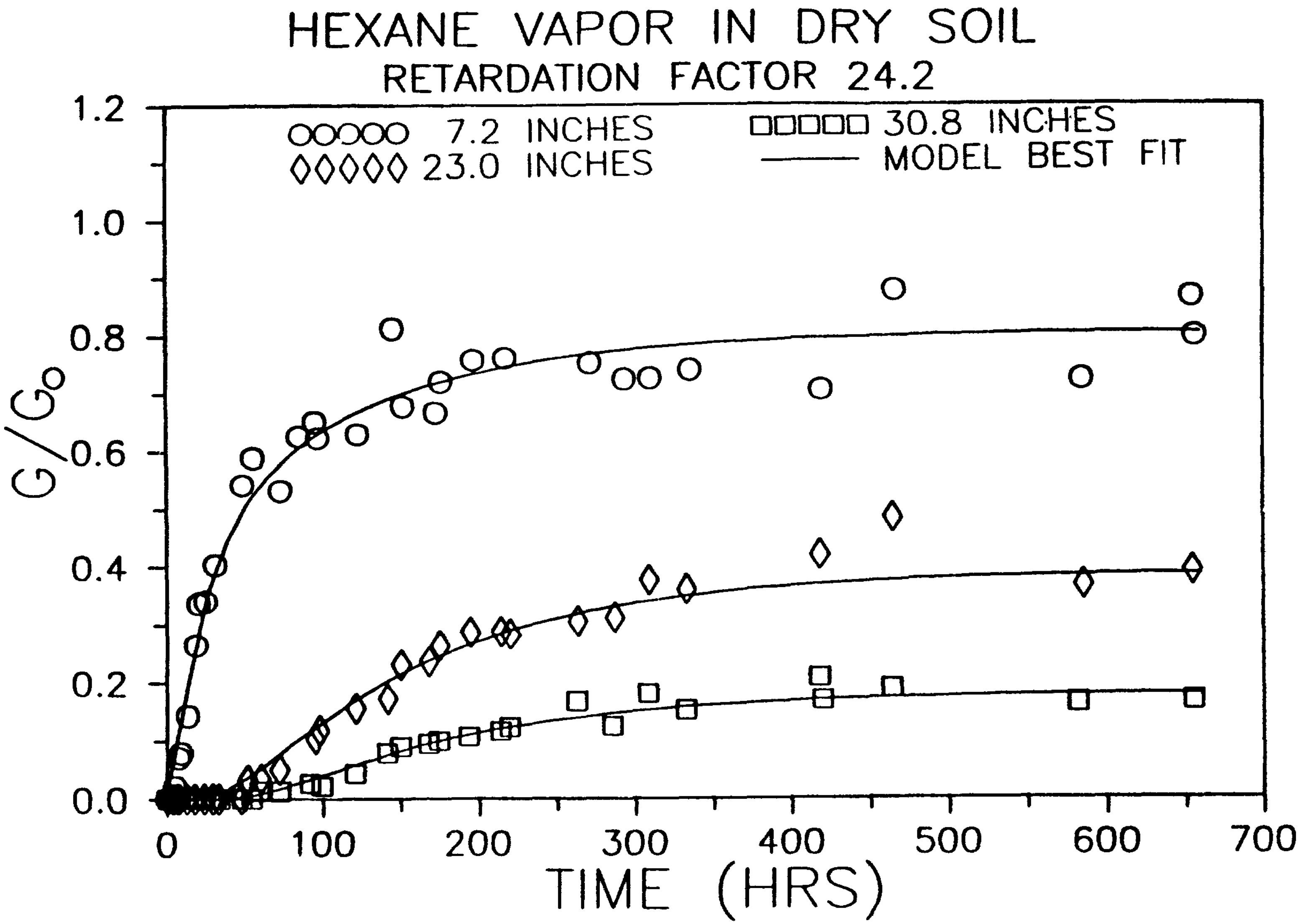


Figure I-16. Experimental and Computed Concentration Versus Time Profiles for Hexane in Dry Soil.

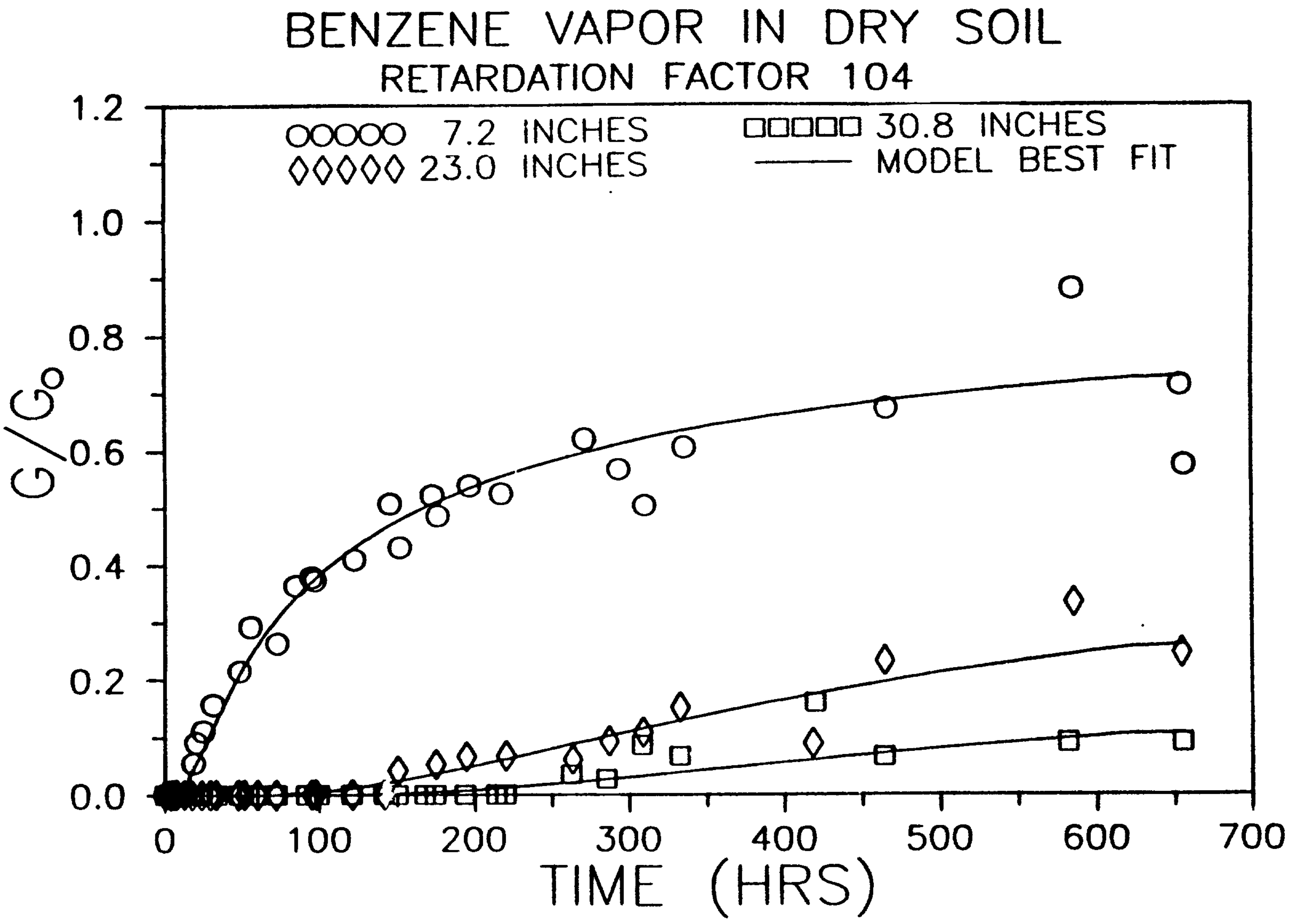


Figure I-17. Experimental and Computed Concentration Versus Time Profiles for Benzene in Dry Soil.

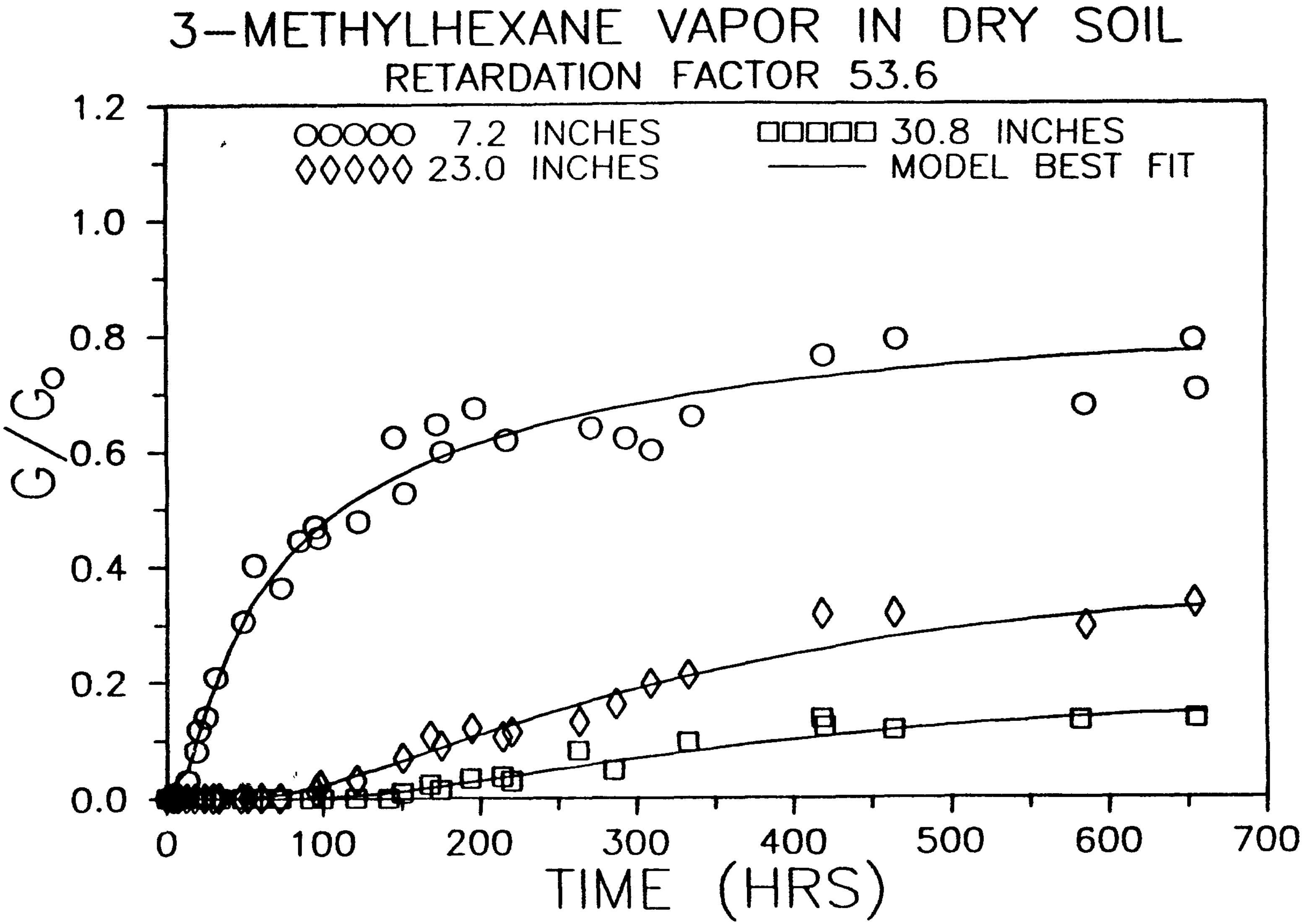


Figure I-18. Experimental and Computed Concentration Versus Time Profiles for 3-Methylhexane in Dry Soil.

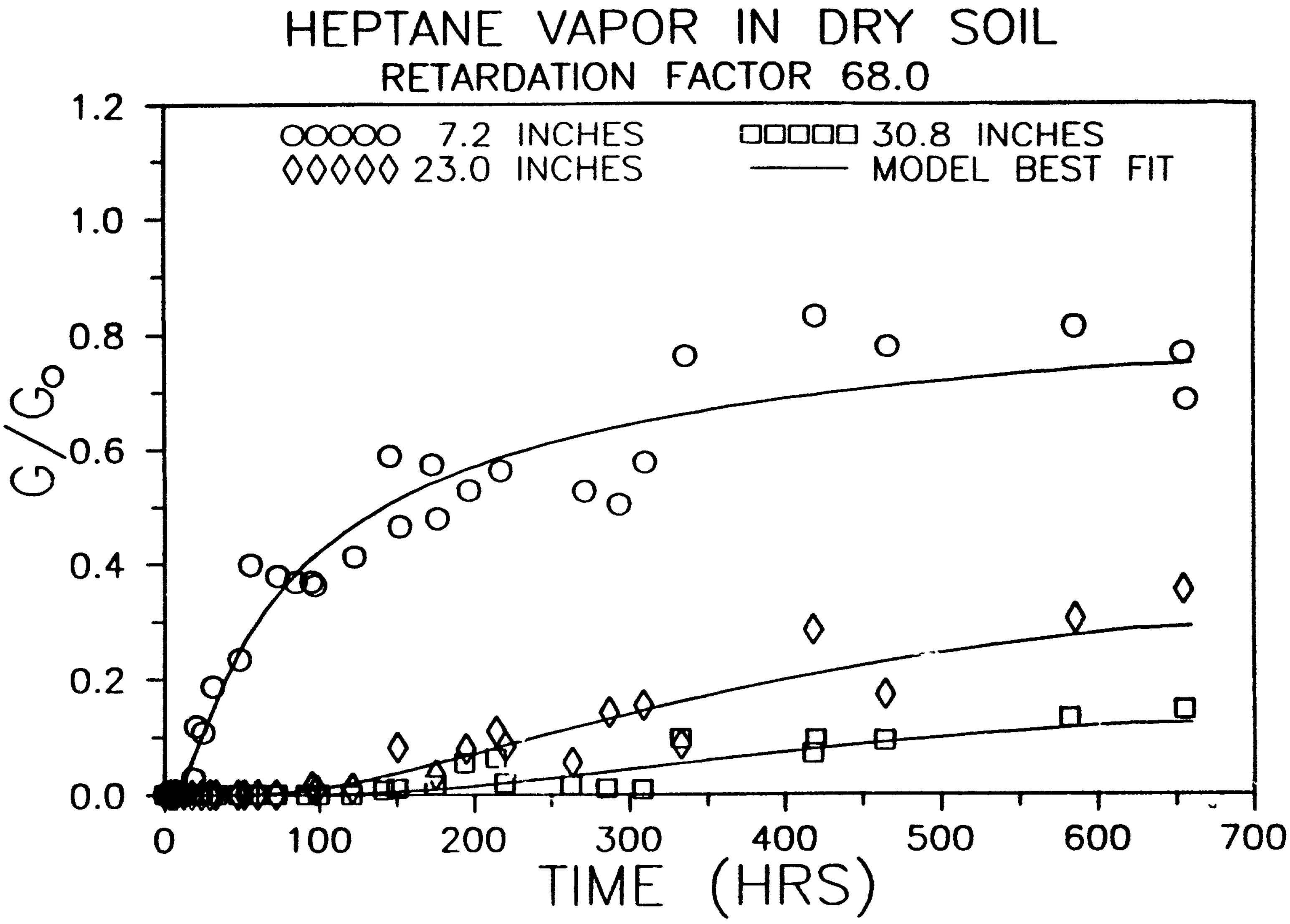


Figure I-19. Experimental and Computed Concentration Versus Time Profiles for Heptane in Dry Soil.

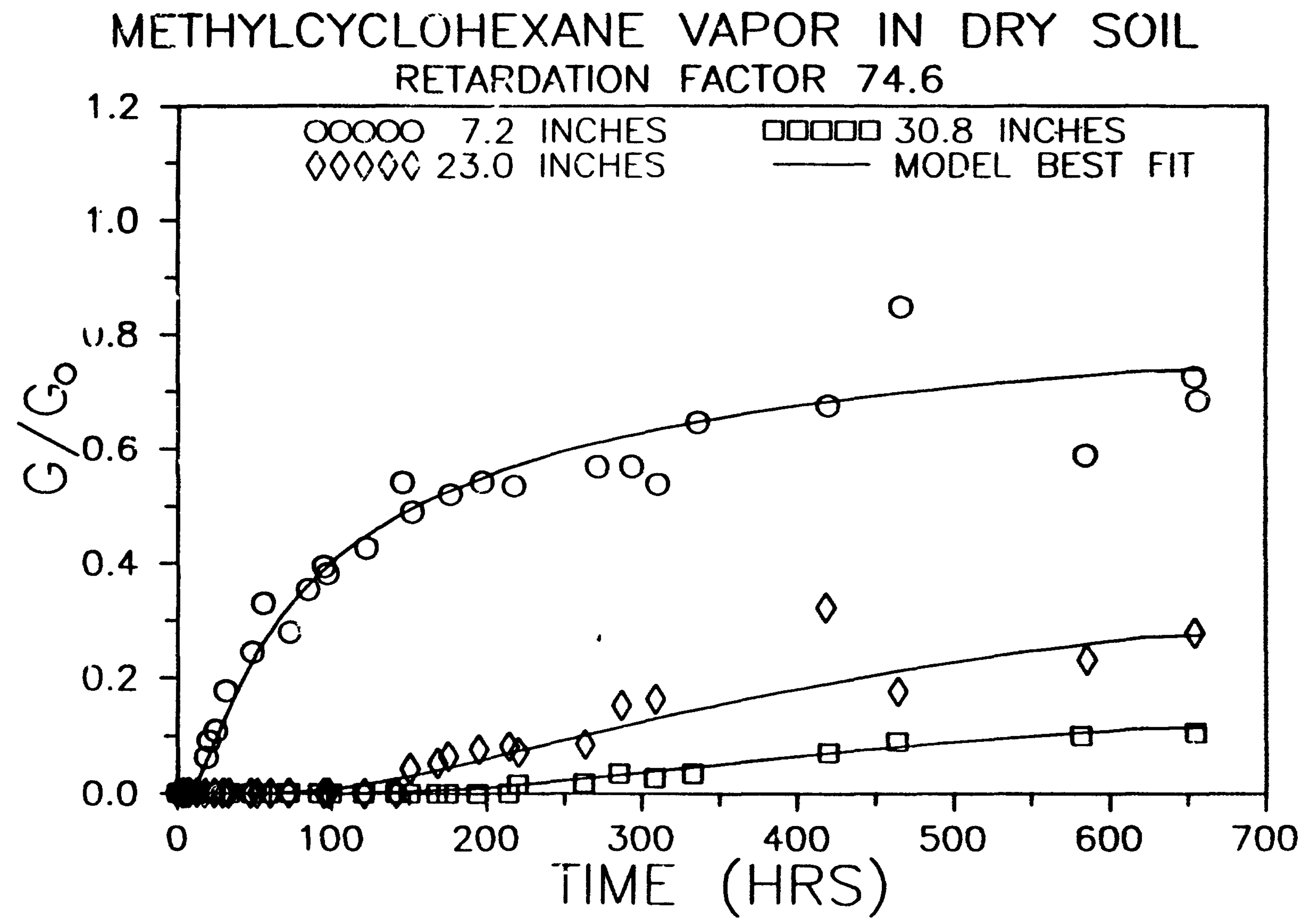


Figure I-20. Experimental and Computed Concentration Versus Time Profiles for Methylcyclohexane in Dry Soil.

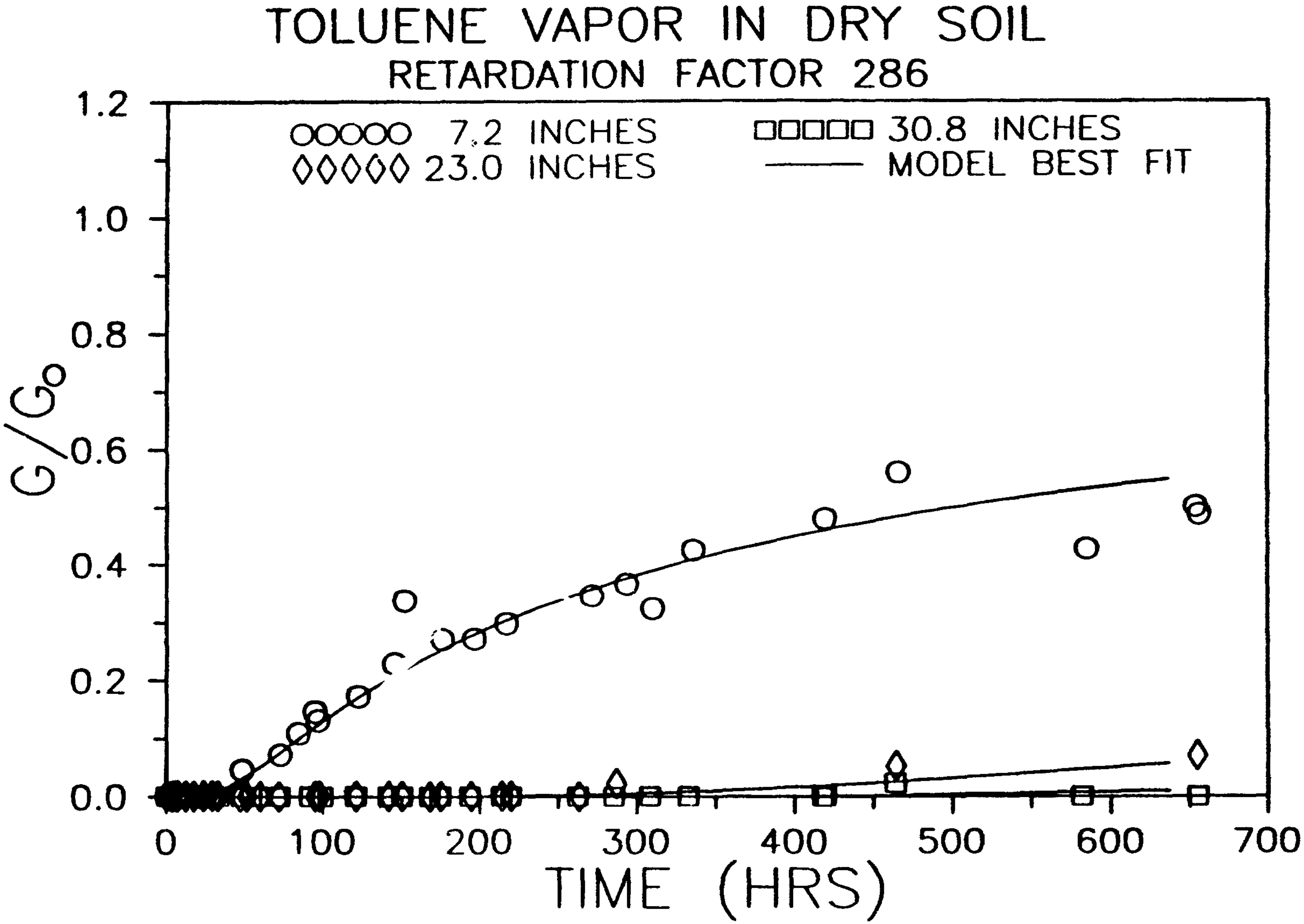


Figure I-21. Experimental and Computed Concentration Versus Time Profiles for Toluene in Dry Soil.

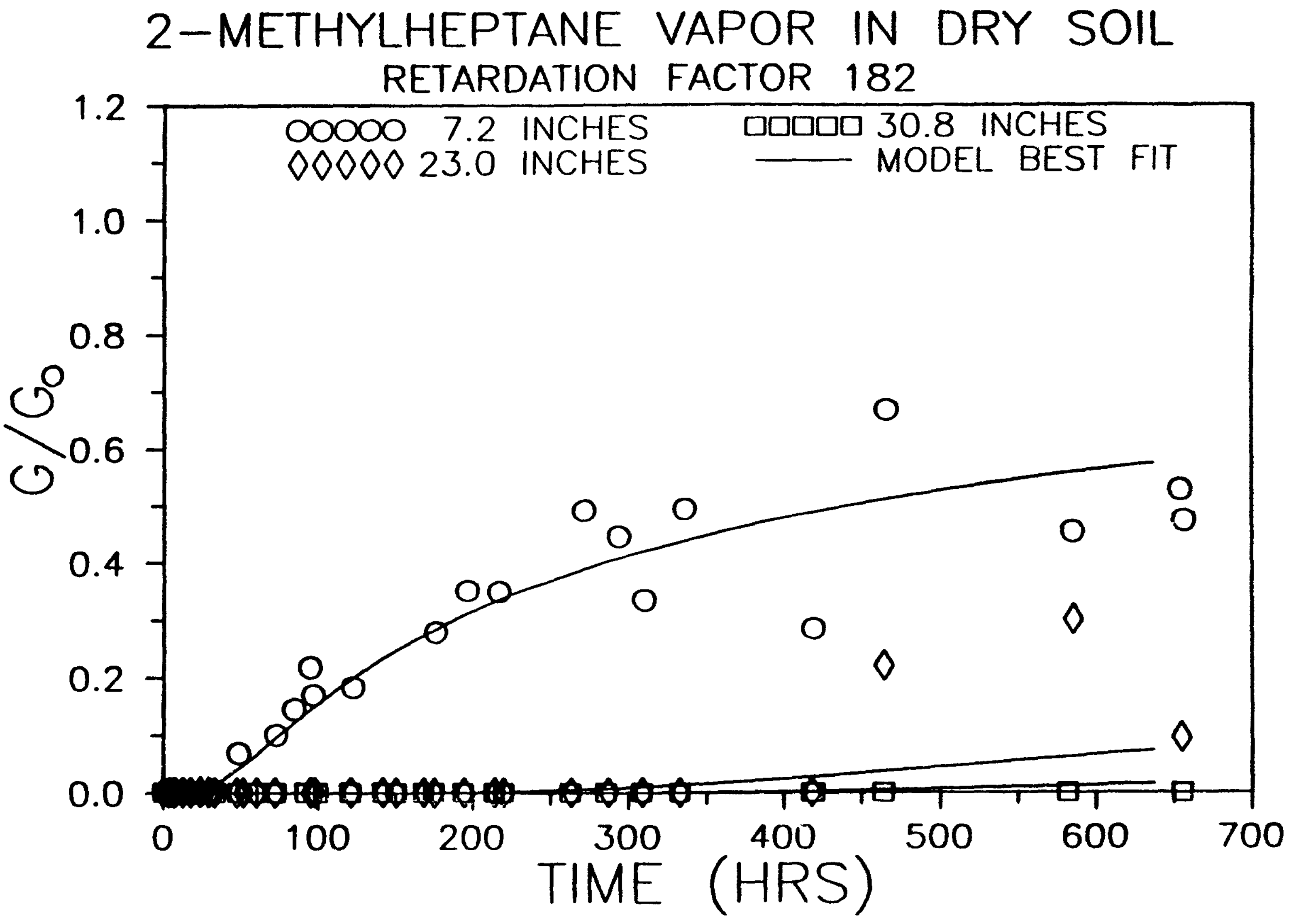


Figure I-22. Experimental and Computed Concentration Versus Time Profiles for 2-Methylheptane in Dry Soil.

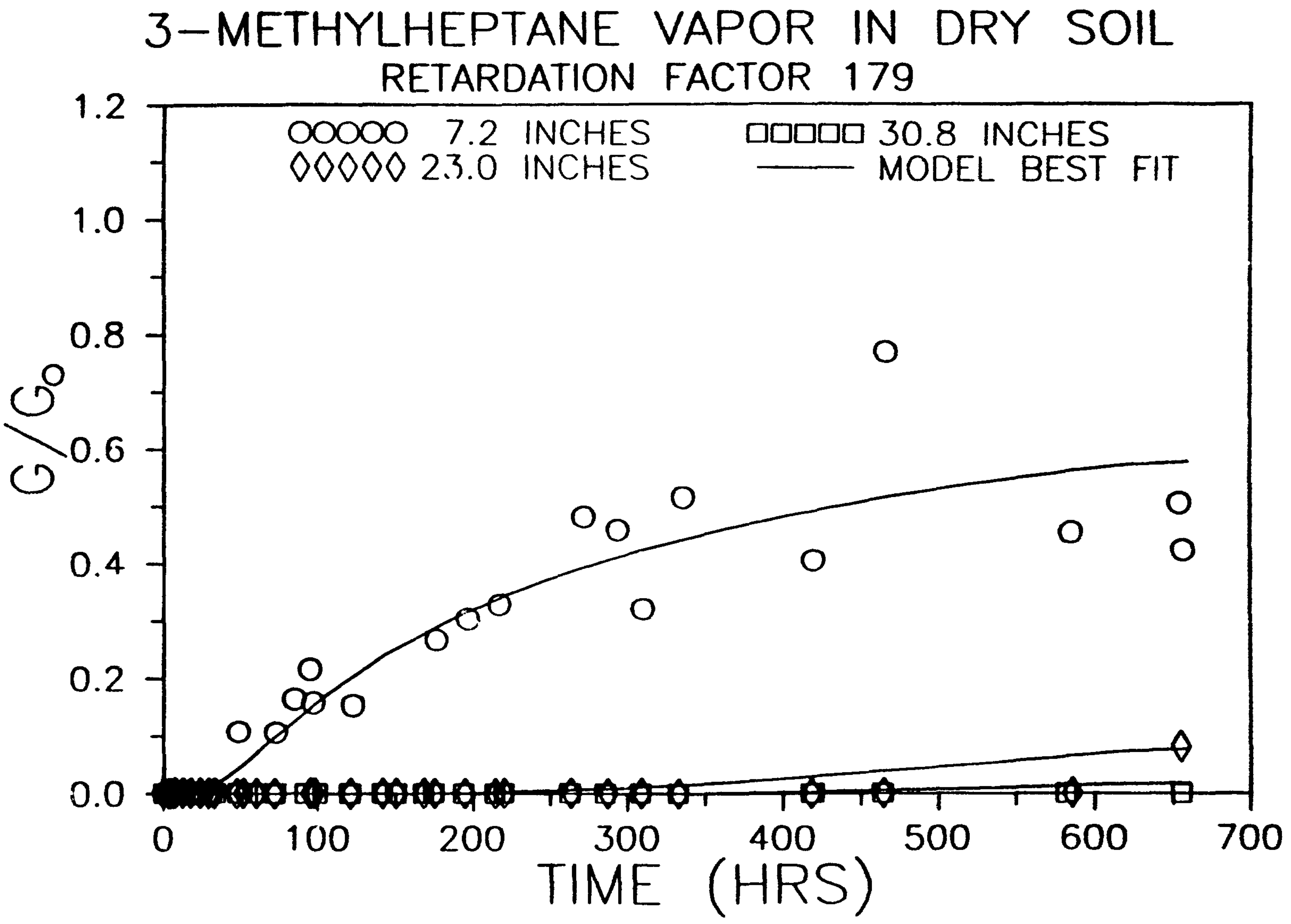


Figure I-23. Experimental and Computed Concentration Versus Time Profiles for 3-Methylheptane in Dry Soil.

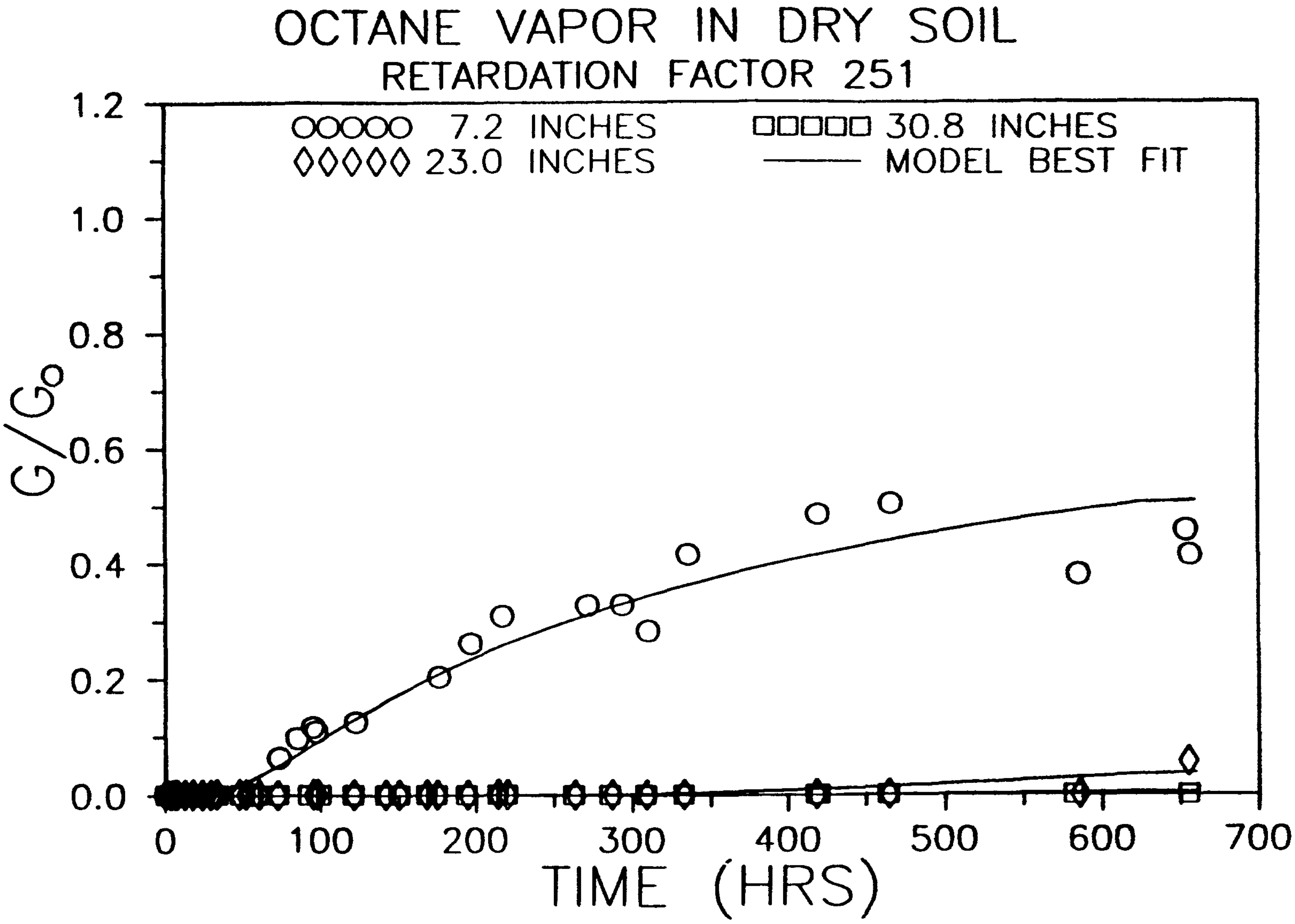


Figure I-24. Experimental and Computed Concentration Versus Time Profiles for Octane in Dry Soil.

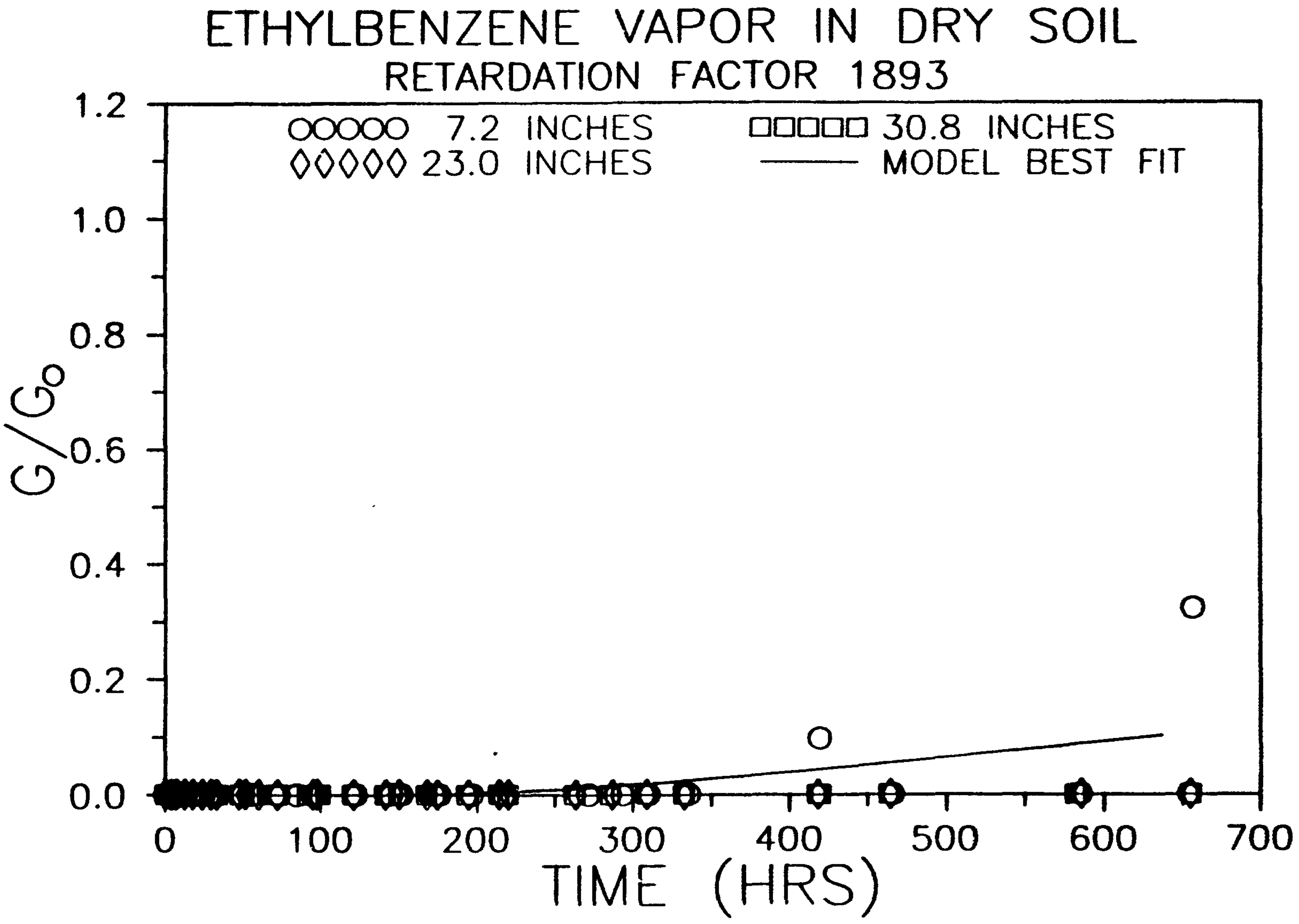


Figure I-25. Experimental and Computed Concentration Versus Time Profiles for Ethylbenzene in Dry Soil.

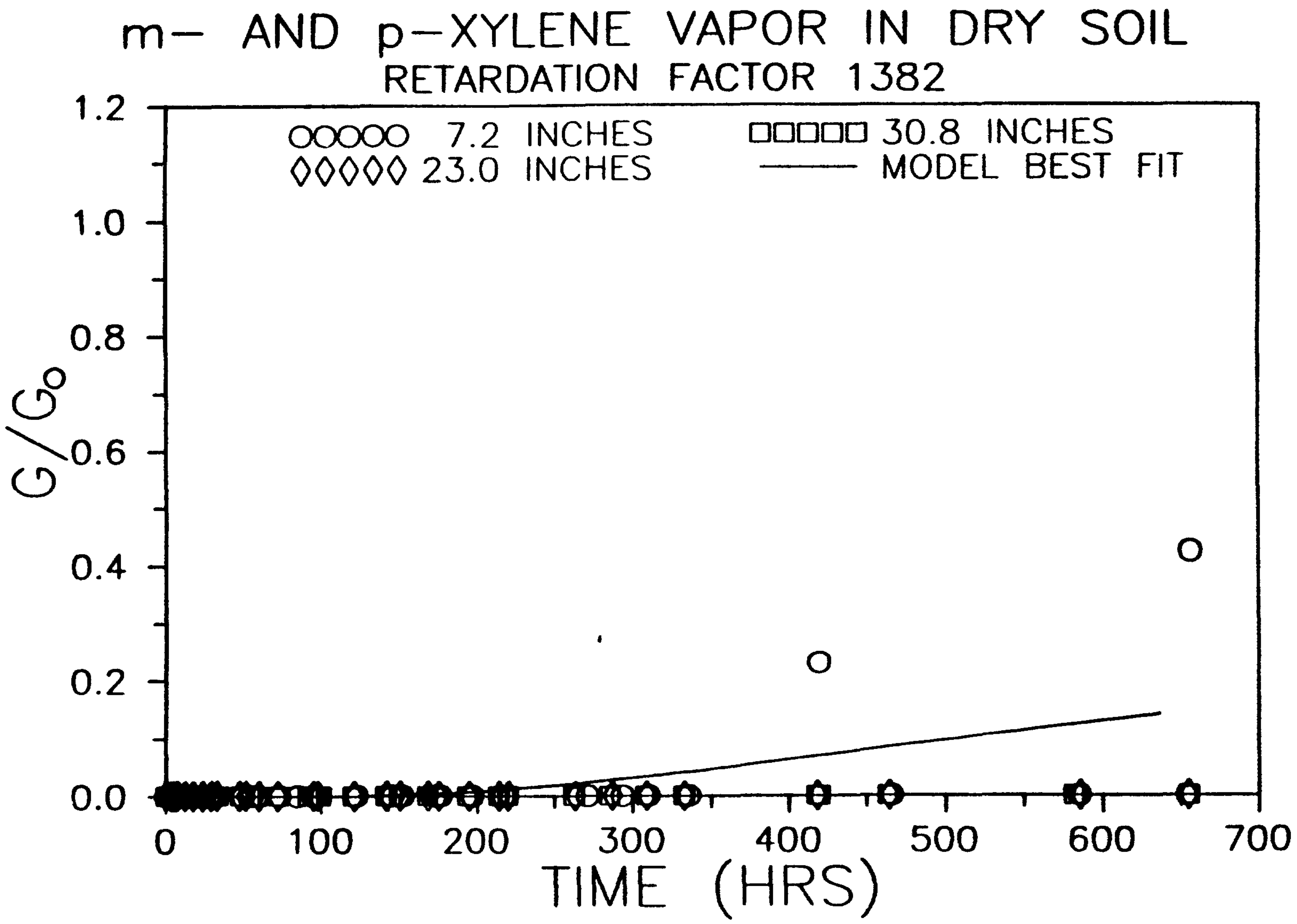


Figure I-26. Experimental and Computed Concentration Versus Time Profiles for m- and p-Xylene in Dry Soil.

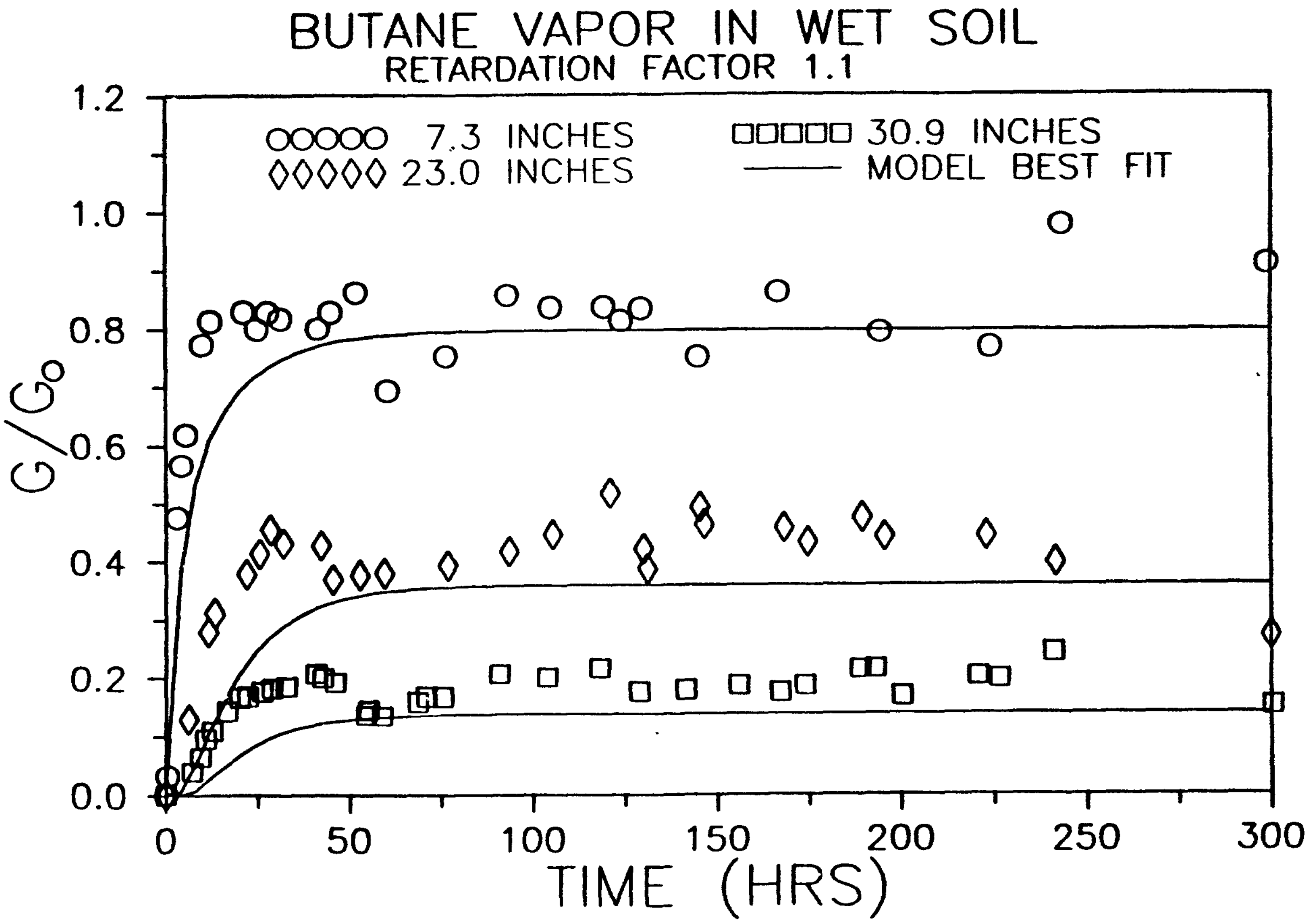


Figure I-27. Experimental and Computed Concentration Versus Time Profiles for Butane in Wet Soil.

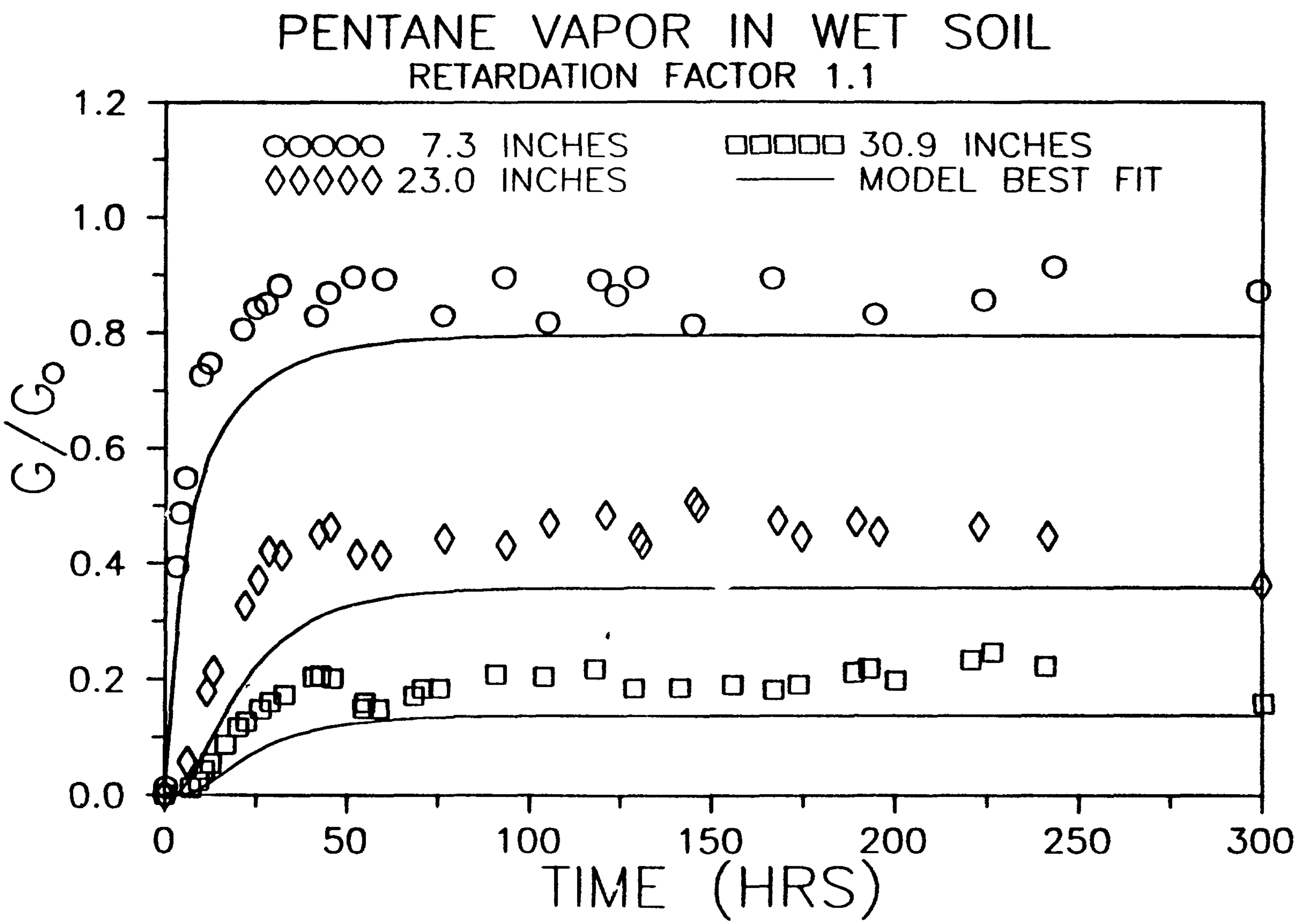


Figure I-28. Experimental and Computed Concentration Versus Time Profiles for Pentane in Wet Soil.

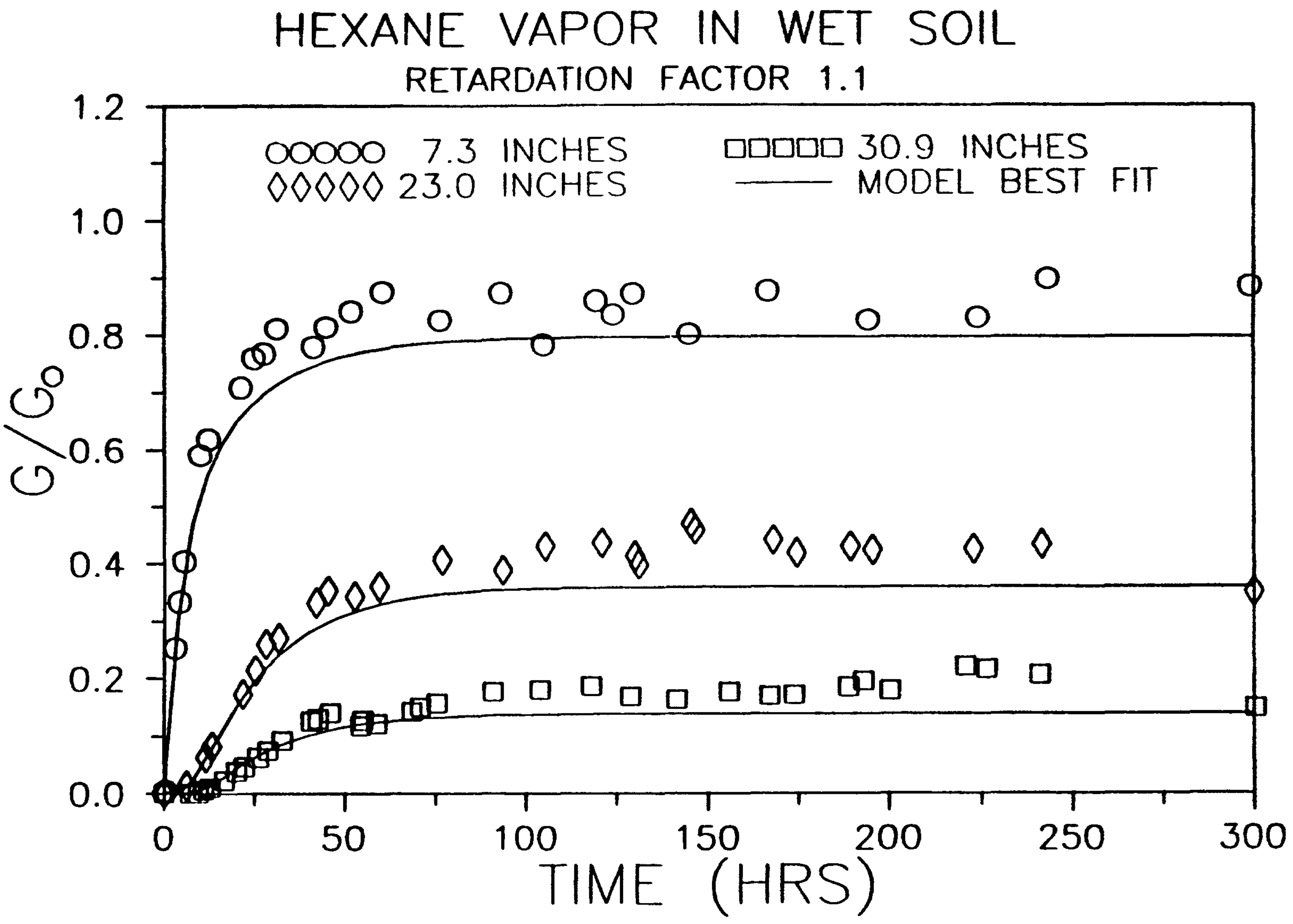


Figure I-29. Experimental and Computed Concentration Versus Time Profiles for Hexane in Wet Soil.

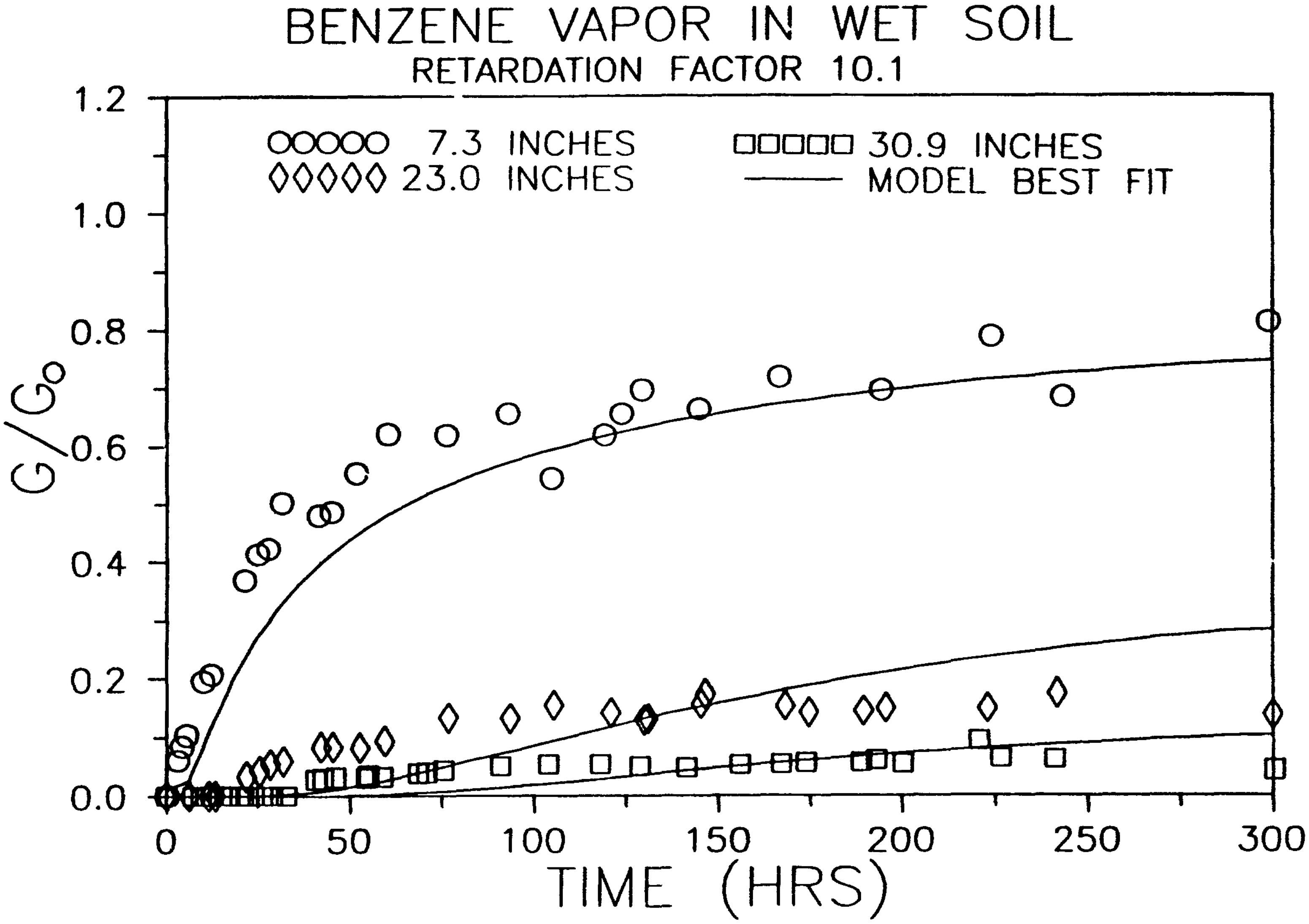


Figure I-30. Experimental and Computed Concentration Versus Time Profiles for Benzene in Wet Soil.

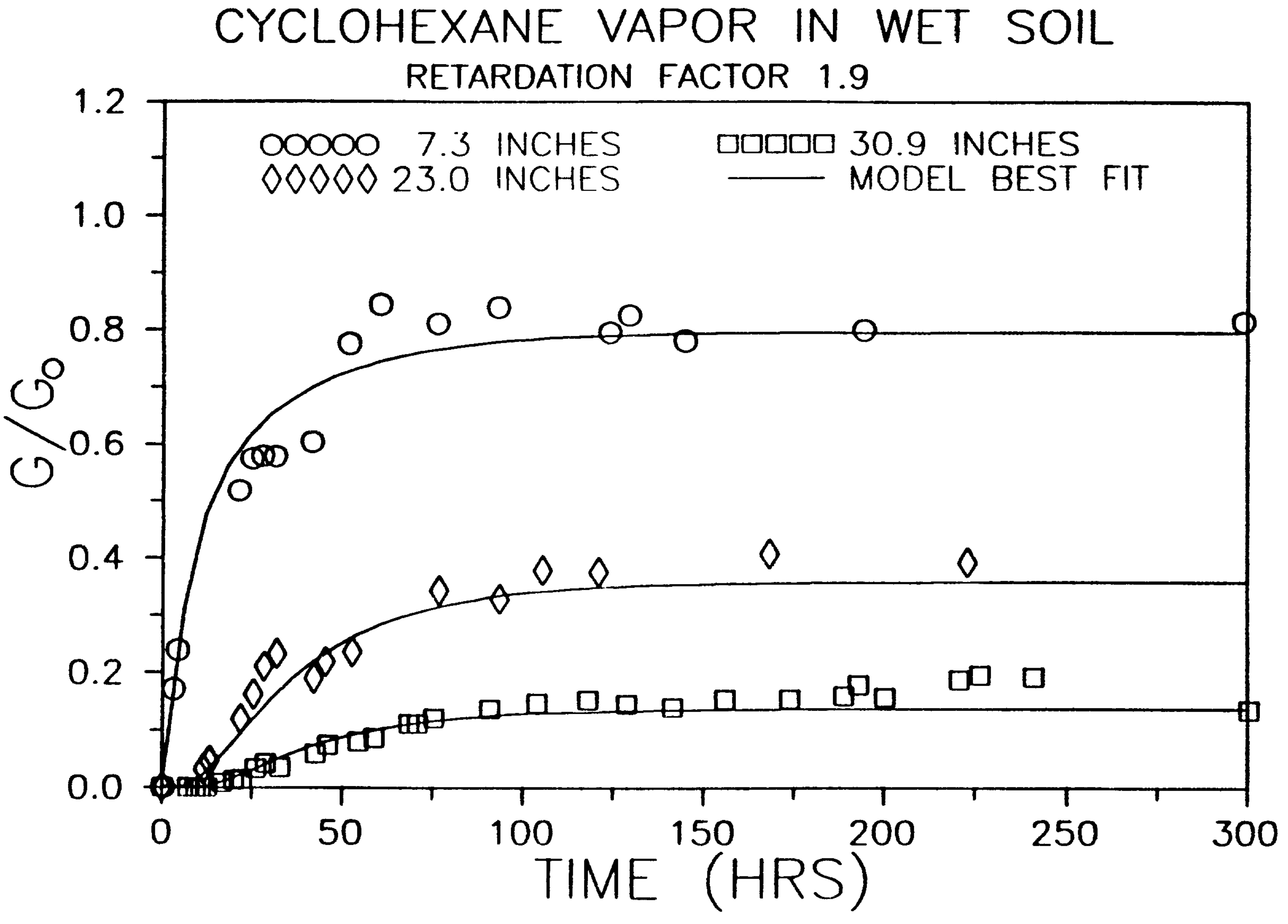


Figure I-31. Experimental and Computed Concentration Versus Time Profiles for Cyclohexane in Wet Soil.

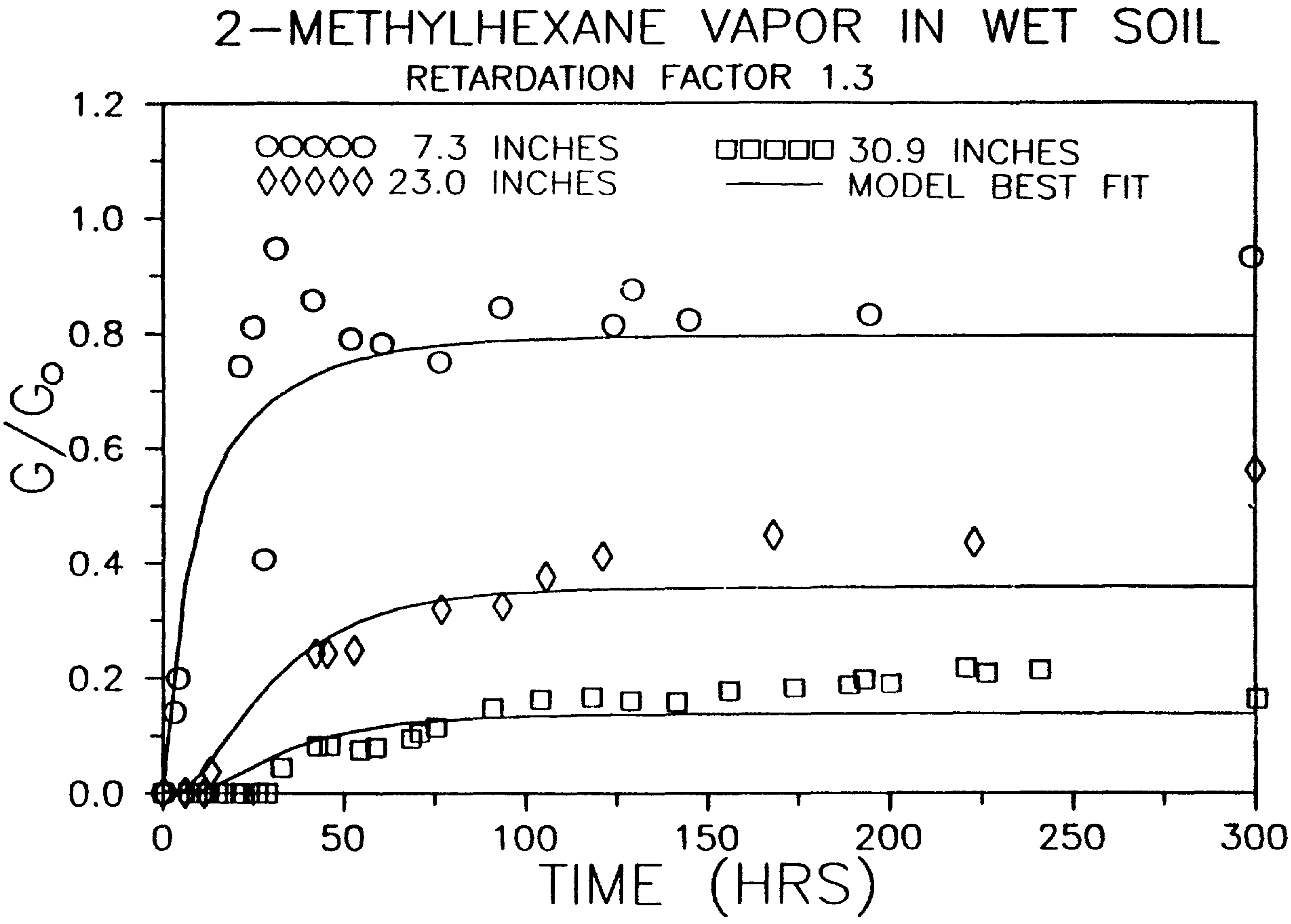


Figure I-32. Experimental and Computed Concentration Versus Time Profiles for 2-Methylhexane in Wet Soil.

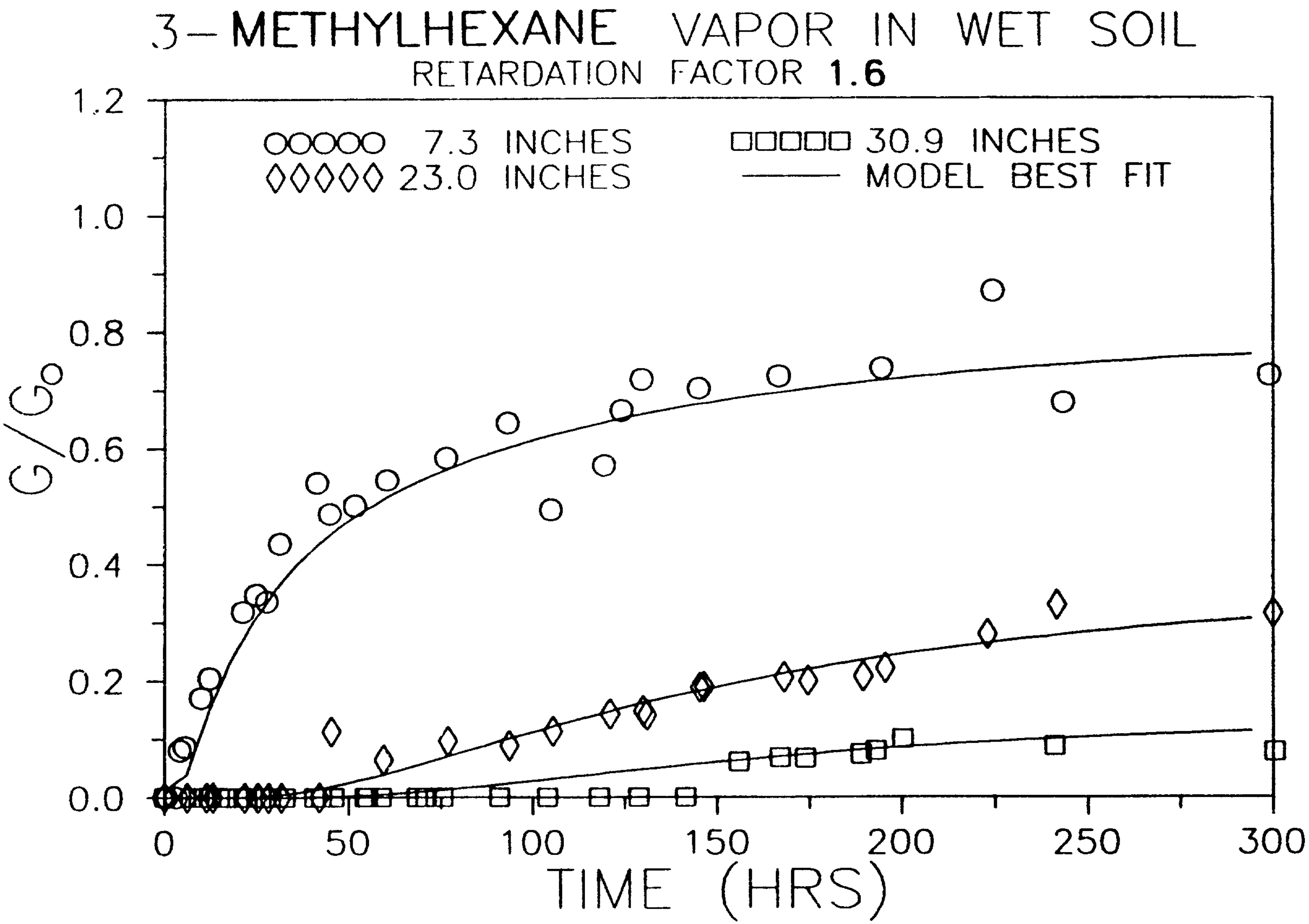


Figure I-33. Experimental and Computed Concentration Versus Time Profiles for 3-Methylhexane in Wet Soil.

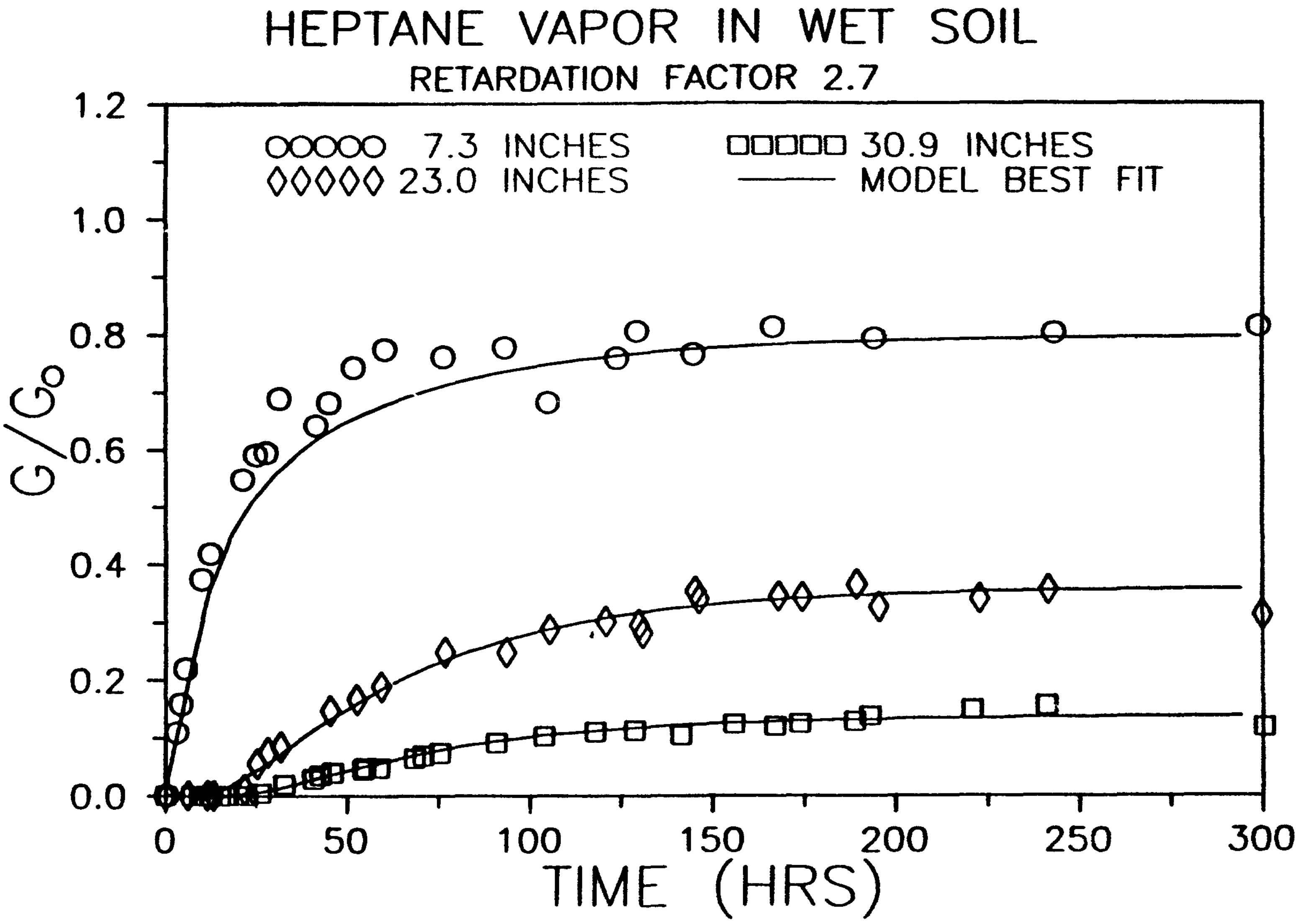


Figure I-34. Experimental and Computed Concentration Versus Time Profiles for Heptane in Wet Soil.

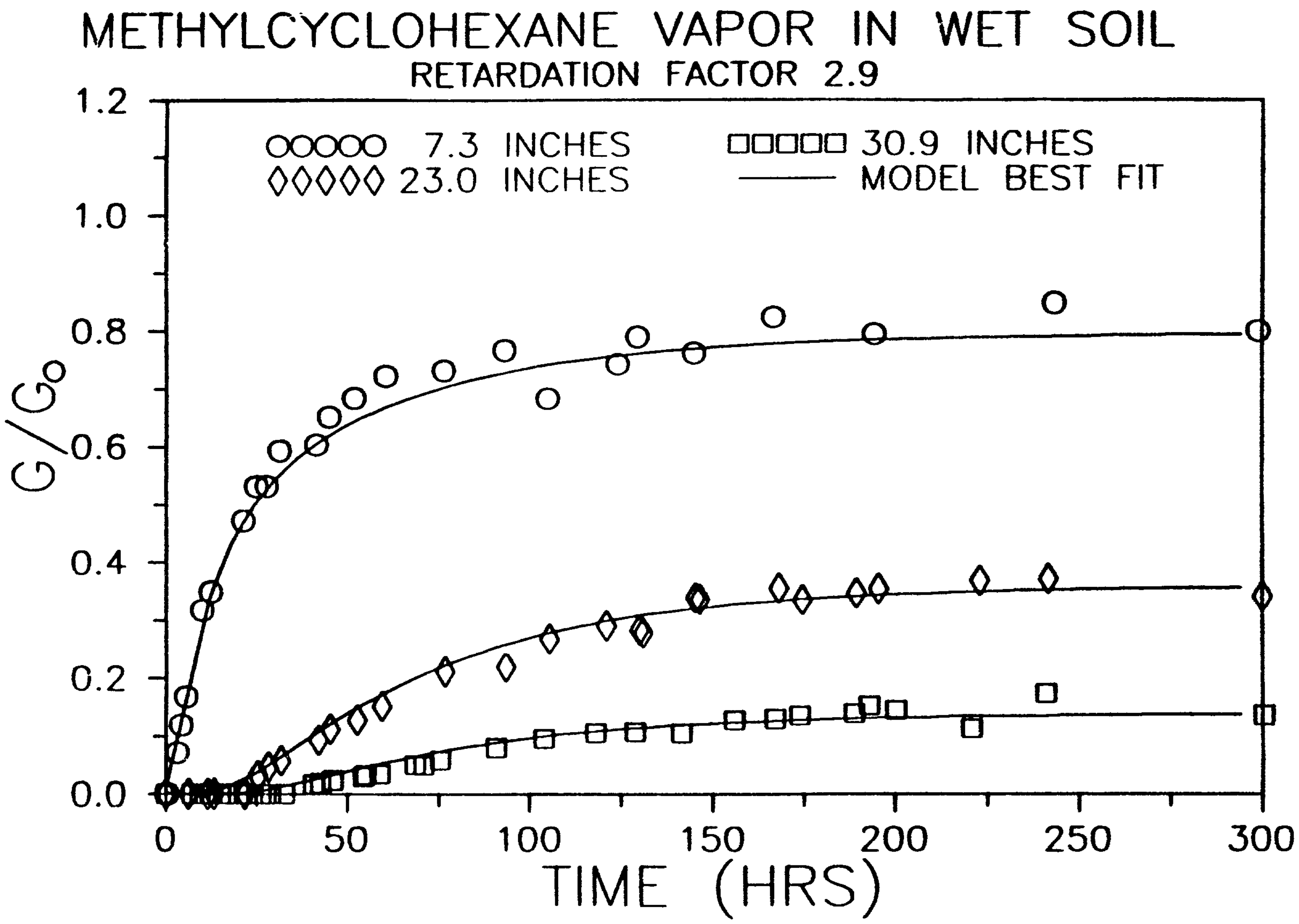


Figure I-35. Experimental and Computed Concentration Versus Time Profiles for Methylcyclohexane in Wet Soil.

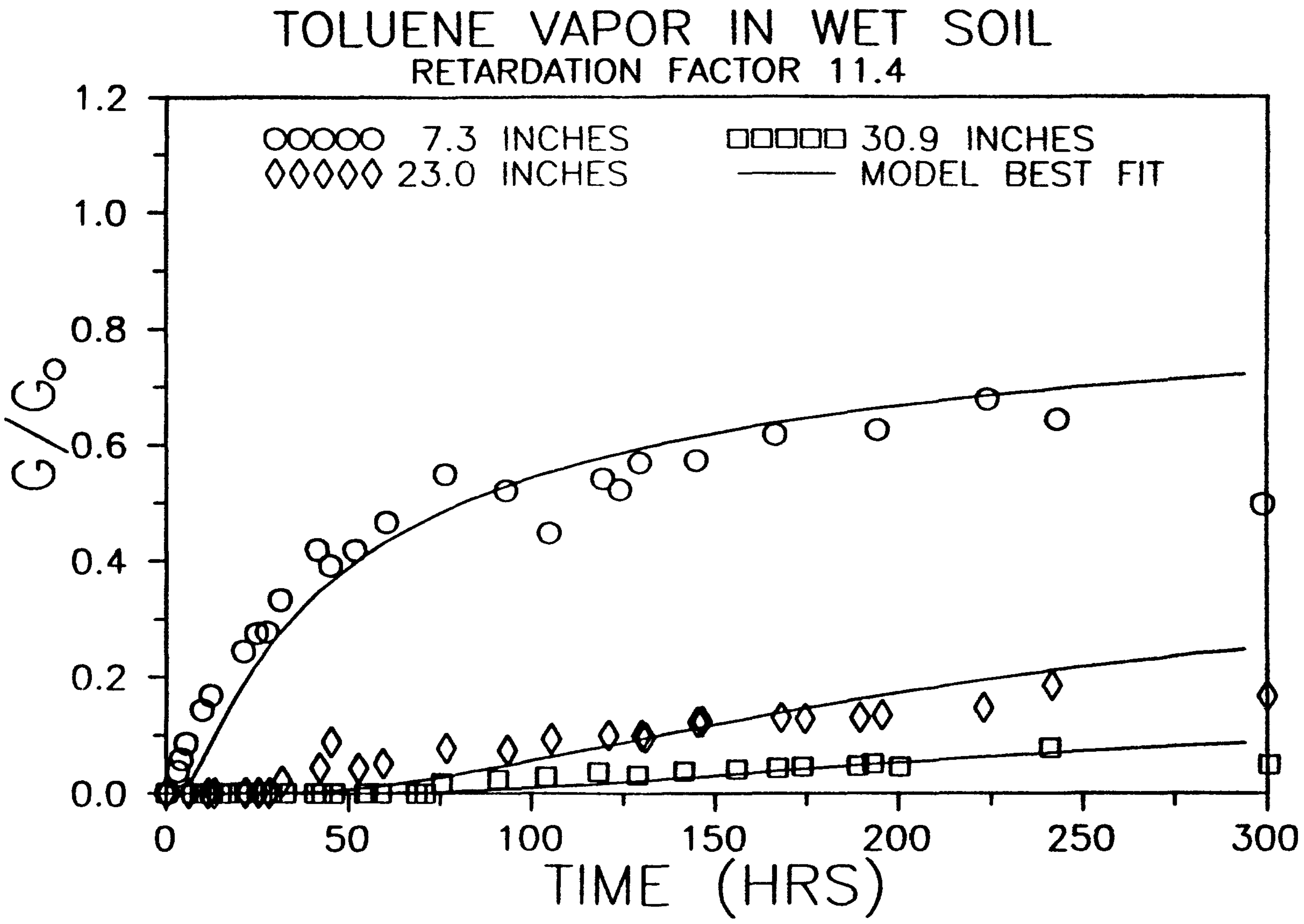


Figure I-36. Experimental and Computed Concentration Versus Time Profiles for Toluene in Wet Soil.

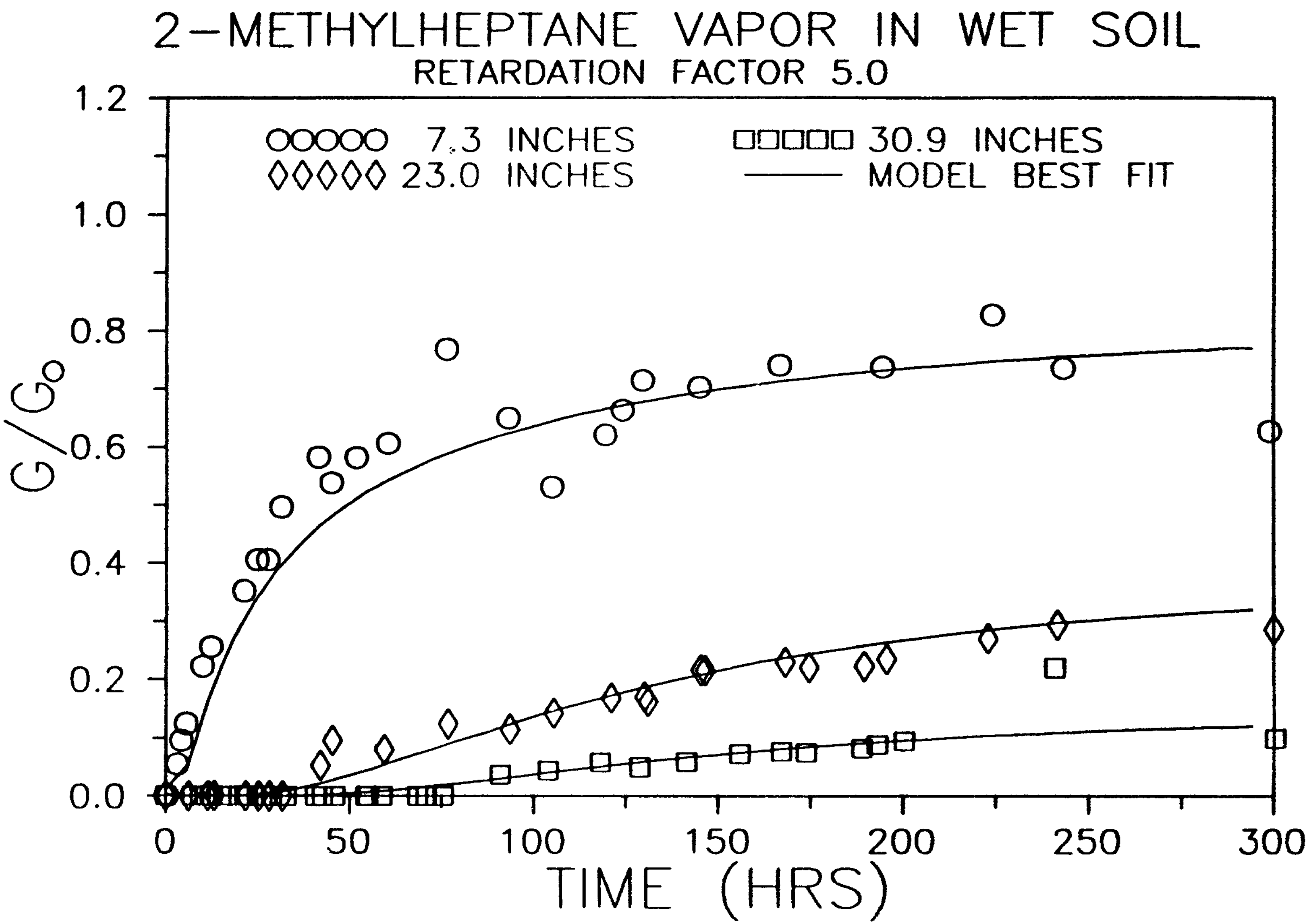


Figure I-37. Experimental and Computed Concentration Versus Time Profiles for 2-Methylheptane in Wet Soil.

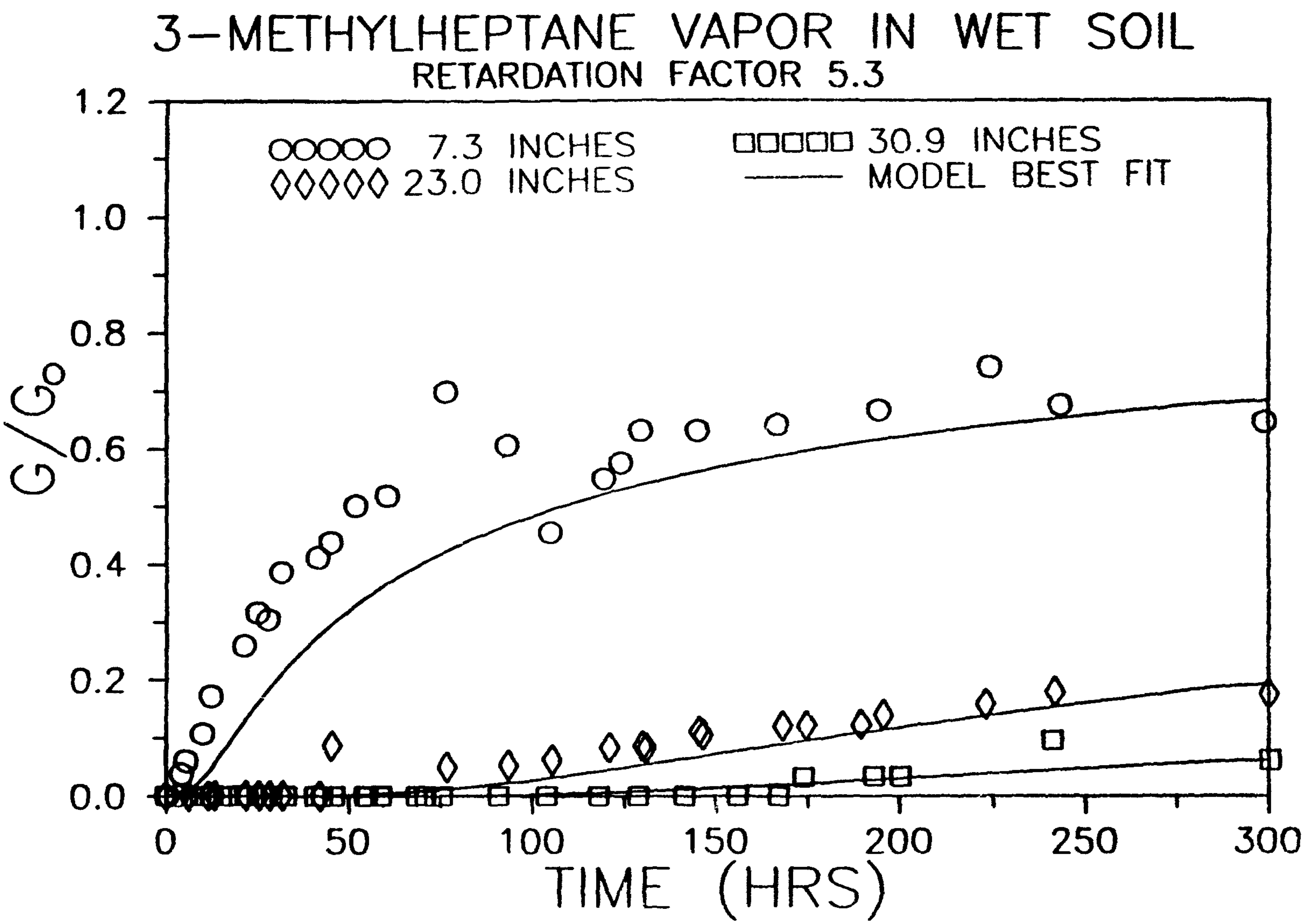


Figure I-38. Experimental and Computed Concentration Versus Time Profiles for 3-Methylheptane in Wet Soil.

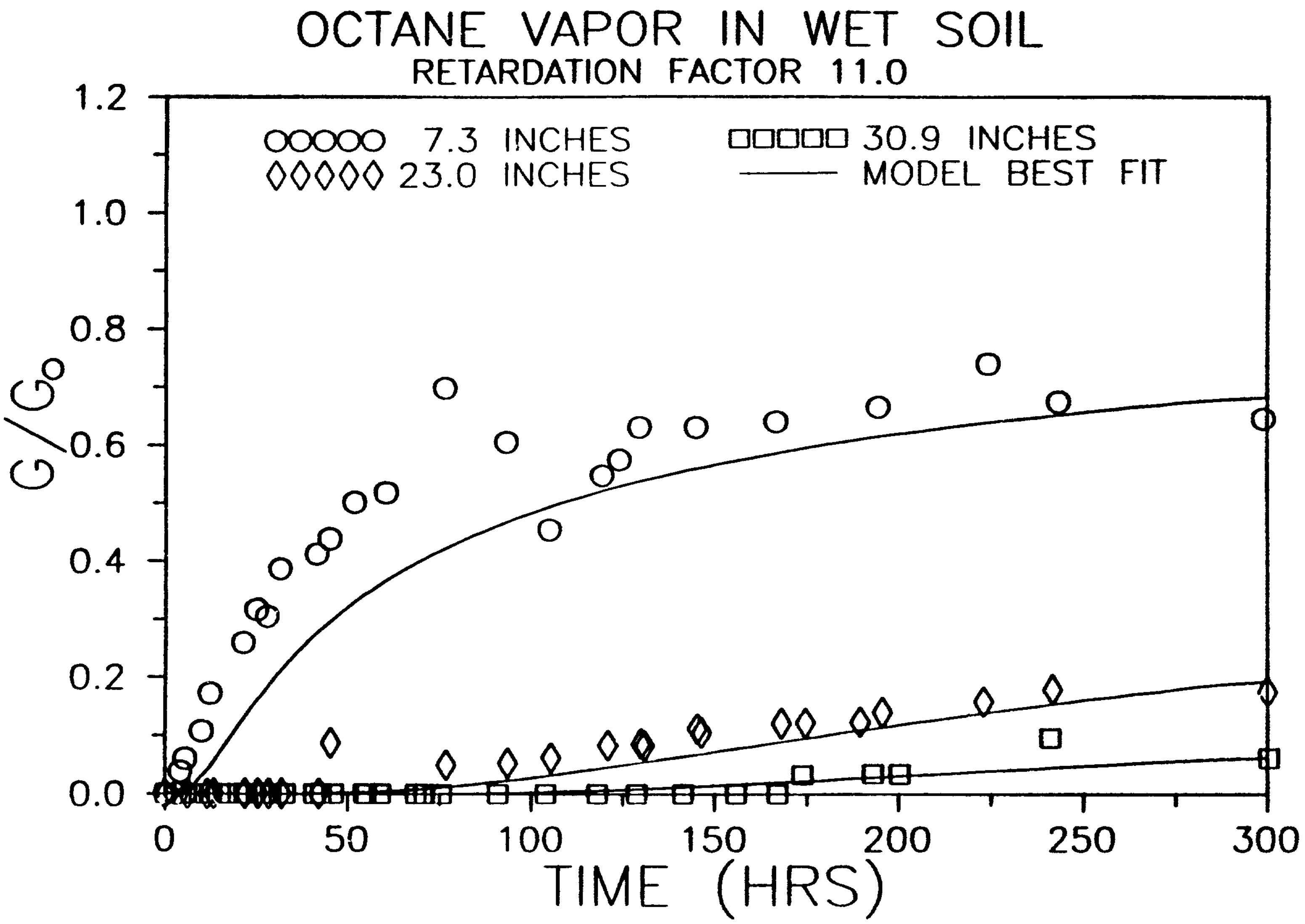


Figure I-39. Experimental and Computed Concentration Versus Time Profiles for Octane in Wet Soil.

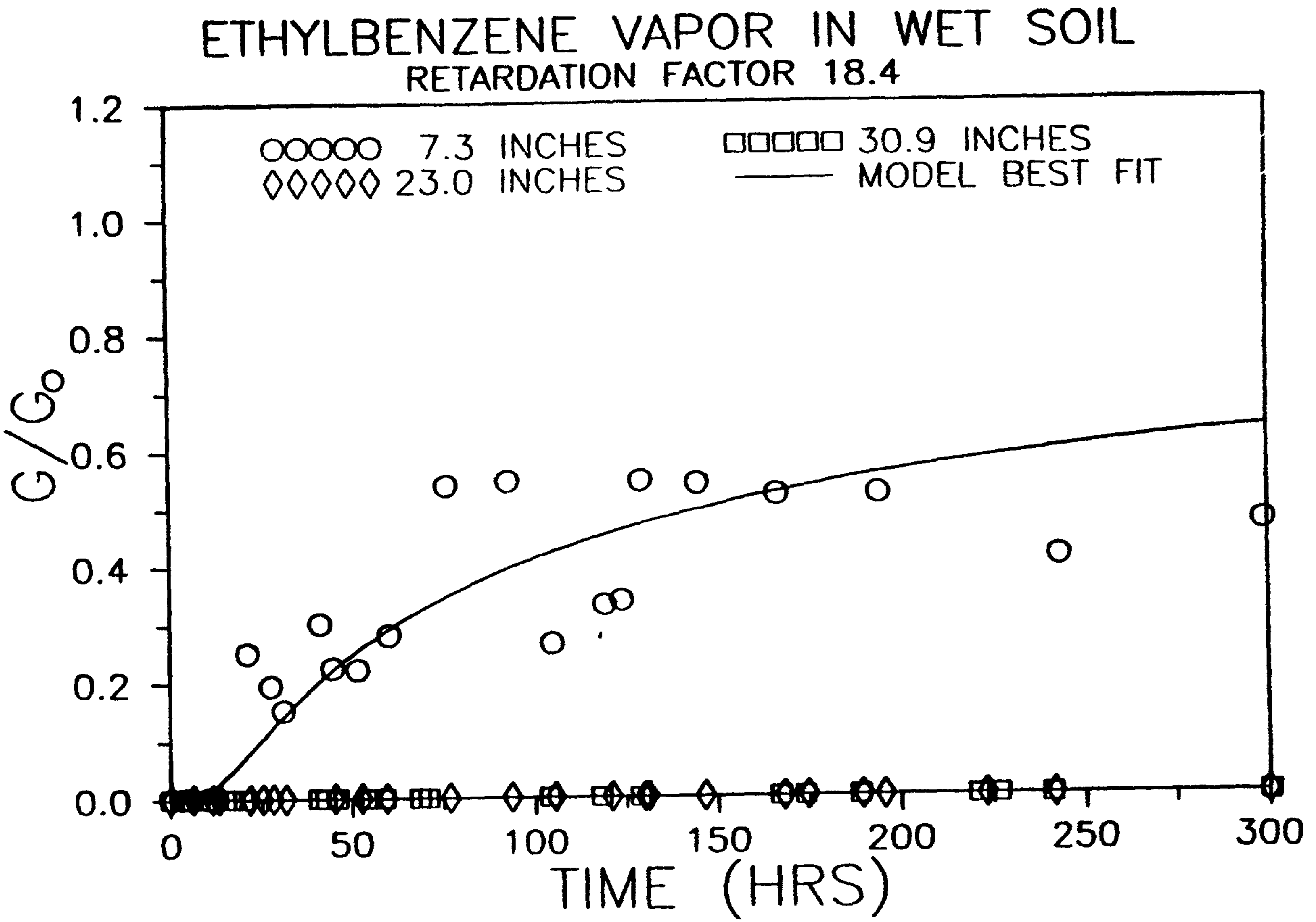


Figure I-40. Experimental and Computed Concentration Versus Time Profiles for Ethylbenzene in Wet Soil.

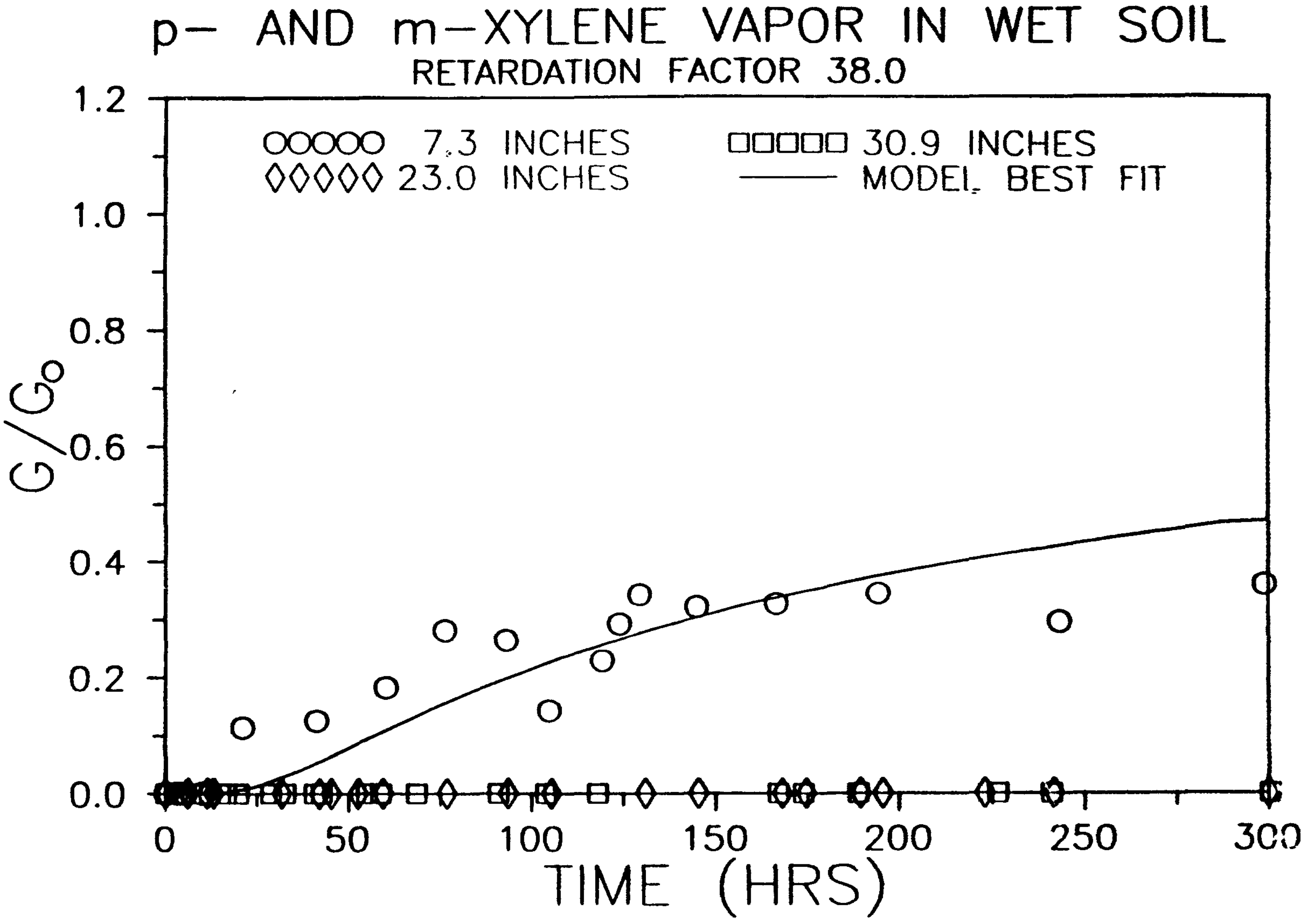


Figure I-41. Experimental and Computed Concentration Versus Time Profiles for p- and m-Xylene in Wet Soil.

APPENDIX J

DATA FOR DISSOLVED JET FUEL TRANSPORT

TABLE J-1. EXPERIMENTAL CONDITIONS FOR THE DISSOLVED JP-4 COLUMN EXPERIMENTS

Condition	Sand	Soil
Diameter	5 cm	5 cm
Length	30 cm	30 cm
Weight of Porous Medium	962.9 g	1027.5 g
% Organic Carbon	0.008 ± 0.001%	1.323 ± 0.008%
Bulk Density	1.635 g/cm^3	1.744 g/cm^3
Particle Density	2.50 ± 0.05 g/cm^3	2.50 ± 0.025 g/cm^3
Total Porosity	0.346	0.302
Volume of JP-4	2 mL	2 mL
Flow Rate	112.0 ± 1.3 mL/hr	108.6 ± 2.4 mL/hr
Influent Cl^- Concentration	200 mg/L as NaCl	200 mg/L as NaCl

TABLE J-2. RETARDATION FACTORS OF SOLUBLE JP-4 COMPONENTS FOR SAND AND SOIL COLUMNS

Component	Retardation Factor Sand	Retardation Factor Soil
Benzene	1.0	1.0
Toluene	1.0	1.8
Ethylbenzene	1.0	3.4
m-, p-Xylene	1.0	3.8
o-Xylene	1.0	3.3

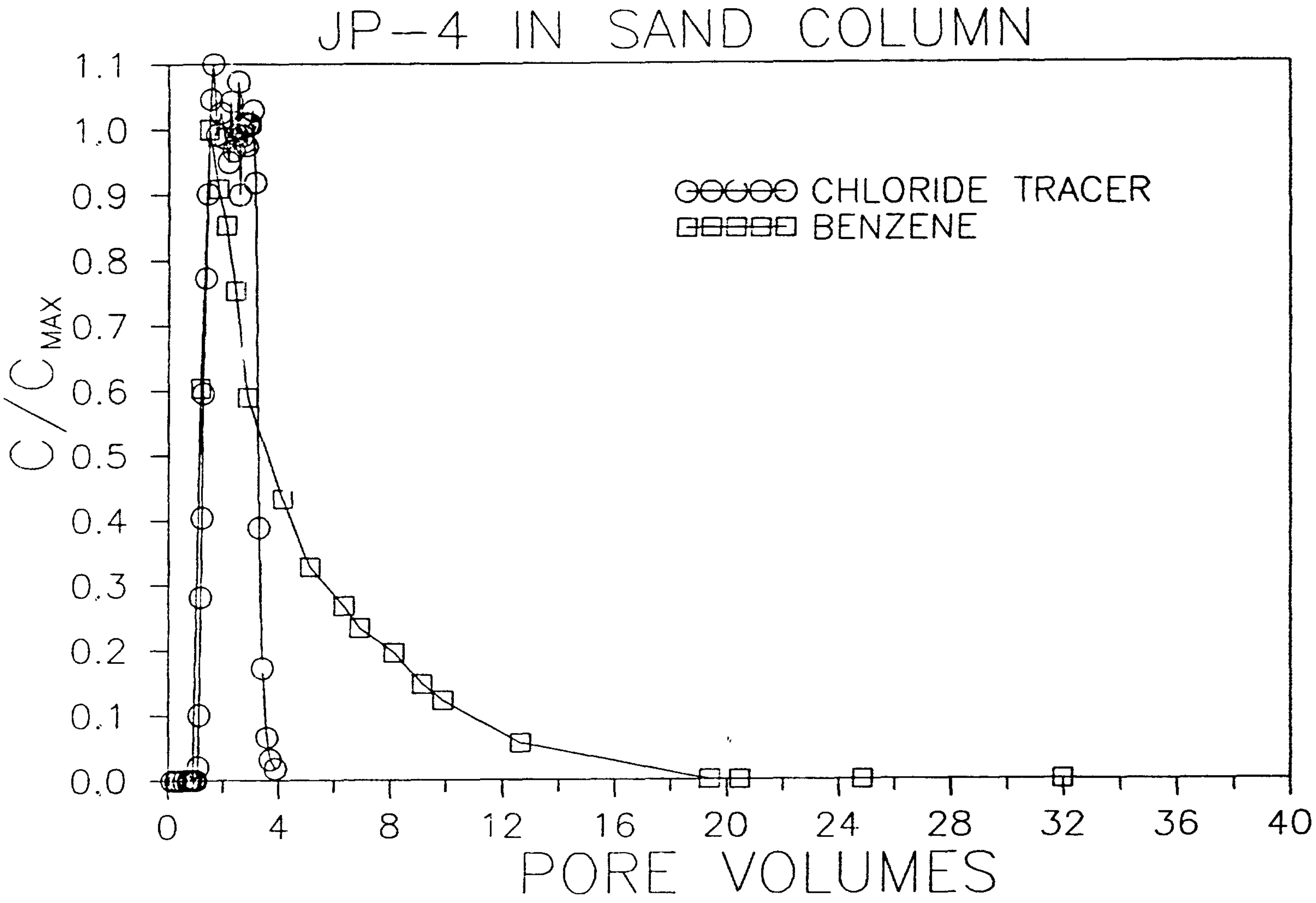


Figure J-1. Experimental Concentration versus Pore Volumes Profiles for Chloride and Benzene in Sand. Retardation Factor = 1.0.

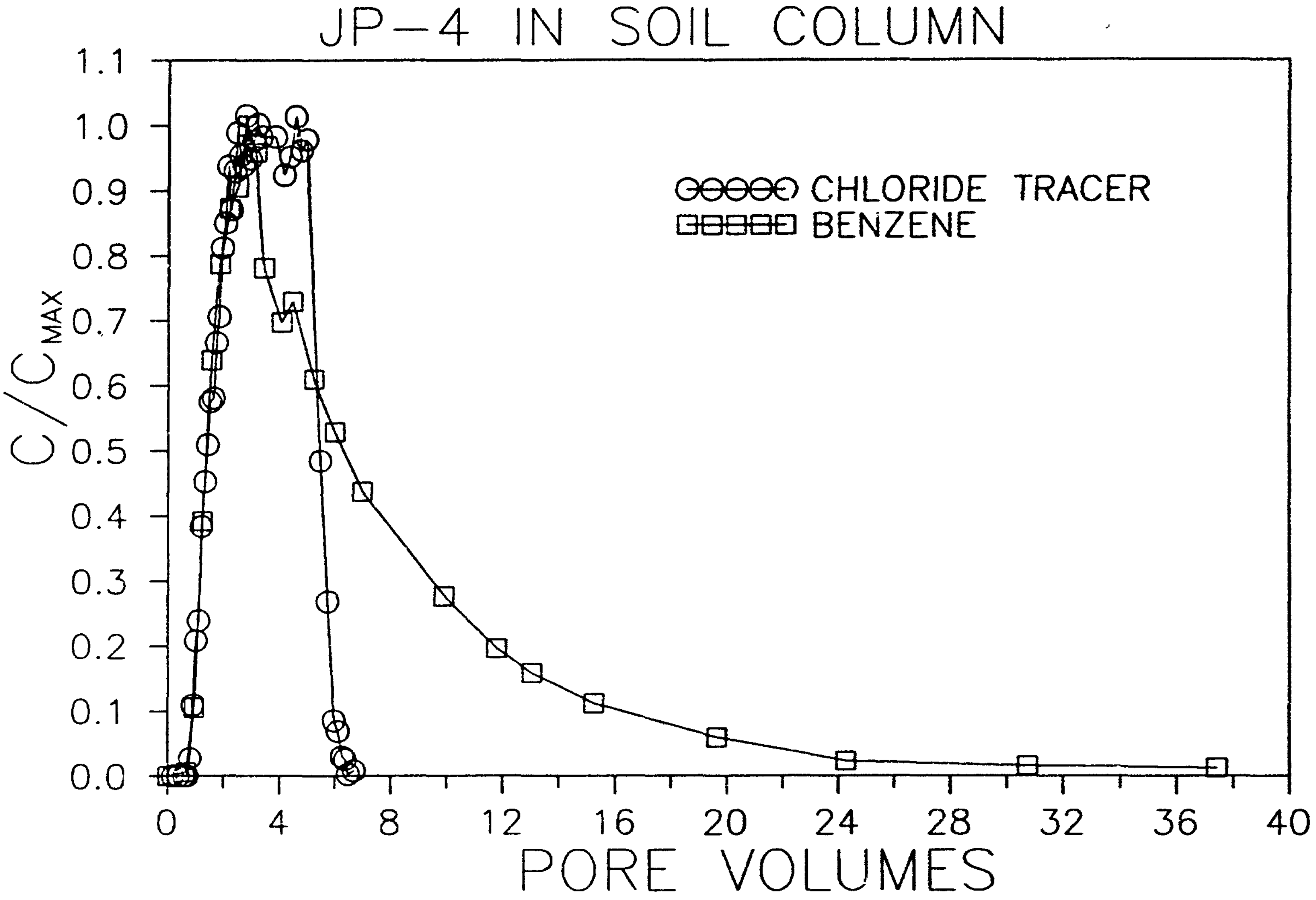


Figure J-2. Experimental Concentration versus Pore Volumes Profiles for Chloride and Benzene in Soil. Retardation Factor = 1.0.

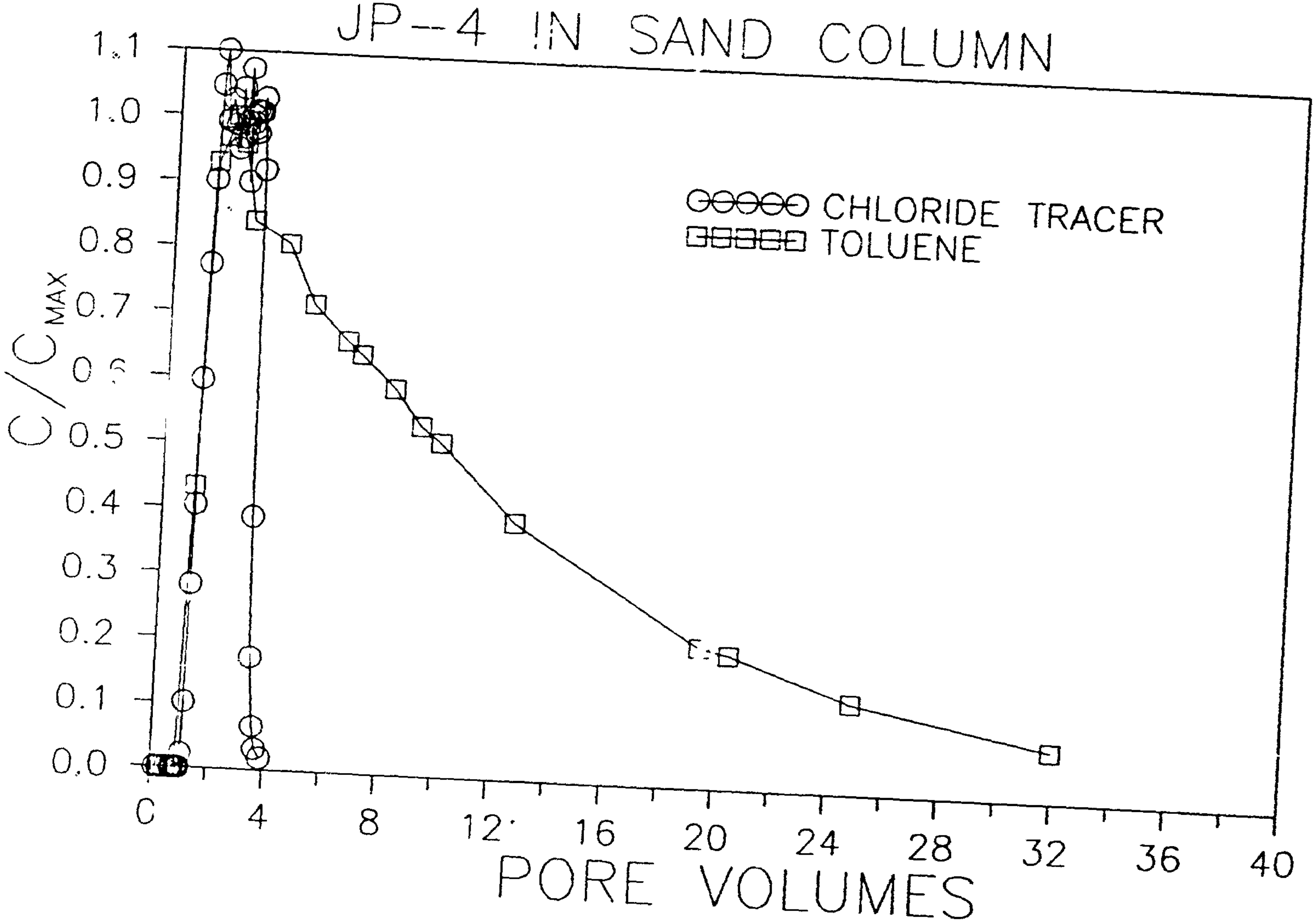


Figure J-3. Experimental Concentration versus Pore Volumes Profiles for Chloride and Tolune in Sand. Retardation Factor = 1.0.

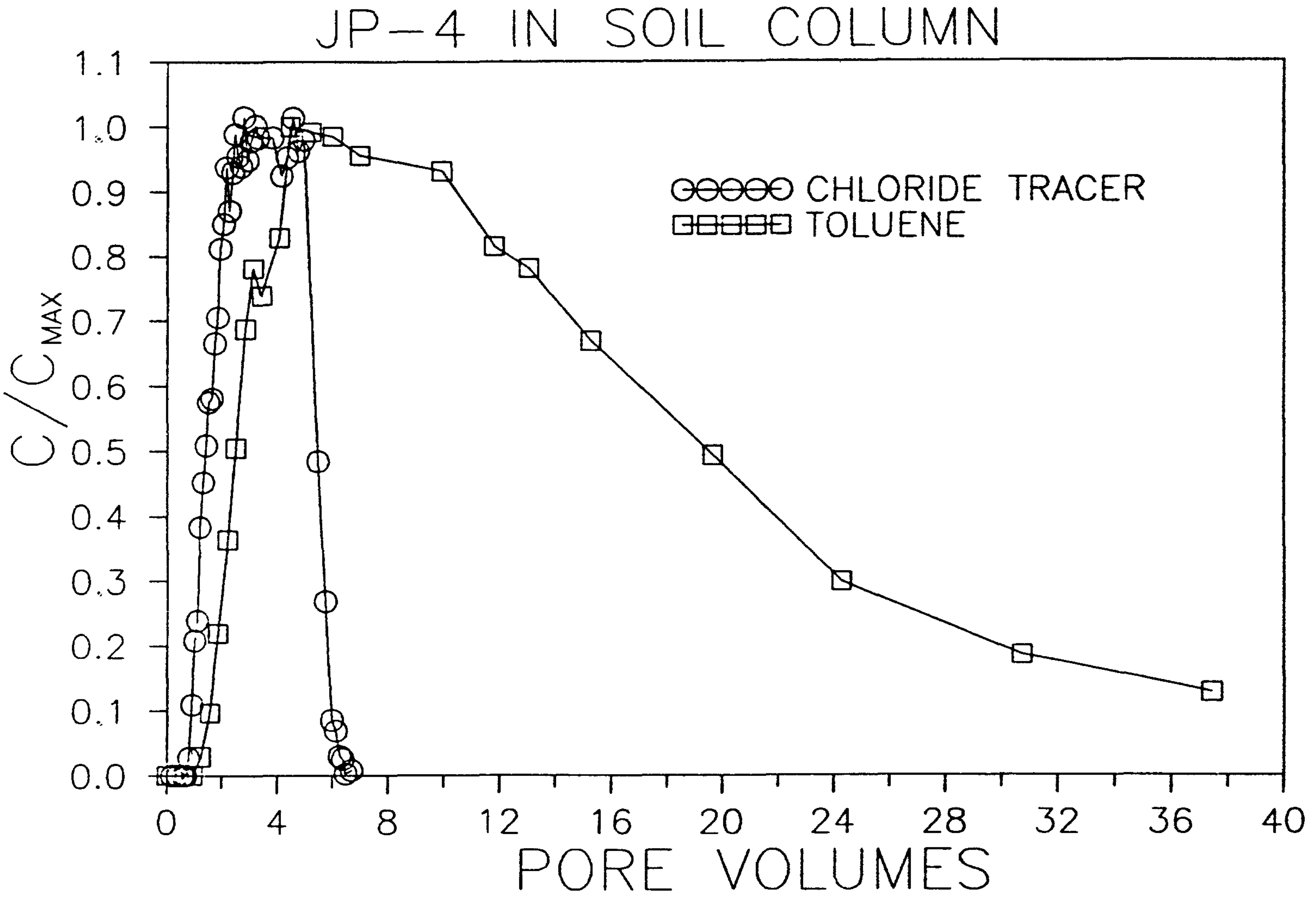


Figure J-4. Experimental Concentration versus Pore Volumes Profiles for Chloride and Toluene in Soil. Retardation Factor = 1.8.

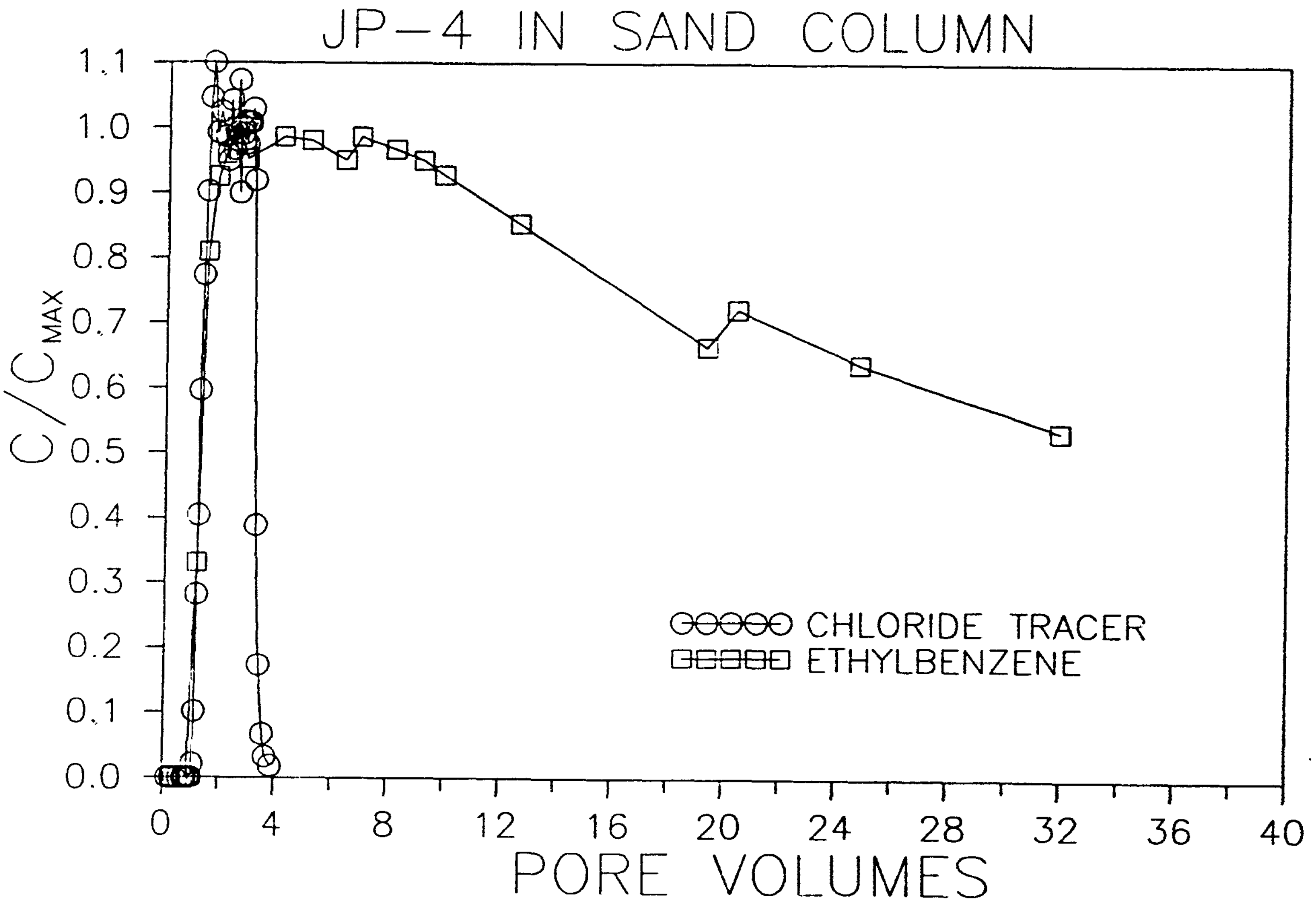


Figure J-5. Experimental Concentration versus Pore Volumes Profiles for Chloride and Ethylbenzene in Sand. Retardation Factor = 1.0.

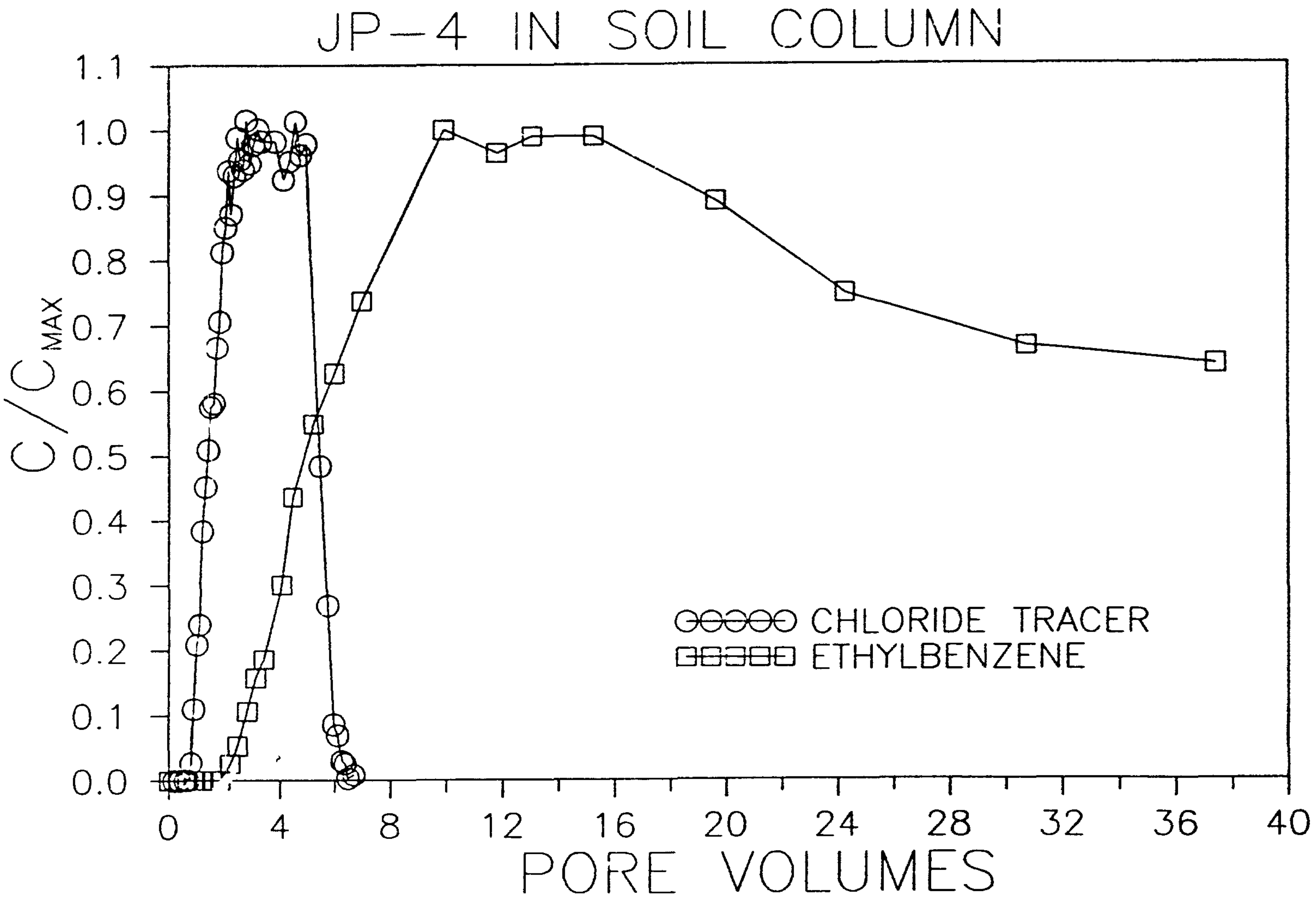


Figure J-6. Experimental Concentration versus Pore Volumes Profiles for Chloride and Ethylbenzene in Soil. Retardation Factor = 3.4.

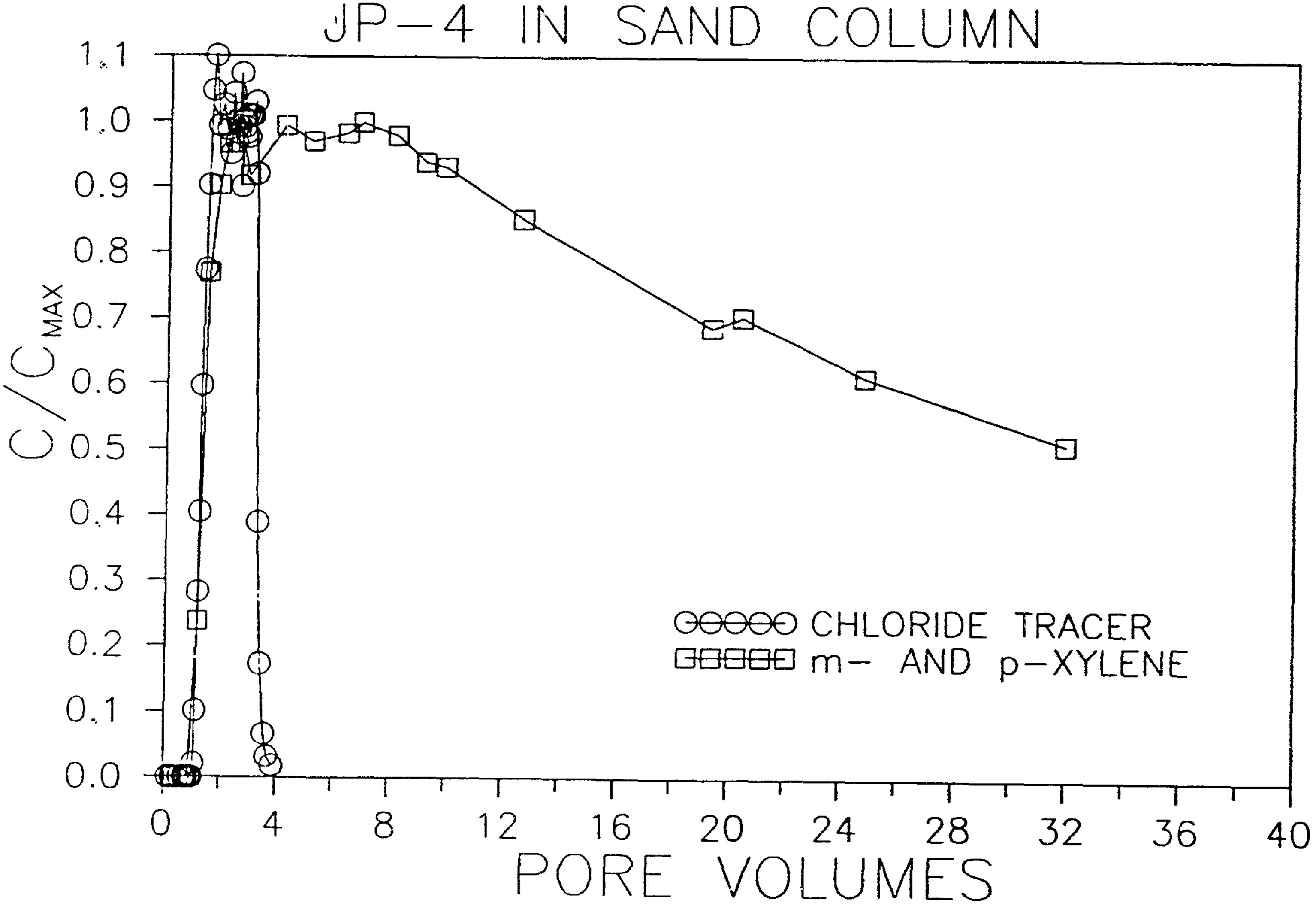


Figure J-7. Experimental Concentration versus Pore Volumes Profiles for Chloride and m-, p-Xylene in Sand. Retardation Factor = 1.0.

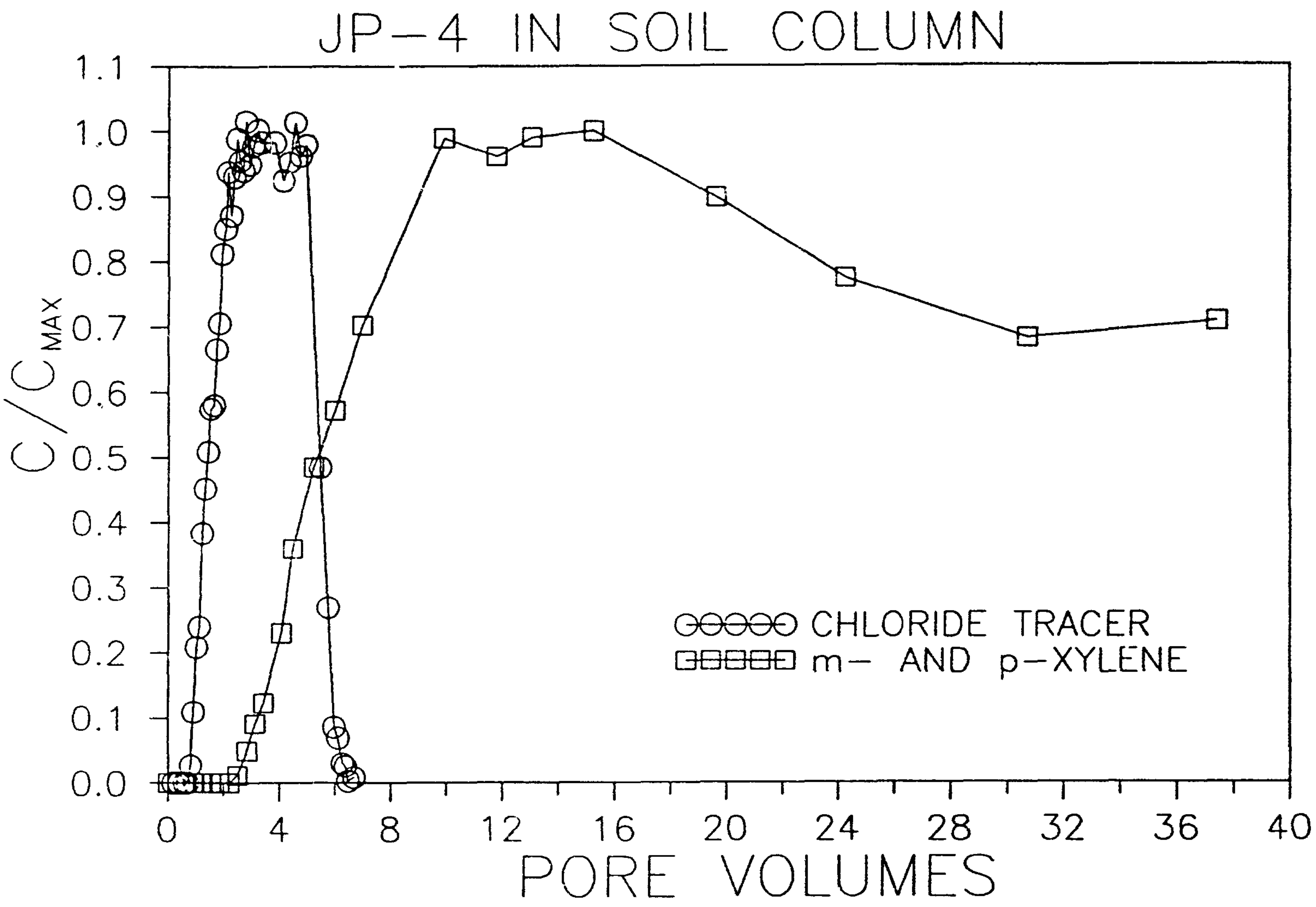


Figure J-8. Experimental Concentration versus Pore Volumes Profiles for Chloride and m-, p-Xylene in Soil. Retardation Factor = 3.8.

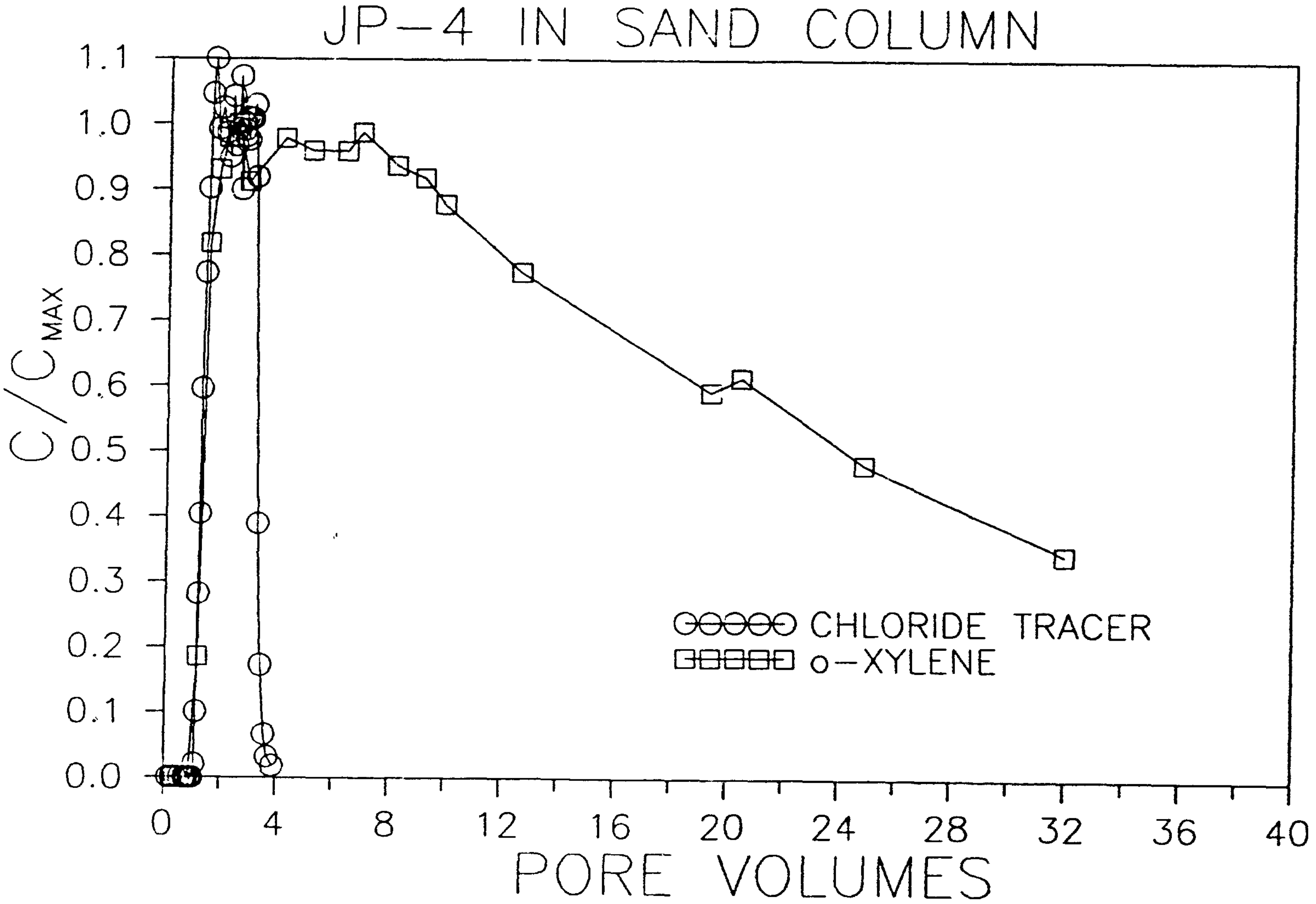


Figure J-9. Experimental Concentration versus Pore Volumes Profiles for Chloride and o-Xylene in Sand. Retardation Factor = 1.0.

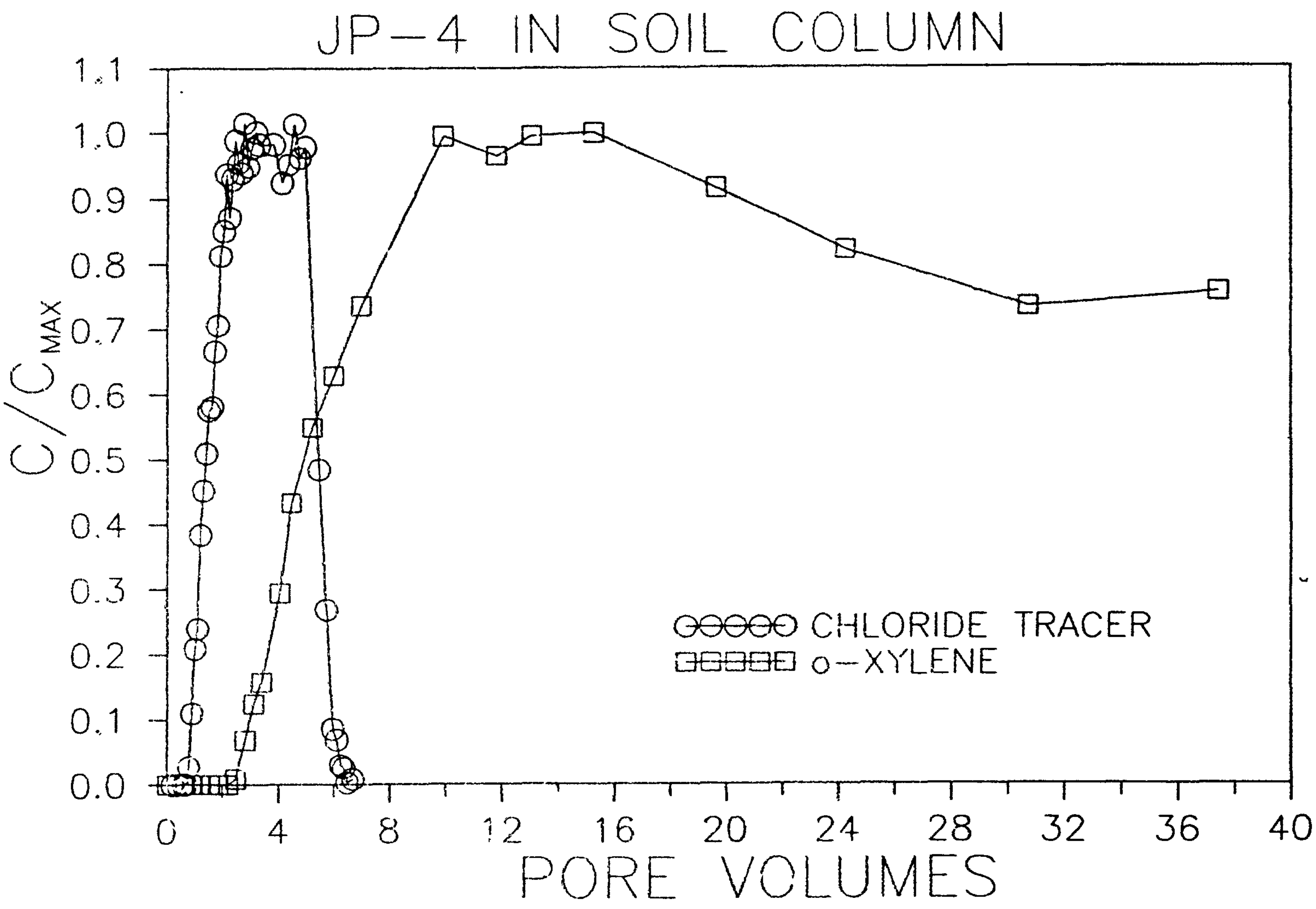


Figure J-10. Experimental Concentration versus Pore Volumes Profiles for Chloride and o-Xylene in Soil. Retardation Factor = 3.3.

APPENDIX K

QA/QC DATA

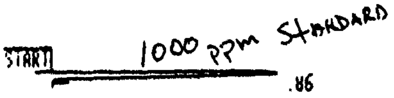
TABLE K-1. NBS STANDARD CALIBRATION TABLE

CAL	RT	LEVEL	AMT	AMT/AREA	REF	NAME
1	7.150	1	1.00000E+00	8.73000E-04		iso-butane
2	8.300	1	1.00000E+00	8.73000E-04		n-butane
3	10.520	1	1.00000E+00	8.73000E-04		iso-pentane
4	11.240	1	1.00000E+00	8.73000E-04		n-pentane
5	13.100	1	1.00000E+00	8.73000E-04		2-mepentane
6	13.450	1	1.00000E+00	8.73000E-04		3-mepentane
7	13.890	1	1.00000E+00	8.73000E-04		n-hexane
8	14.450	1	1.00000E+00	8.73000E-04		mecypentane
9	15.120	1	1.00000E+00	8.73000E-04		benzene
10	15.340	1	1.00000E+00	8.73000E-04		cyclohexane
11	15.480	1	1.00000E+00	8.73000E-04		2-mehexane
12	15.710	1	1.00000E+00	8.73000E-04		3-mehexane
13	16.010	1	1.00000E+00	8.73000E-04		dimecypentan
14	16.230	1	1.00000E+00	8.73000E-04		n-heptane
15	16.780	1	1.00000E+00	8.73000E-04		mecyhexane
16	17.500	1	1.00000E+00	8.73000E-04		toluene
17	17.680	1	1.00000E+00	8.73000E-04		2-meheptane
18	17.850	1	1.00000E+00	8.73000E-04		3-meheptane
19	18.380	1	1.00000E+00	8.73000E-04		n-octane
20	19.460	1	1.00000E+00	8.73000E-04		ethylbenzene
21	19.650	1	1.00000E+00	8.73000E-04		m&p-xylene
22	20.120	1	1.00000E+00	8.73000E-04		o-xylene
23	20.640	1	1.00000E+00	8.73000E-04		n-nonane
24	22.190	1	1.00000E+00	8.73000E-04		n-decane
25	23.900	1	1.00000E+00	8.73000E-04		n-undecane
26	27.030	1	1.00000E+00	8.73000E-04		n-dodecane
27	31.000	1	1.00000E+00	8.73000E-04		n-tridecane
28	33.000	1	1.00000E+00	8.73000E-04		n-tetradecan
29	5.060	1	1.00000E+00	8.73000E-04		propane

CALIB PARAMS:
0 MULTIPLIER = 99.9997
-1 REF WINDOW = 1%
-2 NON-REF WINDOW = 1%
-3 UNCAL RF = 0.000873
-4 HEADING = FID DETECTOR, GAS SAMPLE--FUEL SPILL DISPERSION--
-5 SAMPLE AMT = 0

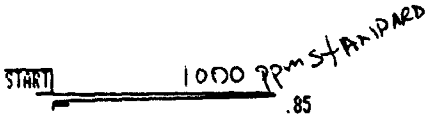
Baseline

```
RUN #  944             MAY/11/89  02:25:13
WORKFILE ID: C
WORKFILE NAME·
NO RUN PEAKS STORED
```



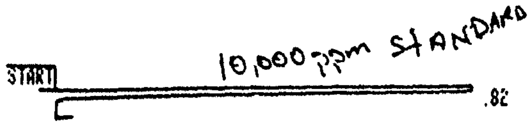
1000 ppm STANDARD

```
RUN #  945             MAY/11/89  02:27·37
WORKFILE ID· C
WORKFILE NAME:

AREA%
   RT          AREA TYPE   AR/HT      AREA%
  0.86     1140100    PB   0.144    100 000

TOTAL AREA=    1140100
MUL FACTOR= 1.0000E+00
```



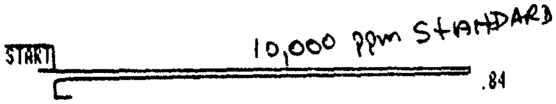
1000 ppm STANDARD

```
RUN #  945             MAY/11/89  02:29:15
WORKFILE ID· C
WORKFILE NAME:

AREA%
   RT          AREA TYPE   AR/HT      AREA%
  0 85     1153800    PB   0.147    100.000
```



10,000 ppm STANDARD

```
RUN #  947             MAY/11/89  02:30:52
WORKFILE ID: C
WORKFILE NAME:

AREA%
   RT          AREA TYPE   AR/HT      AREA%
  0.82  1.0561E+07  SPB   0.144    100.000

TOTAL AREA= 1.0561E+07
MUL FACTOR= 1.0000E+00
```

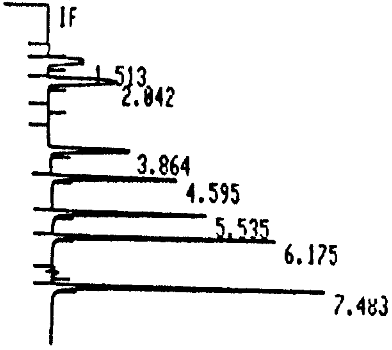


10,000 ppm STANDARD

```
RUN #  948             MAY/11/89  02 32 52
WORKFILE ID· C
WORKFILE NAME·

AREA%
   RT          AREA TYPE   AR/HT      AREA%
  0.84  1.0859E+07  SPB   0 145    100.000

TOTAL AREA= 1.0859E+07
MUL FACTOR= 1.0000E+00
```

Figure K-1. TOHC Butane Standards Chromatograms.

```
*  RUN #    62      FEB  6, 1989  11:44:50
START
```



```
STOP


RUN#     62            FEB  6, 1989  11:44:50

AREA%
        RT          AREA TYPE   WIDTH        AREA%
     1.513         23213   BB    .167      8.21923
     2.042         42247   PB    .165     14.95877
     3.864         31677   PB    .105     11.21616
     4.595         37964   PB    .081     13.44224
     5.535         41110   PB    .072     14.55618
     6.175         46130   PB    .056     16.33366
     7.483         60082   PB    .059     21.27377
```

Figure K-2. Standard Mixture Chromatogram.

```
[hp] 3388A  MANUAL INJECTION @ 14:07  FEB  7, 1989
FID DETECTOR,GAS SAMPLE--FUEL SPILL DISPERSION--
ESTD

  RT               AREA   TYPE CAL

 5.04            265.97    BB          23.219

MULTIPLIER = 100
```

Figure K-3. NBS Propane Standard Chromatogram.

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APPENDIX L

OPERATIONAL INSTRUCTIONS FOR DEVICES TESTED IN THIS STUDY

APPENDIX L

OPERATIONAL INSTRUCTIONS FOR DEVICES TESTED IN THIS STUDY

A. INTRODUCTION

The purpose of this section is to describe the procedures used to operate each JP-4 sensing device tested. For more specific operational instructions refer to the respective manufacturers' operation manual.

B. ARIZONA INSTRUMENT - SOIL SENTRY 12 (17-100L)

1. Introduction

The Soil Sentry monitoring system consists of the following:

- The monitoring system console (with keyboard and printer)
- Polyethylene transport tubing for pulling samples from the backfill around the tanks and pipes
- PVC conduit to protect the vapor tubing
- Diffusing filter/restrictor assemblies and in-line air filters
- Vapor monitoring wells, made from PVC pipe or well screens for vadose zone monitoring (up to 12 monitoring wells can be monitored by each Soil Sentry 17-100L console).

During normal monitoring the Soil Sentry monitoring system pulls vapor samples sequentially (at 8-h intervals) from each active vapor probe, measures the amount of hydrocarbon vapor in the sample, and compares those amounts to the vapor alarm level selected in the monitoring console.

If the Soil Sentry system detects three successive samples above the vapor alarm level, or a single sample with a very high value, the system triggers an audible alarm and alarm light. The printer records the vapor concentration that caused the alarm.

2. Operation

The system features three operating modes: (1) normal automatic operation or "Run Mode"; (2) "Print and Run Mode"; and, (3) manual operation or "Test Mode."

a. "RUN MODE" - Three times each day the system extracts air samples from each active vapor sampling port. If a vapor level above the adjustable alarm level is identified over three successive sampling cycles, or if a dangerously high vapor level is identified during any one cycle, the system's alarms will activate and a printed record identifies the time, location of the vapor sampling point, and the measured vapor level. If any system problem or failure occurs, the system will activate an alarm and the cause will be printed out on the paper tape.

b. "PRINT AND RUN MODE" - The system prints the vapor level observed at each scheduled sampling cycle during normal automatic operation. "Print and Run" establishes site profiles and tracks the movement of any vapors in the monitoring wells. This is designed as a temporary mode only. Frequent visual observations for alarm conditions and low printer paper are required.

c. "TEST MODE" - Several test modes are available which permit the operator to select a port, read vapor levels at any sampling point and obtain a printed record, check the system alarms, or test system diagnostics.

The sensor alarm threshold is set on an eight-dip switch on the inside of the console's front panel. The eight possible alarm thresholds are 250 ppm, 500 ppm, 1,000 ppm, 1,500 ppm, 2,000 ppm, 2,500 ppm, 3,000 ppm, and 3,500 ppm. If the vapor concentration level in the monitoring well exceeds 3,500 ppm, the printout will indicate a rise-per-foot value, which can be converted to ppm mathematically.

3. Maintenance

The system console can be located inside a building, and the system parts located outside (primarily PVC tubing) are simple and rugged, so the Soil Sentry experiences little wear. Also, the Soil Sentry has self-diagnostic capabilities in which it can give a printout indication of any tubing or port blockage. Printer paper must be replaced as needed.

To assure long-term operation, Arizona Instrument Corp. (AZI) recommends semi-annual preventive maintenance servicing and calibration by a factory-certified representative.

C. IN SITU, INC., PETROCHEMICAL RELEASE MONITOR MODEL KW-230 REMOTE STATION MODEL RSE

1. Introduction

The KW-230 Petrochemical Release Monitor (PRM) consists of a well cap assembly with a sensing element extending through the entire length of the well. The well cap assembly has an electrical cable connecting it to the RSE remote station. The sensing element deteriorates on contact with hydrocarbon liquid or vapors; when the element breaks a spring-activated mechanism in the PRM, an electrical impulse is sent to the remote station, triggering both audio and visual alarms. (The unit is not recommended as a dry zone monitor for petrochemicals with low vapor pressure constituents.) The remote station is powered by a AA-size lithium battery. Each RSE remote station can monitor up to eight KW-230 PRMs.

2. Operation

Installation of the KW-230 monitor involves the following steps:

a. Cut the sensing element to a length of 13 in. less than the depth of the well. Thread each end of the element through the sensing element connectors, and use a heat source (i.e., a light bulb) to melt each filament tip so they cannot pull through the connectors. Cut the weight retrieval line to be 3 in. longer than the sensing element. Attach both the sensing element and the weight retrieval line as shown in Figure L-1.

b. Insert the sensing element and the weight into the monitoring well. The well cap assembly (riser adapter) is designed to friction fit 4 in., schedule 40, PVC well casings, but can easily be adapted to other diameter well casings.

c. Connect the electrical cable from the model KW-230 to the RSE remote station. Lift the test handle on the well cap assembly (see Figure L-1) to check for proper operation.

After the system is installed it requires almost no operator input. In Situ, Inc., suggests that the PRM alarms be periodically tested. A Low battery is indicated by an audible alarm that is <u>not</u> accompanied by a visual alarm. This alarm will shut off when the battery is replaced. Both the

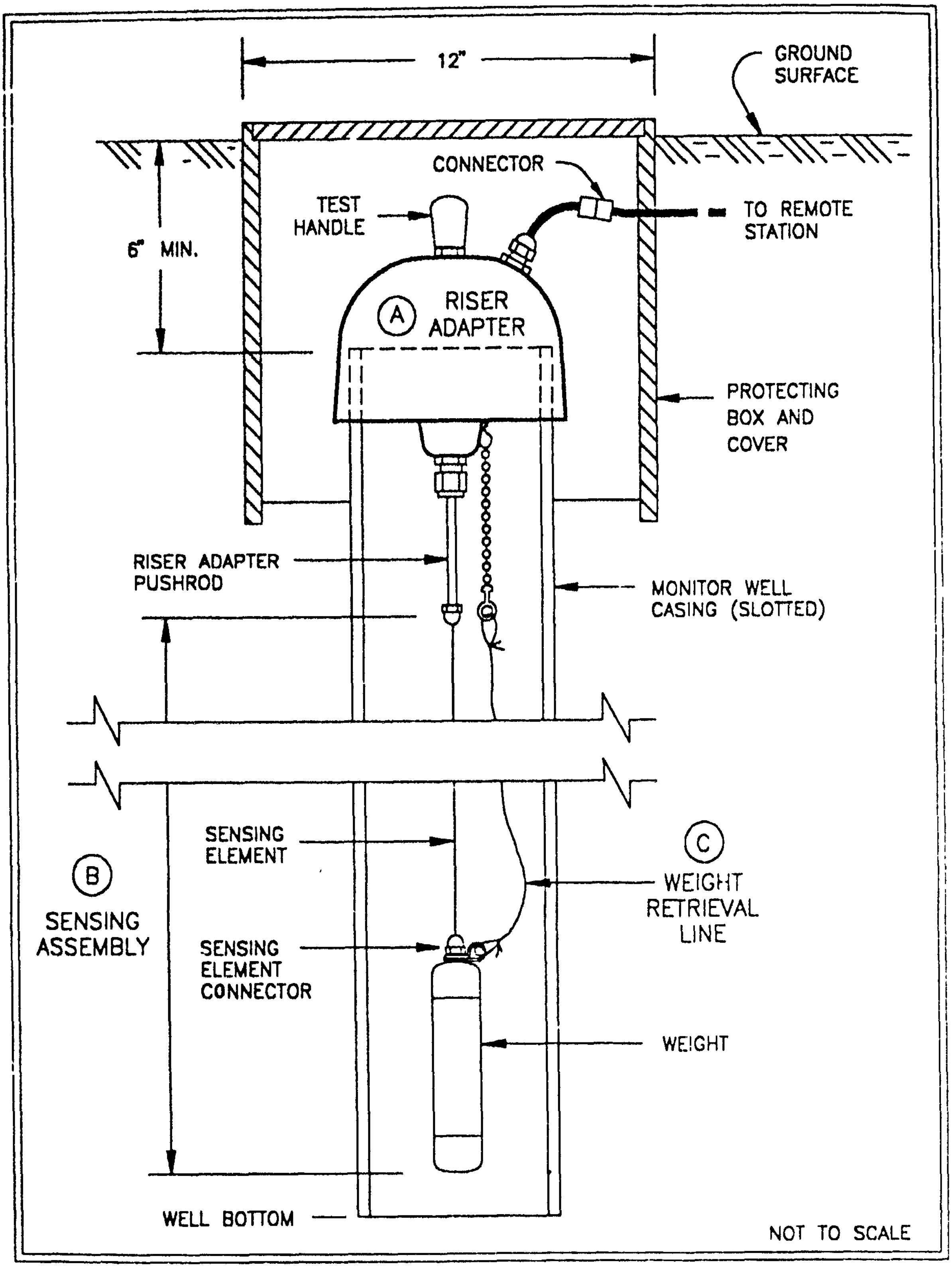


Figure L-1 **Sketch of installed Petrochemical Release Monitor Model KW-230,showing the three basic units: A) riser adapter, B) sensing assembly and C) weight retrieval assembly.**

audible and visual alarms (the visual alarm indicates which PRM is alarming) will activate when the filament degrades to the point of breaking.

3. Maintenance

The sensing elements and the remote station battery should be replaced at least annually. As stated above, the alarms should be tested periodically. A record book should be maintained to record alarm test results and the replacement of any sensing elements or batteries.

D. LEAK-X CORPORATION - M210 CONTROL CENTER LEAK DETECTION SYSTEM

1. Introduction

The Leak-X leak detection control center is an electronic monitoring system that works on the principle of conduction. Groundwater is a conductive or polar fluid. Hydrocarbons are nonconductive or nonpolar substances. The Leak-X control panel is connected in electrical parallel with up to 10 probes. The control panel has three indication lights: amber (water), green (dry), and red (hydrocarbon or other nonpolar substance). The Leak-X probe circuitry can differentiate between polar and nonpolar fluids and provide the appropriate alarms when a nonpolar liquid is detected. The probe consists of a 4-in. PVC well cap with a flexible electrical cable extending to a nitrile float with two adjustable electrical contact screws protruding through the bottom of the float. The well cap has a test switch with three lights, amber, green, and red, which correspond to the indication lights on the control panel. A stainless steel guide cable runs through the center of the cap and the float and is connected to a magnetic weight below the float. When the contact screws are in contact with water or the magnetic plate, the circuit remains open and no alarm will sound. If the contact screws come in contact with a nonpolar substance, the circuit is broken, and audible and visual alarms (red indication light) will be activated on the control panel.

2. Operation

After the electrical connections are made between the control panel and the necessary probes, the devices can be placed in the monitoring wells. Place the PVC well cap and probe assembly on the 4-in. wellhead. While holding the guide cable, lower the weight and float assembly into the well until you feel the weight resting on the bottom of the well.

Remove the PVC cap assembly, allowing it to lay alongside the well. Start pulling the excess flexible electrical cable (not the guide cable) out of the well until you feel the weight of the float assembly being lifted from the water surface. To allow for the up and down movement of the groundwater table, lower folds of flexible cable back into the well until there is about 1 to $1^1/_2$ in. of spacing between folds in the cable. Using the strain relief assembly, attach the flexible cable to the guide cable at this level. With the PVC cap on the wellhead, pull the slack out of the guide cable and tighten the set screw to hold the cable guide in place.

During normal operation the control panel will indicate either water in the wells (amber light) or dry conditions in the wells (green light). In the event of a hydrocarbon spill, the control panel will sound an audible alarm and activate the red light, when a sufficiently thick layer of hydrocarbon is formed to lift the float out of the water or off of the metal weight. To determine which probes are alarming, the test switch on each probe must be depressed to observe which indication light is activated. (Note: It is possible for all three indication lights to be lit simultaneously on the control panel, if the conditions in the wells differ.)

3. Maintenance

Leak-X recommends that the installation be examined every 2 to 3 months to check for damaged wiring. Of more importance is checking the probe site for any debris that might impede the movement of the float. The test switch should be checked on each well cap to make certain that the indication lights are working. If none of the indication lights come on when the test switch is depressed, the system should be checked.

E. RED JACKET ELECTRONICS - PPM 3000/2000 PROBE MONITORS

The PPM 3000 series and the PPM 2000 series probe monitors differ only in the number of probes each can monitor. The PPM 3000 monitor can occupy up to eight probes, the PPM 2000 series can control up to four probes. All other operations of the two systems are identical.

1. Introduction

The PPM 3000/2000 are continuous monitoring systems which detect hydrocarbon and other hazardous vapors. The operation of both systems begins with programming vapor alarm threshold levels for each vapor probe. The alarm thresholds are programmed in PPM differently for each probe based on existing background contamination at each probe site. Once programmed, the systems continuously monitor the vapor concentration at each probe site and will alarm when any probe exceeds the alarm threshold value. The alarm is both audible and visual and will be immediately communicated if a modem has been installed at the communications port.

2. Operation

After making the necessary connections between the probes, the control panel, and the power supply, the system is ready for programming. The control panel has a numeric pad for data entry and a liquid crystal display (LCD). The program switch on the inside cover of the control panel must be placed in the PROGRAM position to input programming data. The LCD will then prompt for the input of programming data, such as date, time, site location I.D., modem telephone number (if needed), and alarm thresholds. Alarm thresholds should be set after placing the probes in the monitoring wells to get background readings. After setting the alarm thresholds, the programming switch has to be placed in the RUN position to begin operation.

The LCD will continuously read TIME, DATE, and STATUS = O.K. under normal monitoring conditions. In an alarm condition, an audible alarm will sound and the display will read TIME, DATE, and STATUS = ALARM. The LCD display will give the location of the alarming probes.

3. Maintenance

There are three test procedures that the operator can use to check for correct operation of the PPM Series monitoring system. The SYSTEM TEST is used to check for correct operation of the vapor probes. The probes need to be removed from their monitoring site, one at a time, and exposed to a detectable vapor (i.e., freon). Each probe should alarm when the vapor concentration level exceeds the alarm threshold level. The COMMUNICATIONS TEST is used to check for proper operation of the communications port for modem use. And the

BATTERY TEST is used to check that the power backup battery is holding a charge.

The operation manual for the PPM Series monitors contains a trouble shooting guide that addresses many potential operational problems. Any problems that cannot be corrected by the operator should be directed to a Red Jacket Electronics service representative.

F. TOTAL CONTAINMENT INC. - TCI LEAK DETECTION SYSTEM

1. Introduction

The TCI Leak Detection System is designed to detect leaks in underground monitoring wells, double-wall tanks, double-wall piping, and in a variety of other applications. The detection system continuously monitors the connected detection probes by means of a remote, electronically operated monitor console. The detection probes, called sensor cables, consist of two separately insulated conductor wires which are twisted together and sheathed. Upon exposure to liquid hydrocarbon, at any point along the sensor cable, the insulated jacket will dissolve causing the conducting wires to make contact, signaling a visual and audible alarm. The sensor cable has a built-in water probe which will signal an visual and audible alarm at the monitor. All sensor cables and connector cables are linked using watertight, four-pin plugs.

2. Operation

Installation of the TCI system is relatively simple. A connector cable with a built-in, four-pin plug is used to connect the monitor console to the first sensor cable. Additional sensor cables are connected in parallel with the first probe via the connector cable. The final sensor cable in the series is fitted with a terminating plug to keep the circuit open. To test the system, remove the terminating plug and the monitor console should indicate an alarm situation.

To locate the source of a product alarm, keep in mind that the function of the monitor is to read the terminating plug attached to the last probe in the cable series and any interruption in the signal due to a cut, disconnection, or short in the cable series will signal an alarm. Follow these steps to find the source of the alarm:

a. Push the Horn Reset button on the monitor console to silence the alarm.

b. Go to the last probe in the series and remove the terminating plug.

c. Take the terminating plug to the first probe in the series and disconnect the connector cable from the probe. Next connect the terminating plug to the probe. If the alarm shuts off, then the source of the alarm is not that probe.

d. Remove the terminating plug from the first probe and reconnect the connector cable; move on to the second probe in the series and repeat the above procedure, and so on. The probe that does not turn off the alarm is the problem.

e. To verify the cause of the alarm, remove the sensor cable and inspect it for degradation due to exposure to product.

To locate the source of a water alarm, each probe must be sequentially removed from its location to see if the alarm is deactivated.

3. Maintenance

The TCI Leak Detection System has been designed to be a simple and fail-safe system. It's a tamper-proof, nonadjustable system and is not affected by stray currents or growth of microorganisms. If there is a short disconnection of plugs or cut in the sensor or connection cable, the monitor will set off an audible and visual alarm. The electronic monitor has a Test Button for periodic testing to make sure all of the visual and audio alarms are working properly. A recommended annual test should be to disconnect the Terminating Plug at the end of the last Sensor Cable (last of the cable series). This should activate the alarm in the monitors. Annual testing by means of immersing the Sensor Cable into a container of gasoline is not practical for it will degrade the cable and require the purchase of a new cable.

G. FIBERCHEM, INC. (FCI) - FIBER OPTIC CHEMICAL SENSORS (FOCS)

1. Introduction

The FOCS system provided by FiberChem for JP-4 detection was a prototype instrument and no operation or service manual was provided. Because of a malfunction the original system provided by FCI, which could accommodate up to 30 sensors, had to be replaced by two separate systems which accommodated one sensor each. Each system consisted of the following: a portable spectrophotometer (light source and detector/reader), fiber optic cable with chemical sensor attached to the distal end, alarm/computer storage mode, and a telephone interface to communicate readings to a remote computer.

2. Operation

The installation of the sensing probe requires a few simple connections. A connector on the fiber optic cable attaches to the light source on the spectrophotometer. The spectrophotometer is then connected to the data storage device and communications port. The sensor element on the free end of the fiber optic cable is then placed in the monitoring well.

After allowing the sensor to equilibrate to the well background, the voltage readout is adjusted to approximately 10 V as the reference point. Any voltage drop indicates the presence of hydrocarbon vapors. The voltage drop can be converted to ppm using the following formula:

$$\text{ppm} = \{[(V_0 - V) / V] / K\}^2$$

where

V_0 = reference voltage
V = current voltage reading
K = calibration constant provided by FCI and different for each sensor.

3. Maintenance

All maintenance problems must be referred to FiberChem, Inc.

H. UNIVERSAL SENSORS AND DEVICES (USD) - COMPUTER ASSISTED TOTAL LEAK ALERT SYSTEM (CATLAS)

1. Introduction

The CATLAS, Computer Assisted Total Leak Alert System, is a fully automated computer-based leak detection system. Based upon a standard PC structure, it can accommodate up to 64 separate input channels which include liquid and vapor leak detection sensors, line leak detectors, and inventory control devices. Optional equipment can include an internal or external telephone modem, a printer, additional software, and a floppy disk setup. With these options, complete records of alarms, background signal variations, or other data such as inventory levels can be permanently maintained or transmitted. The standard system consists of a power/interface enclosure and a computer display control unit along with the interconnection cables. Various types of sensors can be connected to the interface unit.

The power/interface unit provides the point of connection for the sensors, output control, and power input. The unit is designed in two layers, the power input section located on the bottom and the input section on the top. Three wires exit the bottom of the enclosure, green, white, and black. These are for connection to a noninterruptable power source providing 115 VAC 50/60 Hz and capable of supporting 80 W of power.

The top surface is the sensor connection interface board where sensors connect to the terminals located on each side of the board. The configuration of this board may change with different numbers of sensors attached. The switch located to the outside of each sensor connection terminal is for vapor sensor usage. Turn the switch to the off position when using a vapor sensor and on when using a liquid or line leak detector.

The CATLAS display unit provides the sensor control, sensor readout, set point control, alarm status, information storage, and communication and operator interface. The control functions are set up in steps that can be accessed by pressing the appropriate button on the front cover. There are simplified instructions on the label; for more detailed information refer to the section pertaining to that function.

The vapor sensors used in this system are Model LAVS-1 units, which contain a metal oxide semiconductor element that recognizes the presence of most combustible and organic vapors. This sensor is used most often within a monitoring well located in or around the product tank or lines for the detection of vapors from a leak.

2. Operation

The CATLAS system must be installed in strict compliance with USD's instructions. The CATLAS system and its associated parts should be located as close to each other as possible to reduce the possible effect of an outside electrical interference. Signal cables must not be in the same conduit as other power cabling. The sensor home run cable should have its own conduit and no other cabling should be placed within this conduit. Installation and location are very important to the overall operation of the equipment. Do not randomly choose a location. If there are any doubts as to the correct location of this system, contact an authorized individual for more information.

The vapor sensors should be placed in a dry environment near the source of the potential leak. However, to avoid potential damage caused by direct contact with the liquid, the vapor sensor should be installed above the highest liquid level. Furthermore, the sensor port should be placed downward to avoid accumulation of condensate inside the sensor. For more specific installation instructions refer to the owner's manual. Start-up and operation of the CATLAS system requires the following steps:

a. Prior to applying power to the system recheck all connections and review installation instructions. NOTE: A mistake in connection could cause irreparable damage to this system and or any system attached to it.

b. To turn on the system, use the power key provided. (Do not misplace this key; spares are not provided.) NOTE: If your unit has a disk drive, the disk provided must be installed and the door closed. The system will not operate without the disk installed.

(1) When power is first turned on the display will show nothing for the first few min. The disk drive (if available) will activate and initialization will begin. Initialization takes about 5 min to complete. NOTE: Do not touch, connect, or disconnect any sensors or connected systems until the initialization is completed.

(2) After initialization is completed, the system enters into the Main Menu mode. Refer to Figure L-2. NOTE: If for any reason the display should blank out or the system quits functioning, turn off the power switch located on the bottom of the interface unit and check the fuse. If the fuse is damaged, replace it with one of a similar size. After replacing the fuse, turn off the power. All the data (alarm and diagnostics) remain on the diskette.

c. Menu Functions

The following is a list of current menu functions. To access a specific submenu press the UP or DOWN key until the appropriate display is shown and then press ENTER.

(1) Alarm Monitor

The alarm monitor menu operation is the normal operating mode for most applications. It is this program that continually cycles through the sensors. The display will indicate the channel number, the sensor type, the alarm set point, and the present signal reading. This is the default operation menu. (If the system is left unattended for more than a few minutes in any other submenu, it will automatically return to this operation and resume the cycling through of each of the sensors.) There are four subroutines within this operation.

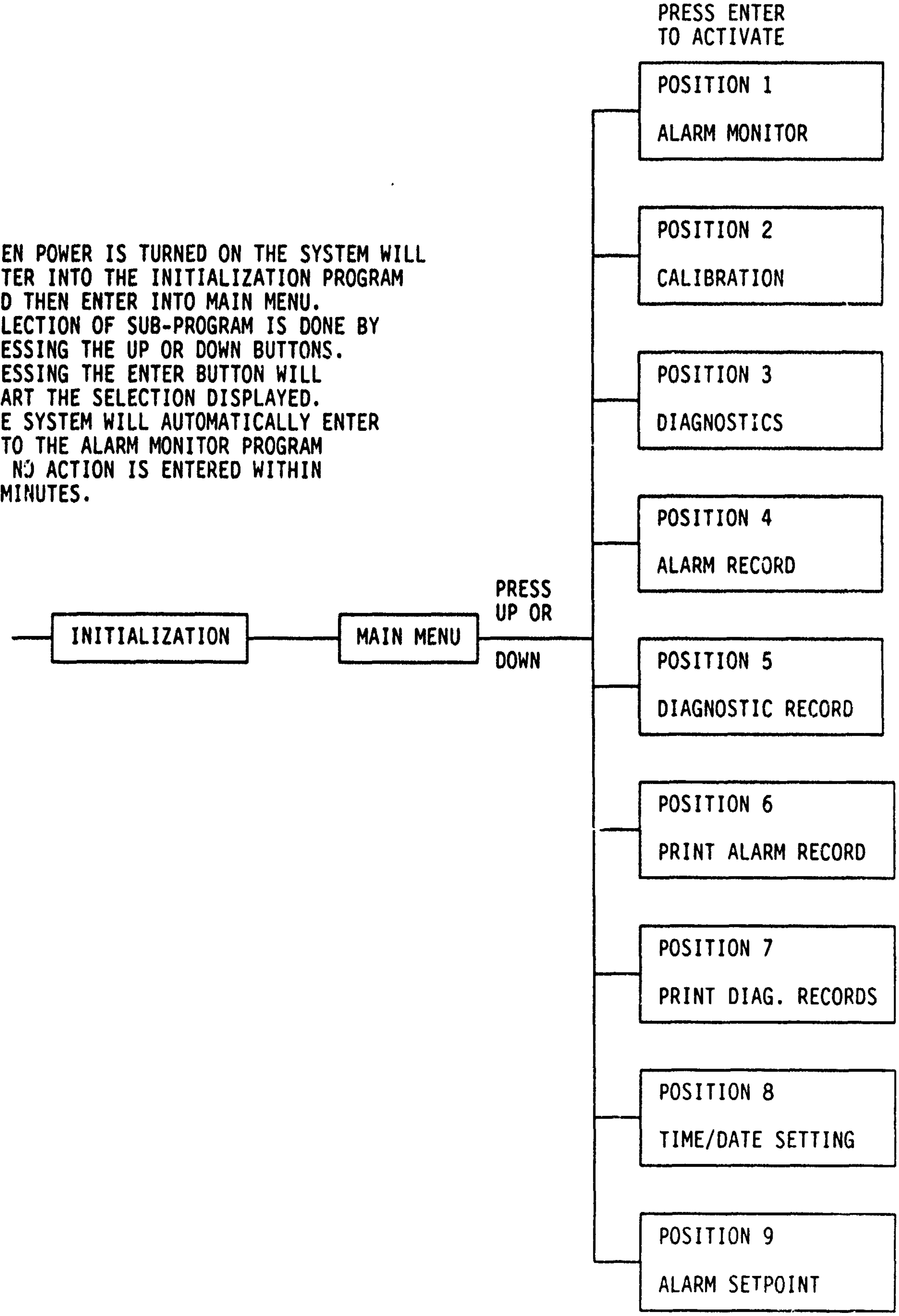
1. Standard cycle through the connected channels.

2. Pressing the ENTER key will allow you to monitor one specific channel. To exit press the ENTER key and the display will return to the standard cycle routine.

3. Pressing the UP key will allow you to print out the current status of each of the sensor channels. This gives you a hard copy of the present signal readings.

   Follow the instructions on the display. Upon completion of one run the system will automatically return to the standard cycle routine.

4. Internal diagnostic routine will activate about every 6 h. This is to test each sensor, the background, and



WHEN POWER IS TURNED ON THE SYSTEM WILL ENTER INTO THE INITIALIZATION PROGRAM AND THEN ENTER INTO MAIN MENU. SELECTION OF SUB-PROGRAM IS DONE BY PRESSING THE UP OR DOWN BUTTONS. PRESSING THE ENTER BUTTON WILL START THE SELECTION DISPLAYED. THE SYSTEM WILL AUTOMATICALLY ENTER INTO THE ALARM MONITOR PROGRAM IF NO ACTION IS ENTERED WITHIN 3 MINUTES.

Figure L-2

the system for any errors that might occur. This information is stored for later use. Upon completion of each test the system returns to the standard cycle routine.

(2) Alarm Record

The alarm record routine is used to display the past alarm record for a selected channel. To select a channel press the UP or DOWN key until the channel of choice is displayed, then press the ENTER key. If there are no alarm records for the selected channel the display will state this and then give the option to select another channel or end the routine. To display each record for the selected channel press the UP or DOWN key. To exit this routine press the INTERRUPT key.

(3) Print Alarm Record

To print the alarm records press the ENTER key. The display will show channel 1; to select a different channel press the UP or DOWN key until the desired channel is displayed. Press the ENTER key to select a channel. If there is no sensor attached to that channel, the display will indicate such. If the channel displayed has a sensor and alarm records, the unit will indicate the number of alarm records available. To continue to print out the alarm records press the ENTER key and follow the instructions to turn on the printer, then press the ENTER key again to activate the printer. Follow the same steps for each channel checked. Don't forget to turn off the printer after the alarm records are complete. At any time if you wish to exit this routine press the INTERRUPT key.

(4) Alarm Set Point

The alarm set point default value is 500 ppm. If a different value is desired, contact the manufacturer for more information. NOTE: At the end of each test cycle (3 weeks) the disk should be changed. The old disk should be returned to the manufacturer.

To change the disk, it is important to return the operation of the system to the Main Menu. This will prevent the system from storing data onto the disk while you are changing it.

After the disk has been replaced, put the disk in the mailer provided and return it to Universal Sensors and Devices, Inc. A new disk then will be provided by USD.

3. Maintenance

The CATLAS system contains no user repairable or replaceable parts. All maintenance and repair should be referred to a qualified repair representative.

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APPENDIX M

CONCEPTUAL NETWORK DESIGN FOR UNDERGROUND STORAGE TANK MONITORING DEVICES

APPENDIX M

CONCEPTUAL NETWORK DESIGN FOR UNDERGROUND STORAGE TANK MONITORING DEVICES

A. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) developed regulations in 1988 for USTs storing either petroleum or certain hazardous chemicals. An UST is defined as any tank, including underground piping connecting to the tank, that has at least 10 percent of its volume underground. A summary of these regulations is as follows:

- An UST installed after December 1988 must meet the requirements for new USTs concerning correct installation, spill and overfill prevention, corrosion protection, and leak detection.
- An UST installed before December 1988 must meet the corrosion protection, spill and overfill protection, and leak detection requirements within a certain time period established by EPA.
- Appropriate corrective action must be taken in response to a leak.
- When closing an UST temporarily or permanently, appropriate closure requirements should be met.
- In the event of a leak, the owner of the tank is financially responsible for clearing the affected property and compensating the affected people.

Under these laws, the Air Force is required to monitor its underground tanks storing jet fuel and other petroleum products for leaks. Detailed regulations are being developed at state and local levels to delineate the monitoring alternatives. These alternatives include visual monitoring, tank testing (such as tank tightness or leak rate monitoring by volumetric changes), inventory reconciliation, soil testing, vadose zone monitoring, and groundwater monitoring. The scope of this report is limited to consider the last two techniques, vadose zone and groundwater monitoring, in a conceptual network design for UST systems at two typical Air Force bases.

The federal, state, and local regulations either require at present or may require in the near future intermittent or continuous monitoring of soil gas, pore liquids, and groundwater for petroleum hydrocarbon (such as diesel, gasoline, and jet fuel) vapors, dissolved components, and free-floating liquids. It is extremely difficult to predict the distribution of a vapor concentration in soil subsequent to a leak especially under complex environmental conditions. Modeling transport and distribution of free liquids and dissolved hydrocarbons in the subsurface also requires a significant effort and is limited by available input data. Detailed modeling of vapor and liquid (both dissolved and free-liquid) for site specific-conditions is beyond the scope of this report. The conceptual design of monitoring network will be based on existing federal, state, and local regulatory standards.

The state of California has developed the most comprehensive underground tank regulations under California Administrative Code, Title 23 (Waters), Chapter 16. The existing regulations were revised in August 1987. The sections of these regulations on vapor and groundwater monitoring are listed in Plate M-1 at the end of this appendix. For the present conceptual network design, regulatory standards from other states were also considered. The regulations for vapor monitoring and groundwater monitoring for a number of states are listed in Table M-1 and Table M-2, respectively. Also, local regulations obtained from Santa Clara County, California were used where applicable.

B. SCENARIO 1: UNDERGROUND STORAGE TANK COMPLETELY SUBMERGED IN GROUNDWATER

1. Site Description and Assumptions

A 15,000-gallon underground tank located at a Minutemen Launch Control Facility (LCF) stores diesel fuel. The tank is 7.5 feet in diameter and 40 feet long. It is buried 40 feet below the ground level. A network of fuel delivery pipelines extends perpendicular from the tank to the LCF. The following assumptions were made in order to design the spatial vadose and groundwater monitoring network:

a. The highest and lowest perennial water tables are 10 and 25 feet below the grade, respectively.

b. The tank excavation was back-filled with organic soil which extends 10 feet in each direction up to the bottom of the tank.

c. No clay layers are more than 5 feet thick within 55-foot depth.

TABLE M-1. TYPICAL STATE REQUIREMENTS FOR DESIGN OF VAPOR MONITORING NETWORK

State	Vapor Well Location Requirements	Vapor Well Depth Requirements
CALIFORNIA		
Santa Clara County	General: every 25 feet of long dimension (if passive monitoring device need more wells) At Station: one per tank one piping one pump island	At least to bottom of tank
City of Torrance	For one tank: one at each end >One tank: every 20 feet	NA
City of Vernon	Design for 15 feet diameter of influence	NA
DELAWARE	One per tank w/in 5 feet of tank	2 feet below tank bottom or to groundwater, whichever is less
MAINE	According to manufacturer's specifications At a minimum: - one within 5 feet of each dispenser - one at each piping joint - no piping run > 15 feet from well - one at each end of tank	Manufacturer's specifications
IOWA	- one at longitudinal ends of a single tank - if cluster of tank where tank < 10 feet apart, at least four wells, one on each side of cluster - all wells within excavation zone	

*Source: Release Detection Handbook (Draft Final), U.S. EPA, Office of UST, 1989

TABLE M-2. TYPICAL STATE REQUIREMENTS FOR DESIGN OF GROUNDWATER MONITORING NETWORK

Fremont, California:

Single tank - One downgradient well within 10 feet of the excavation perimeter.
Multiple tanks - One well placed every 35 feet on the longest dimension of the excavation with a minimum of two wells.

Torrance, California:

Single tank - One well on the downgradient side of the tank. If the groundwater gradient is not known, two wells on opposite sides of the tank.
Multiple tanks - To be evaluated.

Vernon, California:

Wells shall be placed downgradient of the tank(s) being monitored.

Delaware:

New installations - Four wells placed around the tank excavation field.
Existing Installations - Three wells placed in the excavation around the tank(s).

Florida:

Four wells placed in the excavation around the tank(s).

Iowa:

Single tank - One well at each longitudinal end of the tank.
Multiple tanks - Four wells placed on each side of the tank field.
Wells must be placed within 1 to 20 feet of the nearest tank.

Maine:

Groundwater is >15 feet - No fewer than two wells at either end of each tank.
Groundwater is <15 feet - No fewer than four wells for each tank or for multiple tanks located in the same excavation, one well at both ends of each tank and at each end of the excavation.

TABLE M-2. (Continued)

Maryland:

Two wells placed at opposite corners of the tank field.

Nebraska:

Groundwater is >15 feet - One well per tank.
Groundwater is <15 feet - Two wells per tank.

South Carolina:

Minimum of two wells placed every 30 feet.

Wisconsin:

Three wells required only for new UST installations.

Source: Release Detection Handbook (Draft Final), U.S. EPA, Office of UST, 1989

d. The hydraulic gradient slopes to the north, in the opposite direction of the LCF relative to the storage tank.

e. All the pipelines are at the top of tank elevation.

f. The responses of monitoring devices tested under the present study are similar to both JP-4 and diesel fuel responses.

g. The pressure inside the UST and pipelines is higher than the static head of groundwater so that a fuel leak is possible. (Note that this is a somewhat unlikely condition. In reality most USTs are not operated under pressure and a tank located below the water table is more likely to leak water in than product out. This points out the importance of monitoring for water in the tank and to take action when water is found inside the tank.)

2. Monitoring Network Outline

a. Vadose zone and groundwater monitoring are performed continuously, and the leak detection systems are connected to an aboveground alarm system (Section 2641-11, A; California code). Continuous monitoring alternatives appear to be the most stringent in the California code for groundwater protection. Other, less-frequent (not continuous) monitoring alternatives for vadose zone and groundwater monitoring have restrictions such as "the alternative shall not be used when first groundwater is less than 50 feet deep and:

(i) first groundwater has actual or potential beneficial uses (municipal, domestic, industrial, or agricultural supply), or

(ii) first groundwater is hydraulically connected to groundwater which has or potentially has beneficial uses."

b. Based on the tests conducted in this study, destructive-type devices (such as In Situ or TCI) may be used for liquid-phase monitoring. These devices responded to free-floating, fresh JP-4 layers at a thickness of 1/32 inch. During an alarm, it will be necessary to sample the wells to confirm the presence of free-floating petroleum products. In the absence of free-floating liquid, it is advisable to analyze headspace gas samples and water samples for relevant hydrocarbons (the results obtained in the present study for FCI to detect dissolved petroleum hydrocarbon were inconclusive;

therefore, a dissolved phase groundwater monitoring device cannot be recommended).

c. For vapor-phase monitoring, metal oxide semiconductor (MOS) type devices (such as USD and AZI) may be used. AZI can be used only if the backfill material can permit a gas flow of 1.5 L/min when the water table is at its highest elevation (worst case scenario). If the background is slightly contaminated, an AZI background probe also can be setup. For USD, the alarm threshold needs to be set above the background level. If background contamination is high, an Adsistor-type device (such as Red Jacket) may be used. In the event of an alarm, however, gas samples from the well headspace need to be analyzed to confirm that an alarm is caused by excessive petroleum hydrocarbons. The MOS devices (such as USD and AZI) were subjected to false alarms in the presence of interfering gases such as carbon monoxide and hydrogen sulfide and vapors such as trichloroethylene.

d. Vadose zone monitoring wells requirements vary from one state to the other. The most stringent regulations appear to be in California (City of Vernon) and Maine which require monitoring wells for a 15-foot diameter of influence. No piping greater than 15 feet from the well is allowed (Maine). The state of Maine also requires one well within 5 feet of each dispenser and one well at each piping joint. Iowa regulations require monitoring wells to be installed at least 1 foot away from the nearest tank but within the excavation zone. Based on these requirements, the number of vadose zone monitoring wells for the diesel storage tank at LCF should be at least eight. Their locations are given in Figure M-1.

e. The required number of groundwater monitoring wells also varies from one state to the other. California regulations require a minimum of 1 downgradient well within 10 feet of the excavation perimeter. Florida regulations require that 4 wells be placed in the excavation around the tank. Since the 15,000 gallon diesel storage tank at the LCF is completely covered with groundwater all the time, it is advisable to install more downgradient wells. Because of the complex nature of multi-phase liquid transport, it is difficult to predict whether free product will get to the liquid monitoring well under each possible leak scenario. Vadose zone monitoring devices (especially active units) are likely to detect a leak before the occurrence of

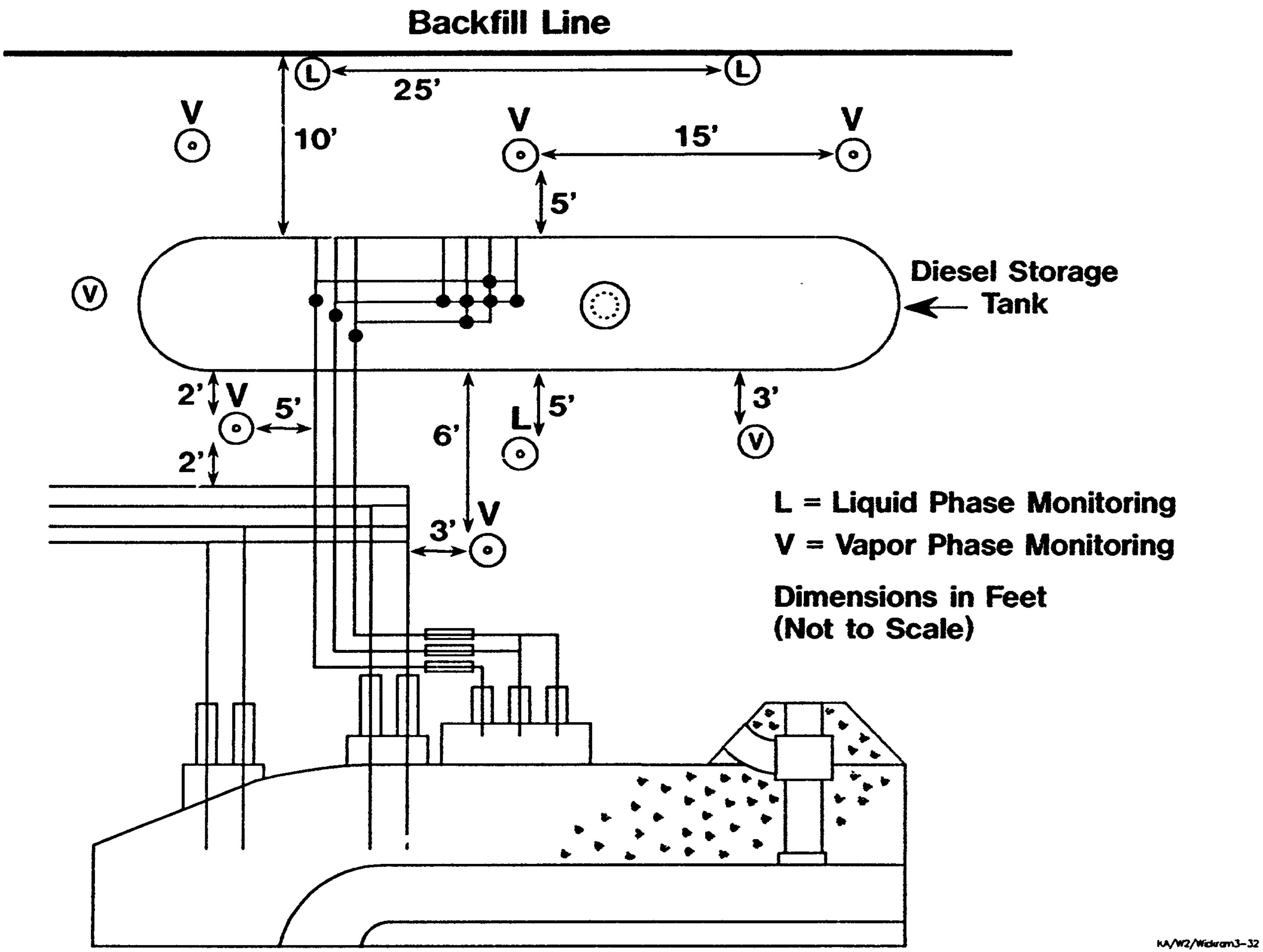

FIGURE M-1. LOCATIONS OF VAPOR AND LIQUID MONITORING WELLS FOR LCF free liquid in a downgradient well. The conceptual lay out of liquid-phase monitoring wells are shown in Figure M-1. Figure M-2 shows a diagram for a groundwater monitoring well.

f. The groundwater monitoring wells extend to a depth of 65 feet to conform to Section 2647-C of the California Code, which states that, at a minimum, the groundwater monitoring wells will exceed the depth of the bottom of the UST by 15 feet. The vadose zone wells extend to 27 feet, just below the lowest perennial groundwater, to assure that the entire depth of the vadose zone is monitored in each well. (See Table M-2 for State regulations).

g. The groundwater wells are positioned downgradient of the UST and pipeline, because any leaking liquid will migrate downgradient with the groundwater prior to reaching the unsaturated zone (Section 2641, Article 2 - Table 4.1, California Code).

h. All of the monitoring wells are placed as close as reasonably possible (5 feet) to the UST or pipeline (Section 2647-B, California Code).

i. The well configuration is based on the belief that vapor-phase monitoring will give the broadest spatial coverage of the detection field.

j. Background soil and water samples are taken and analyzed at the time of well installation (Section 2641-11, C, California Code).

3. Other Considerations

This design is based primarily upon conforming with the most rigid currently applicable regulations. In many localities actual requirements may be more or less stringent; in most cases, however, they will be less stringent, requiring fewer sensors.

This is an installation in a fine-grained organic soil, well below the water table. Based on the research conducted here, we cannot predict under these conditions what leak rate will be detected or how long that detection will occur after the leak has begun. The most probable scenario for a leak under these conditions involves free-phase product leaking from the tank and slowly rising to the water table. Very little is known about light nonaqueous phase liquid (LNAPL) behavior when released below the water table. As such the rate at which this LNAPL will migrate upwards is not predictable. Assuming upward migration does occur and the product encounters the water

Groundwater Monitoring Well

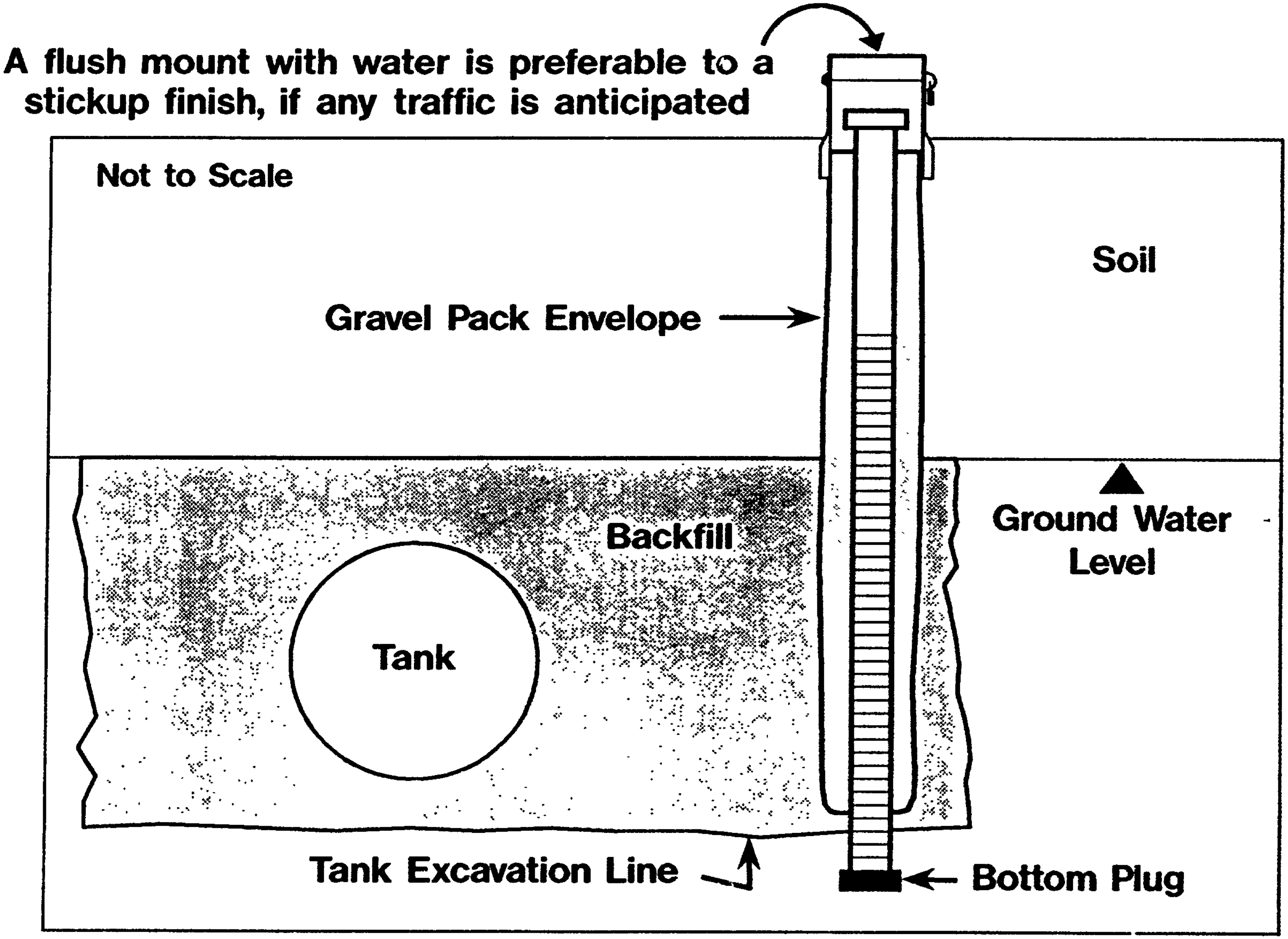

FIGURE M-2. DIAGRAM OF GROUNDWATER MONITORING WELL FOR THE LCF table prior to entering the liquid-phase monitoring wells, the product will migrate as a gas in the vadose zone and as specific phase liquid on the water table towards the sensors. This rate of migration will be fairly slow and, based upon laboratory studies, several days or weeks could be required for measurement at 15 feet. It is very likely that an alternative approach such as California's monitoring alternative 9 (California Administrative Code Title 23, Subchapter 16, Article 4) would be preferable. This alternative requires daily inventory reconciliation, weekly or bimonthly rate of volume change (RVC) testing, continuous pipeline leak detectors, and tank testing every 3 years. Based upon this research we cannot recommend external tank monitoring alone as an option for this type of installation.

Figure M-1 shows liquid sensors installed within 5 feet of the existing tank. (It was assumed that the tank and all piping was below the vadose zone). Prior to drilling these wells the tank location must be established as precisely as possible. Both the tanks and associated piping are at risk when wells are drilled at this close proximity. At a depth of 40 feet it would be difficult for a driller to detect the presence of a tank before damage was done. If hit, piping would very likely be ruptured. Field locations of old tanks and piping are frequently inaccurate. The degree of certainty as to the tank's location and consequences of damaging or rupturing the tank and/or piping must be considered to use external monitoring.

C. SCENARIO 2: JP-4 FUELING HYDRANT SYSTEM

1. Site Description and Assumptions

A JP-4 fuel hydrant system consisting of eight 50,000-gallon USTs are being discussed. The tanks are 12 feet in diameter by 60 feet long. They are buried 4 feet below ground level. There is an extensive pipeline network running between the tanks and extending to the hydrant system. The following assumptions were made in order to design the vadose and groundwater monitoring network:

a. The highest and lowest perennial water tables are 16 and 20 feet below grade, respectively.

b. The tank and pipeline excavations were backfilled with a medium grade sand.

c. There are no clay layers that are more than 5 feet thick within 40 feet depth.

d. The hydraulic gradient slopes to the north, in the opposite direction of the hydrant filling system relative to the storage tanks.

e. All pipelines, including the hydrant system, are at the top of the tank elevation (4 feet).

f. The hydrant fueling system extends 500 feet in the downgradient direction from the USTs.

2. Monitoring Network Outline

a. Vadose zone and groundwater monitoring are performed continuously, and the leak detection systems are connected to an aboveground alarm system (Section 2641-11, A; California Code). Continuous monitoring alternatives appear to be the most stringent in the California code for groundwater protection. Other, less-frequent (not continuous) monitoring alternatives for vadose zone and groundwater monitoring have restrictions such as "the alternative shall not be used when first groundwater is less than 50 feet deep and:

> (i) first groundwater has actual or potential beneficial uses (municipal, domestic, industrial, or agricultural supply), or
>
> (ii) first groundwater is hydraulically connected to groundwater which has or potentially has beneficial uses."

b. Based on the tests conducted in this study, destructive-type devices (such as In Situ or TCI) may be used for liquid-phase monitoring. These devices responded to free-floating, fresh JP-4 layers at a thickness of 1/32 inch. During the alarm, it will be necessary to sample the wells to confirm the presence of free floating petroleum products. In the absence of free-floating liquid, it is advisable to analyze headspace gas samples and water samples for relevant hydrocarbons (the results obtained in the present study FCI were inconclusive; therefore, a dissolved phase groundwater monitoring device cannot be recommended).

c. For vapor-phase monitoring, MOS-type devices (such as USD and AZI) may be used. AZI may be used only if the backfill material (sand) is likely to permit a gas flow of 1.5 L/min when the water table is at its highest elevation (worst case scenario). If the background is slightly contaminated, an AZI background probe also can be installed. For USD, the alarm threshold needs to be set above the background level. If background contamination is high, an Adsistor-type device (such as Red Jacket) may be used. In the event of an alarm, however, gas samples from the wellheadspace need to be analyzed to confirm that an alarm is caused by excessive petroleum hydrocarbons. The MOS devices (such as USD and AZI) were subjected to false alarms in the presence of interfering gases such as carbon monoxide and hydrogen sulfide and vapors such as trichloroethylene.

d. Vadose zone monitoring wells requirements vary from one state to the other. The most stringent regulations appear to be in California (City of Vernon) and Maine which require monitoring wells for a 15-foot diameter of influence. No piping greater than 15 feet from the well is allowed (Maine). The state of Maine also requires one well within 5 feet of each dispenser and one well at each piping joint. Iowa regulations require monitoring wells to be installed at least 1 foot away from the nearest tank but within the excavation zone. Based on these requirements, the number of vadose zone monitoring wells for the eight USTs should be at least 33. Their locations are given in Figure M-3. (Figure M-3 is not to scale. The approximate locations of vapor monitoring wells are given in the figure. The exact distribution of piping is not necessarily the way it is shown in the figure. Consequently, care should be taken, especially for the wells marked with an asterik (*), not to damage the piping network during the drilling installation of wells.) See Figure M-4 for the vapor-phase monitoring well diagram.

e. The hydrant fueling system cannot be efficiently monitored using vertical vapor monitoring wells. One possible method of monitoring the 500-foot length of piping is to place vapor monitoring devices in a trench excavated the full length of the hydrant system. Ideally, the trench would be dug as close as possible to the pipeline, to a depth of at least 1 foot below the bottom of the pipeline. A series of slotted casings would be placed along the trench. The chosen vapor detection device would be placed in the horizontal, perforated casings. Each series of casings would be set up to monitor a different segment of the pipeline. In this manner the pipeline can be divided into four or five monitoring segments, making it possible to locate which segment is leaking.

f. The required number of groundwater monitoring wells also varies from one state to the other. California regulations require a minimum of one downgradient well within 10 feet of the excavation perimeter. Florida regulations require that four wells be placed in the excavation around the tank. Because of the large number of tanks four monitoring wells were placed on the downgradient side of the tank excavation. Each well is located just inside the tank backfill at the end of each tank on the downgradient side. One groundwater monitoring well is located downgradient to the hydrant system. The location of the groundwater monitoring wells is shown in Figure M-3.

g. The groundwater monitoring wells extend to a depth of 35 feet to conform to Section 2647-C of the California Code, which states that, at a minimum, the groundwater monitoring wells will exceed the depth of the bottom of the UST by 15 feet. The vadose zone wells extend to 22 feet, just below the lowest perennial groundwater, to assure that the entire depth of the vadose zone is monitored in each well. (See Table M-2 for state regulations).

h. The groundwater wells are positioned downgradient of the UST and pipeline because any leaking liquid will migrate downgradient with the groundwater prior to reaching the unsaturated zone (Section 2641, Article 2 - Table 4-1, California Code).

i. The monitoring wells are positioned to give the greatest coverage with a minimum number of wells.

j. The well configuration is based on the belief that vapor-phase monitoring will give the broadest spatial coverage of the detection field.

k. Background soil and water samples are taken and analyzed at the time of well installation (Section 2641-11, C, California Code).

D. CONSTRUCTION AND SAMPLING GUIDELINES FOR GROUNDWATER AND VADOSE ZONE MONITORING WELLS

The following general guidelines were adapted from the California Administrative Code, Title 23 Waters, Subchapter 16, Chapter 4, Sections 2646, 2647, and 2648.

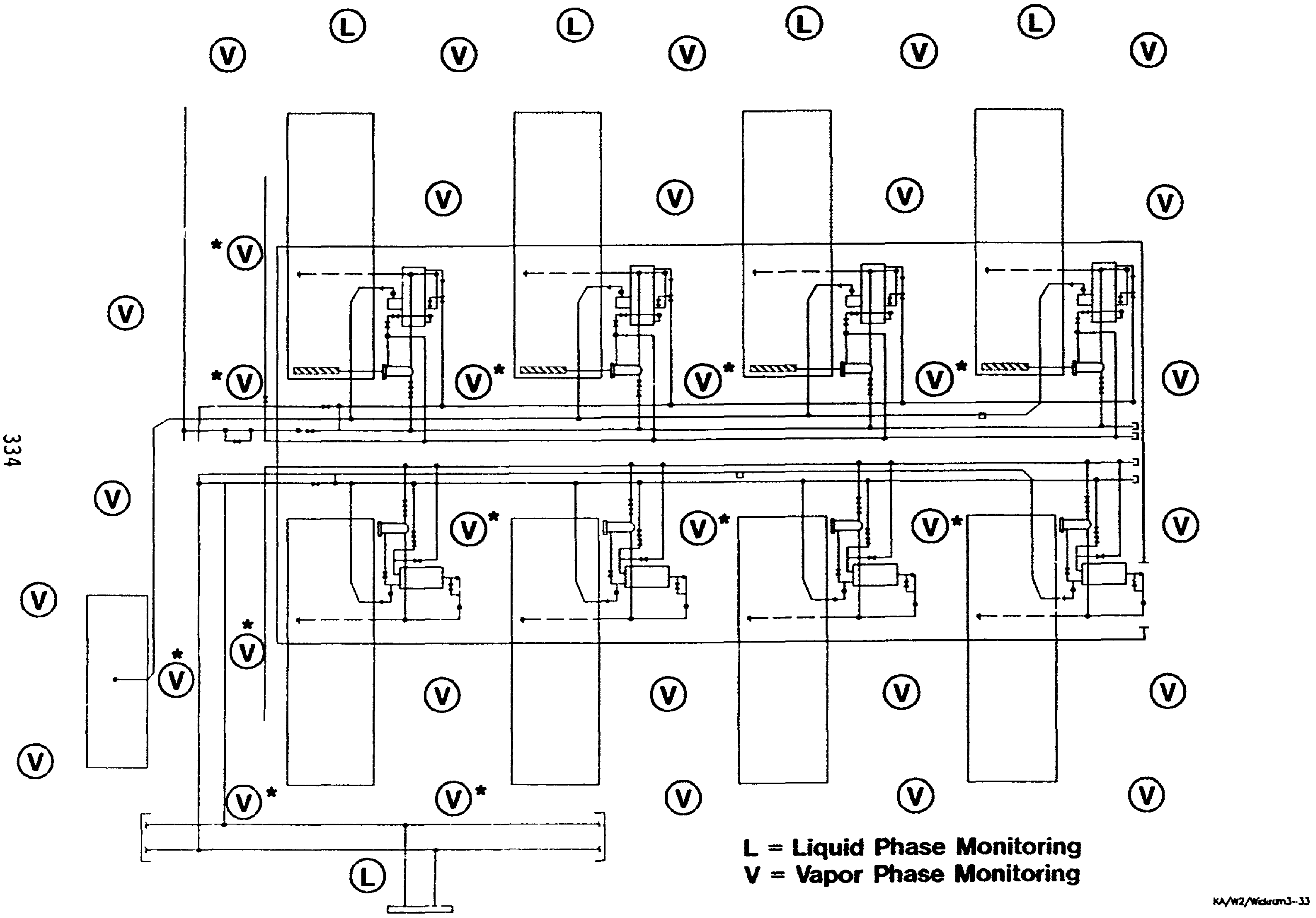

FIGURE M-3. LOCATION OF VAPOR AND LIQUID-PHASE MONITORING WELLS FROM THE FUEL HYDRANT SYSTEM

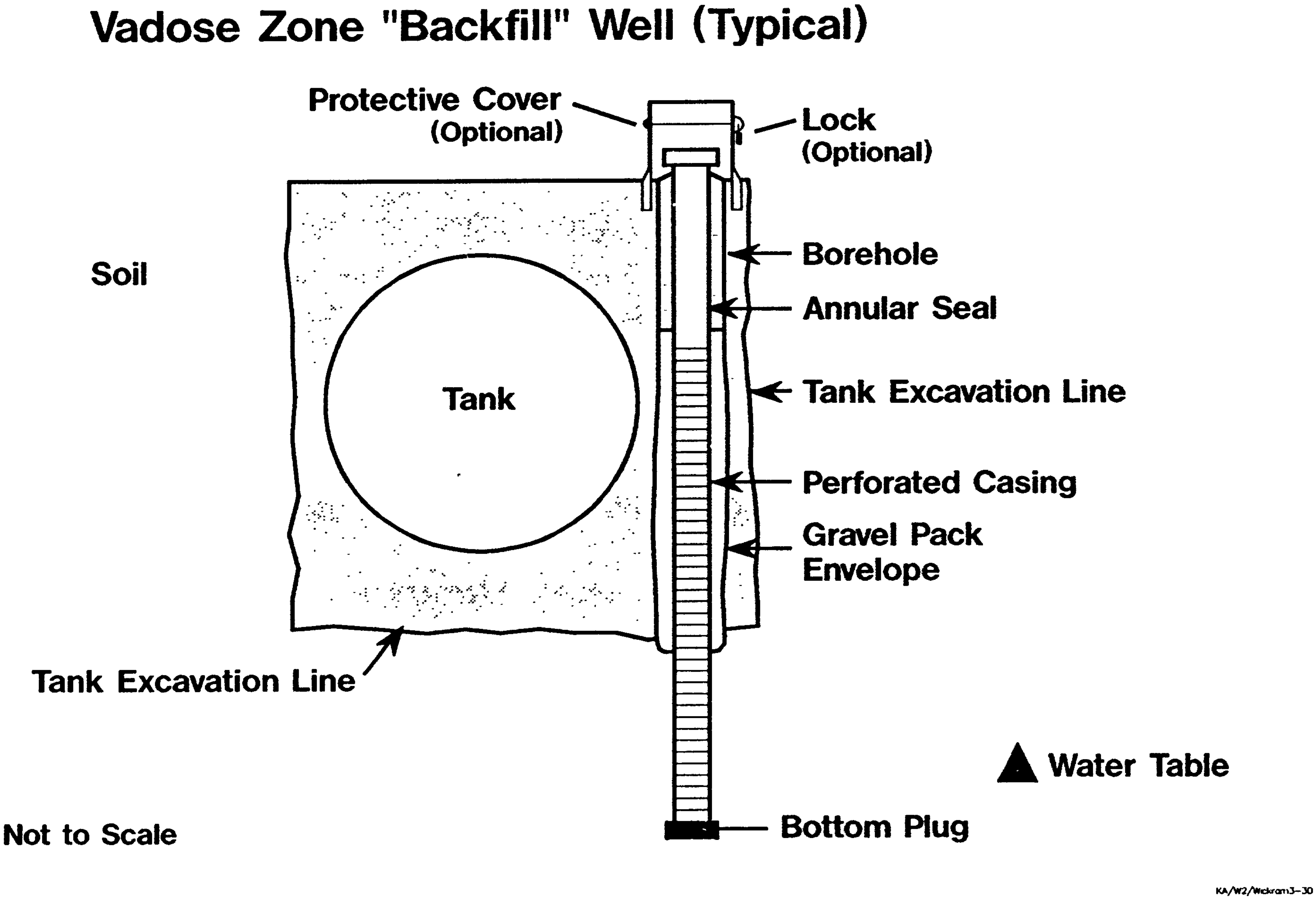

FIGURE M-4. DIAGRAM OF A VAPOR-PHASE MONITORING WELL FOR THE FUEL HYDRANT SYSTEM

1. Vadose Zone Monitoring Wells

a. Wells for vapor monitoring should be fully perforated except for the portion adjacent to a surface seal and that portion of the bottom of the well where a plugged, blank segment of casing is used as a free-liquid trap.

b. The number, location, and depths of vadose zone monitoring points should be selected so as to give the earliest possible warning of any unauthorized release from the UST.

c. Subsurface vadose zone monitoring systems should, if possible, be located within the backfill surrounding the UST.

d. Vapor monitoring wells placed in the backfill should be constructed so that any unauthorized release that may pond at the horizontal interface between the backfill and natural soils can be detected in the vapor well.

e. Vapor wells constructed wholly within backfill that surrounds the UST and which extends to the ground surface need not be sealed against infiltration of surface water.

f. All wet zones in the vadose zone should be noted and accurately logged.

[Other Considerations - This plan calls for installation of wells in quite close proximity to the existing tanks and piping. To prevent damage to the tanks or associated piping all well locations less than 5 to 10 feet from tanks or piping should be hand augured to a depth of 8 feet prior to drilling. The hand auguring should be done accurately to allow the identification of any subsurface structure without damage. Prior to initiating drilling the tanks and piping should be precisely located, where a location is in question hand auguring should be utilized regardless of distance from the suspected locations.]

2. Groundwater Monitoring Wells

a. All groundwater monitoring wells should be located as close as possible to the UST or the perimeter of the underground storage tank cluster consistent with optimum coverage of potential plumes.

b. Groundwater monitoring wells should extend at least 20 feet below the lowest anticipated perennial groundwater level and at least 15 feet below the UST bottom. However, wells should not extend through laterally extensive clay layers that are below the water table and that are at least 5 feet thick. In these situations the well should be terminated 1 to 2 feet into this clay layer.

c. Groundwater monitoring well casings should extend to the bottom of the boring and be factory perforated from a point 1 foot above the bottom of the casing to an elevation 10 feet above the highest anticipated groundwater level or to the bottom of the surface seal or to the ground surface, whichever occurs at the lowest elevation.

d. Groundwater monitoring wells should be designed and constructed as filter-packed wells with factory-perforated casings such that the migration of the natural soil and filter media into the well will be prevented.

e. All well casings should have a bottom cap or plug.

f. Groundwater monitoring wells should be constructed with casings having a minimum inside diameter of 2 inches which are installed in a boring whose diameter is at least 4 inches greater than the inside diameter of the casing.

g. All groundwater monitoring wells must be appropriately developed until the discharge water contains less than 10 ppm settleable solids.

h. Groundwater levels shall be measured and recorded each time the well is sampled.

3. General Construction Guidelines

a. Soil and water sampling equipment and materials used to construct a well must be compatible with the stored hazardous substance and shall not donate, capture, mask, alter the constituents for which analyses will be made.

b. All drilling tools must be thoroughly cleaned immediately before a boring is started.

c. All well casings, casing fittings, screens, and other components that are installed in the well must be thoroughly cleaned before installation in the boring.

d. All soil and water samplers must be cleaned before each sample is taken.

e. All exploratory borings and borings used for the installation of monitoring systems must be drilled and sampled by techniques that do not introduce liquids into the boring and that will allow the accurate detection of perched and saturated zone groundwater. If these prerequisites cannot be met using standard drilling techniques, the borings may be completed by any appropriate drilling techniques.

f. Drilling fluid additives should be limited to inorganic, nonhazardous materials that conform to the provisions of Subsection (a) of this section. All additives used and the depth at which they were used should be accurately recorded in the boring log.

g. All perforated casing used in the construction of monitoring wells shall be factory perforated.

h. Representative samples of additives, cement, bentonite, and filter media shall be retained for at least 90 days for possible analysis of contaminating or interfering constituents.

E. DISCUSSION

The conceptual monitoring network design for two scenarios was developed for a rather stringent set of regulations combined from different state and local codes. Consequently, the monitoring networks may appear to be overdesigned for both sites. More specific site and regulatory information should be considered in the final design.

Laboratory studies conducted as part of this project showed significant variation in the transport of liquid and vapor in the subsurface. For example, jet fuel (JP-4) that leaked in the sand tanks reached one well located 3 feet from the leak within 20 hours whereas the fuel took over 300 hours to reach another well located at the same distance from the well. Therefore, even if the groundwater monitoring wells are located downgradient of a potential leak, a leak may go undetected depending on the soil properties in the backfill material. Equipping vapor monitoring wells with devices that are sensitive to JP-4 vapors is necessary to detect leaks with more certainty.

Vapor transport is also affected by the physical and chemical characteristics of backfill materials. Figures M-5 through M-13 show concentration ratios of butane, benzene, and heptane at distances of 5, 10, and 15 feet from a leak in dry sand, dry soil, and wet soil. These figures are for transport of vapors in a cylindrical column; therefore, in nonrestrictive subsurface environments (i.e., without any control boundaries), the vapor concentration distribution will be comparatively low. Based on the column experiments where vapor transport is diffusion driven in dry sand, relatively high fractions of butane, benzene, and heptane may be found even at a distance of 15 feet (Figures M-5, M-6, and M-7) within 2 days. However, in dry organic-rich soil, vapors such as benzene and heptane may not appear at a distance of 15 feet for almost 10 days. Therefore, if the backfill material is organic-rich soil, it is advisable to have vapor monitoring wells very close to locations where leakage is likely to occur. If the backfill material is sand, a leak may be detected even if the vapor monitoring well is located at 10 feet or more from the leak. The presence of moisture in sand can retard transport of some water-soluble vapors, but it becomes less significant with time.

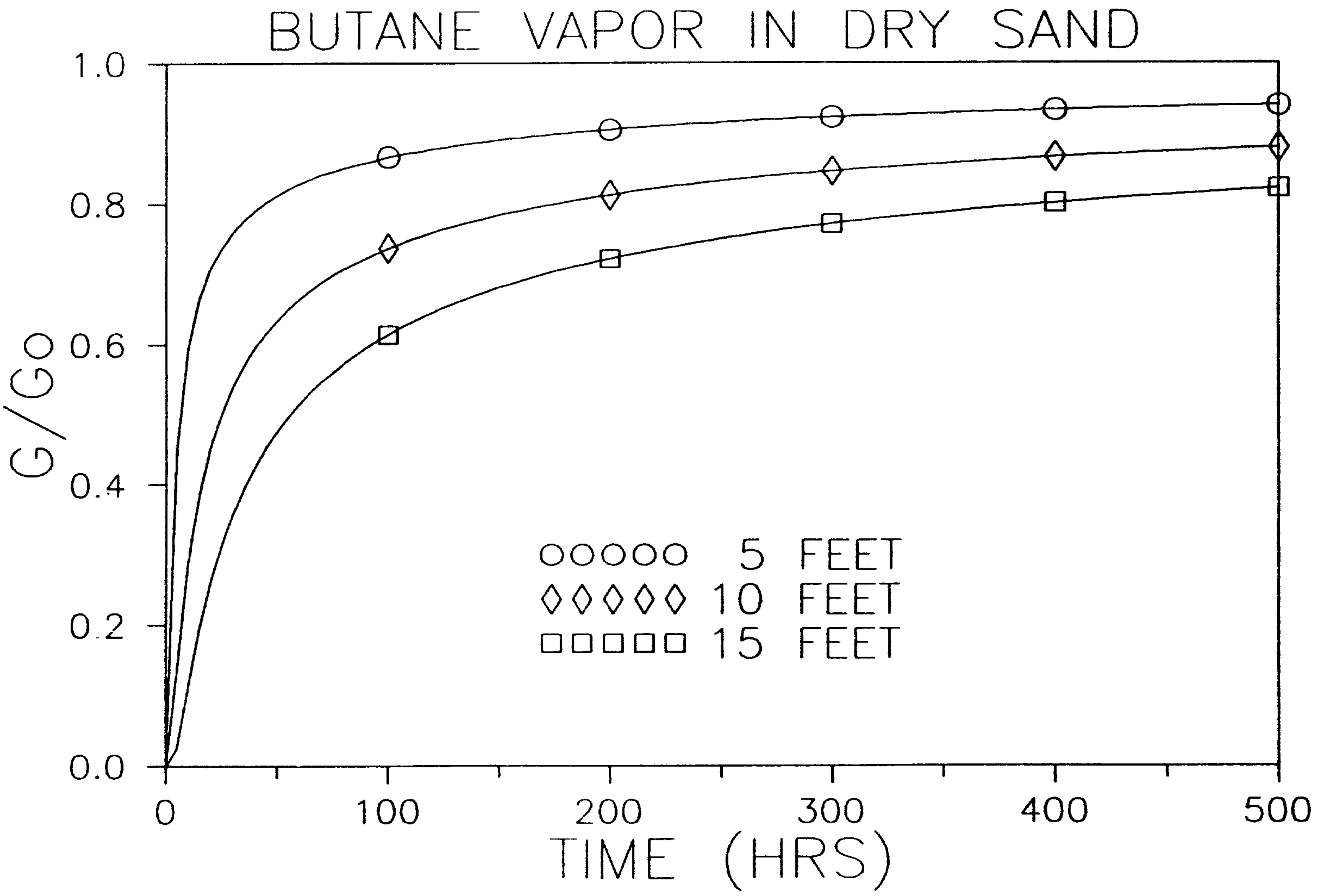
BUTANE VAPOR IN DRY SAND
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET

FIGURE M-5

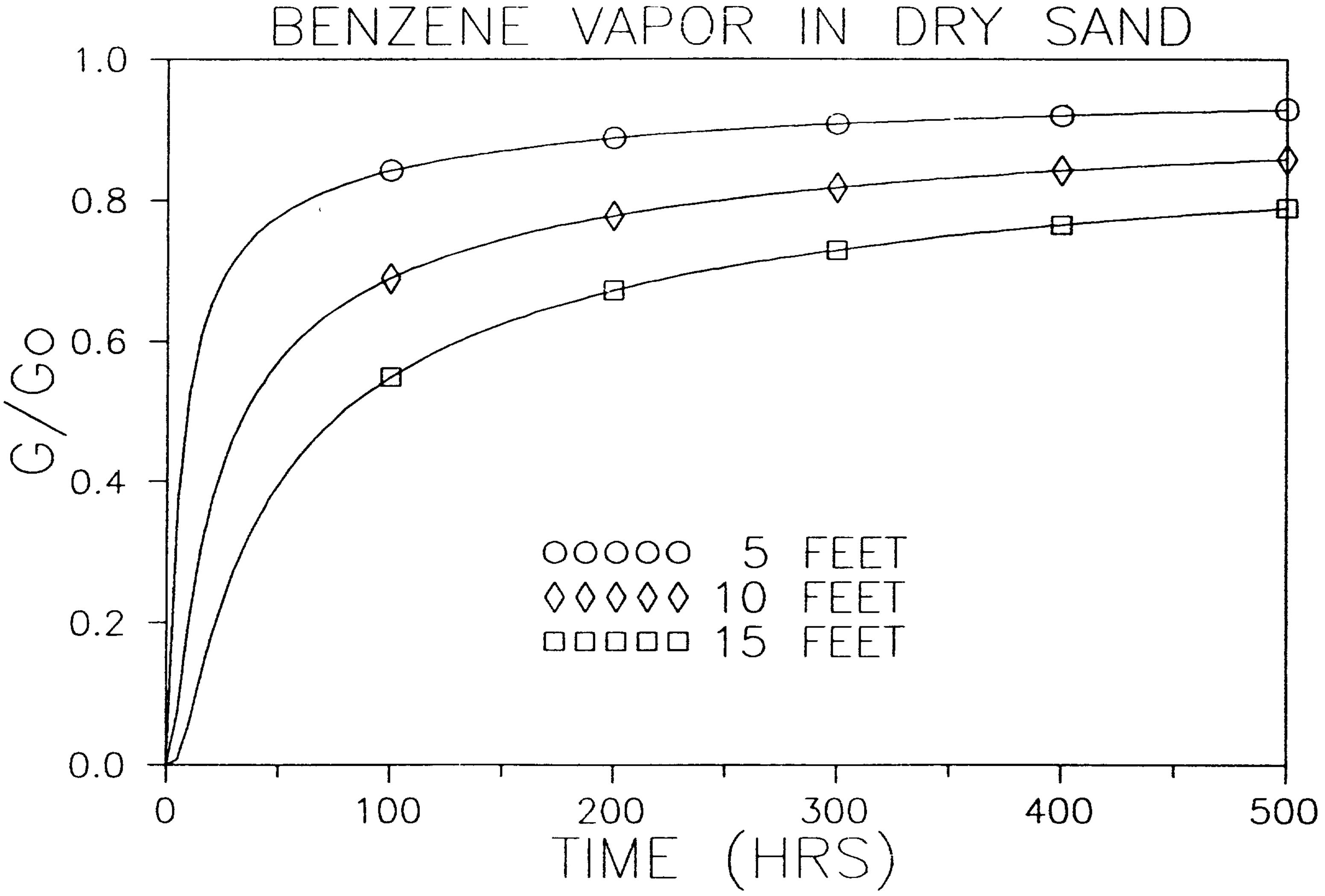
BENZENE VAPOR IN DRY SAND
G/Go
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET

FIGURE M-6

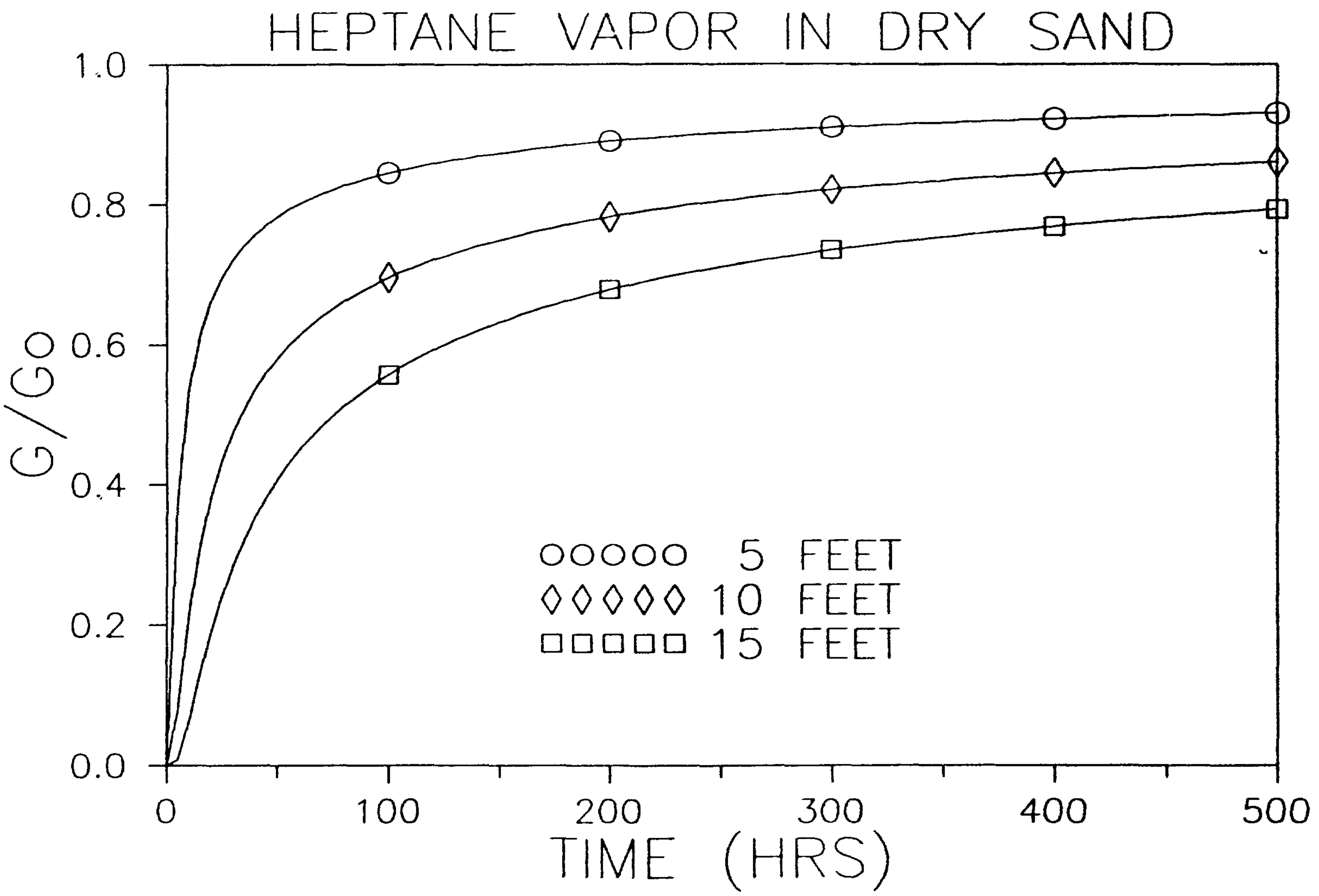
HEPTANE VAPOR IN DRY SAND
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET

FIGURE M-7

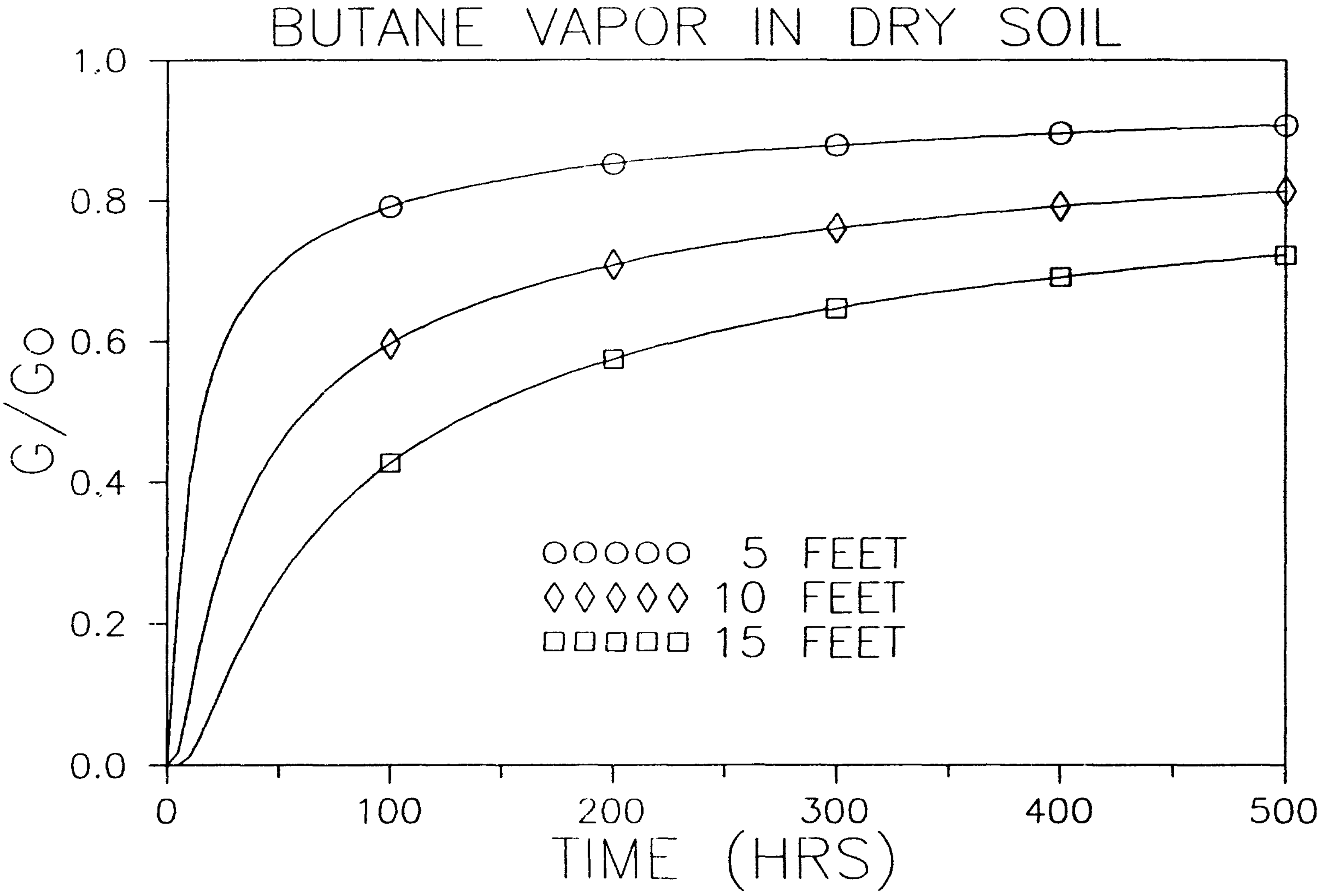
BUTANE VAPOR IN DRY SOIL
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET

FIGURE M-8

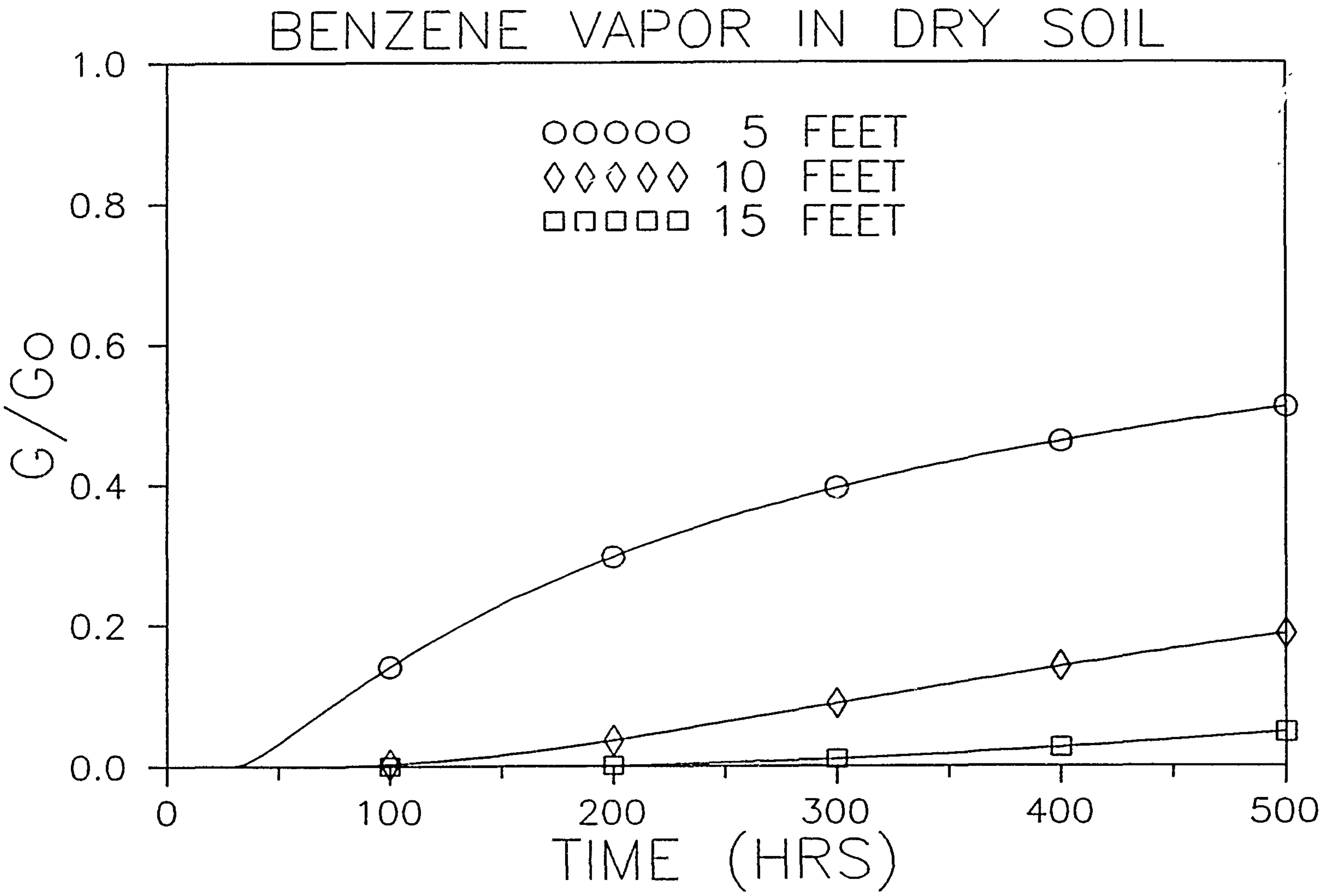
BENZENE VAPOR IN DRY SOIL
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)

FIGURE M-9

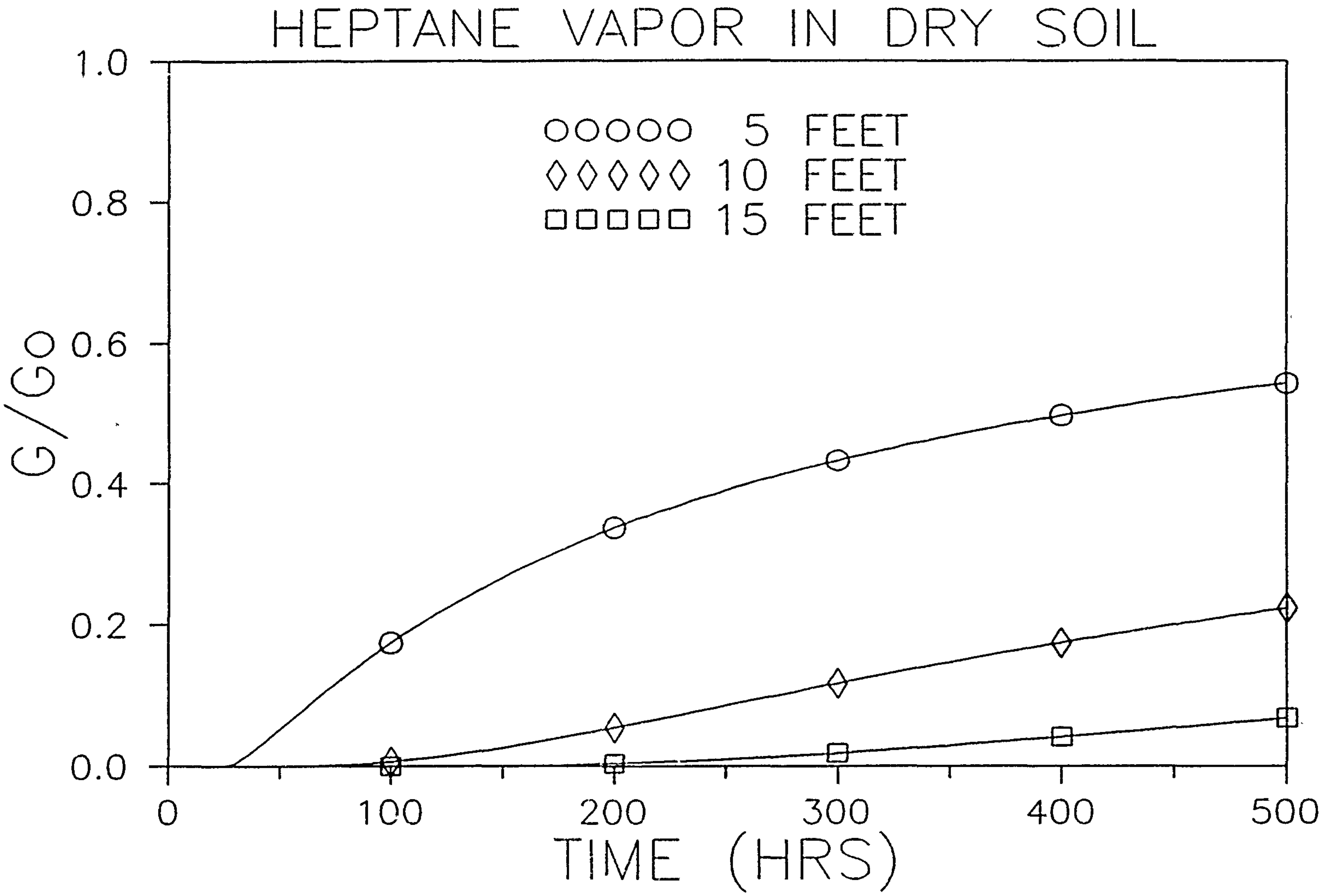
HEPTANE VAPOR IN DRY SOIL
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)

FIGURE M-10

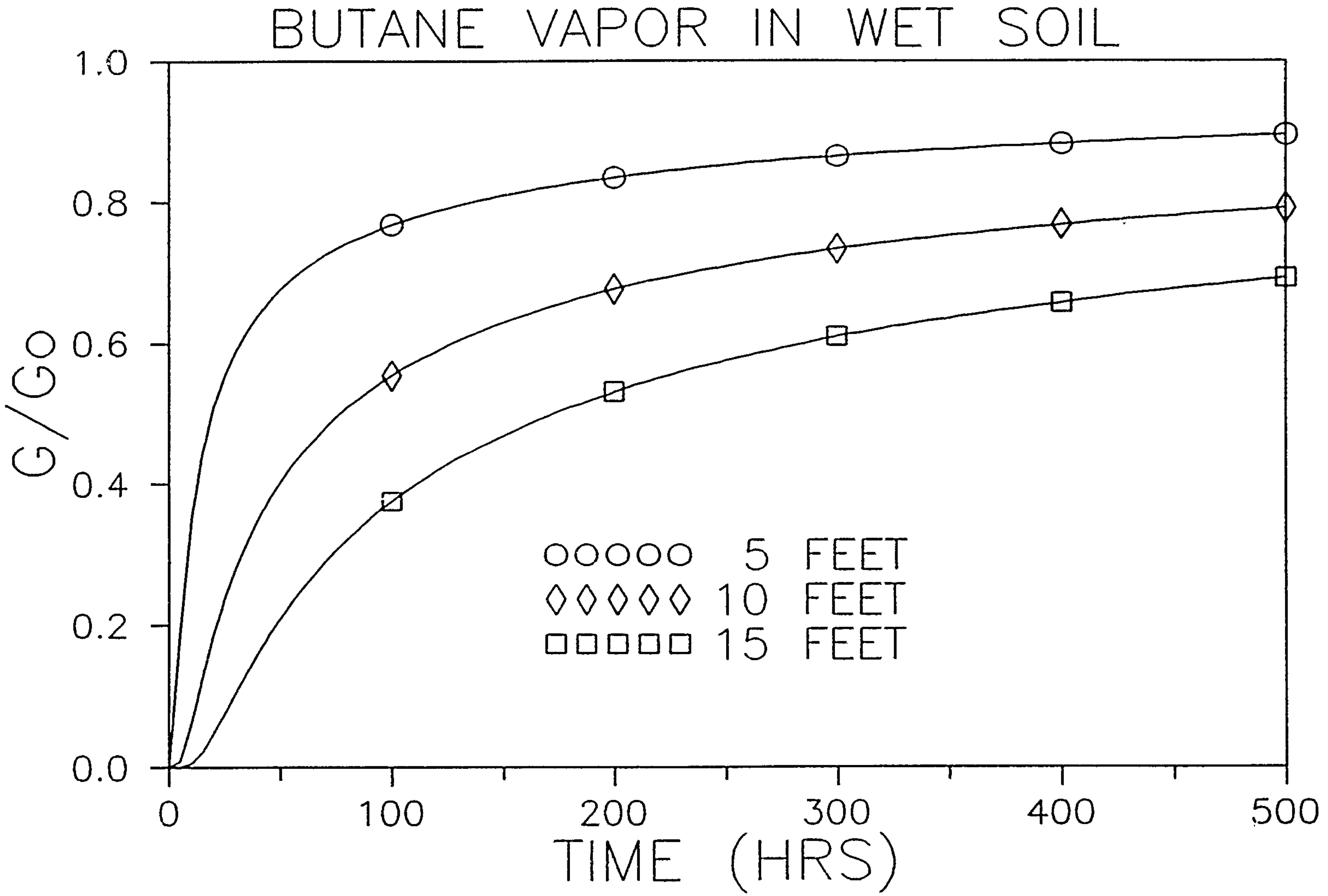
BUTANE VAPOR IN WET SOIL
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET

FIGURE M-11

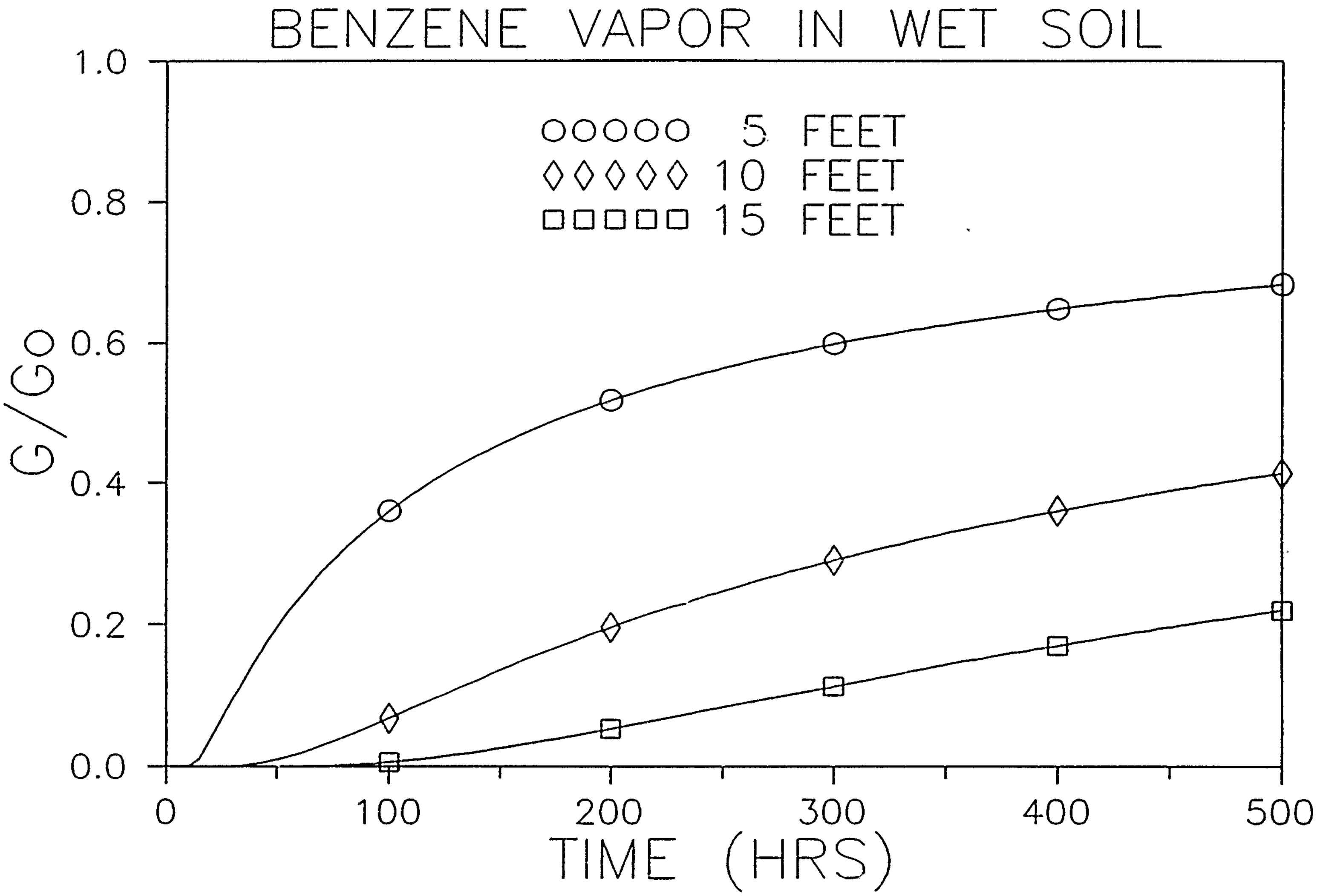
BENZENE VAPOR IN WET SOIL
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET
G/GO
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
TIME (HRS)

FIGURE M-12

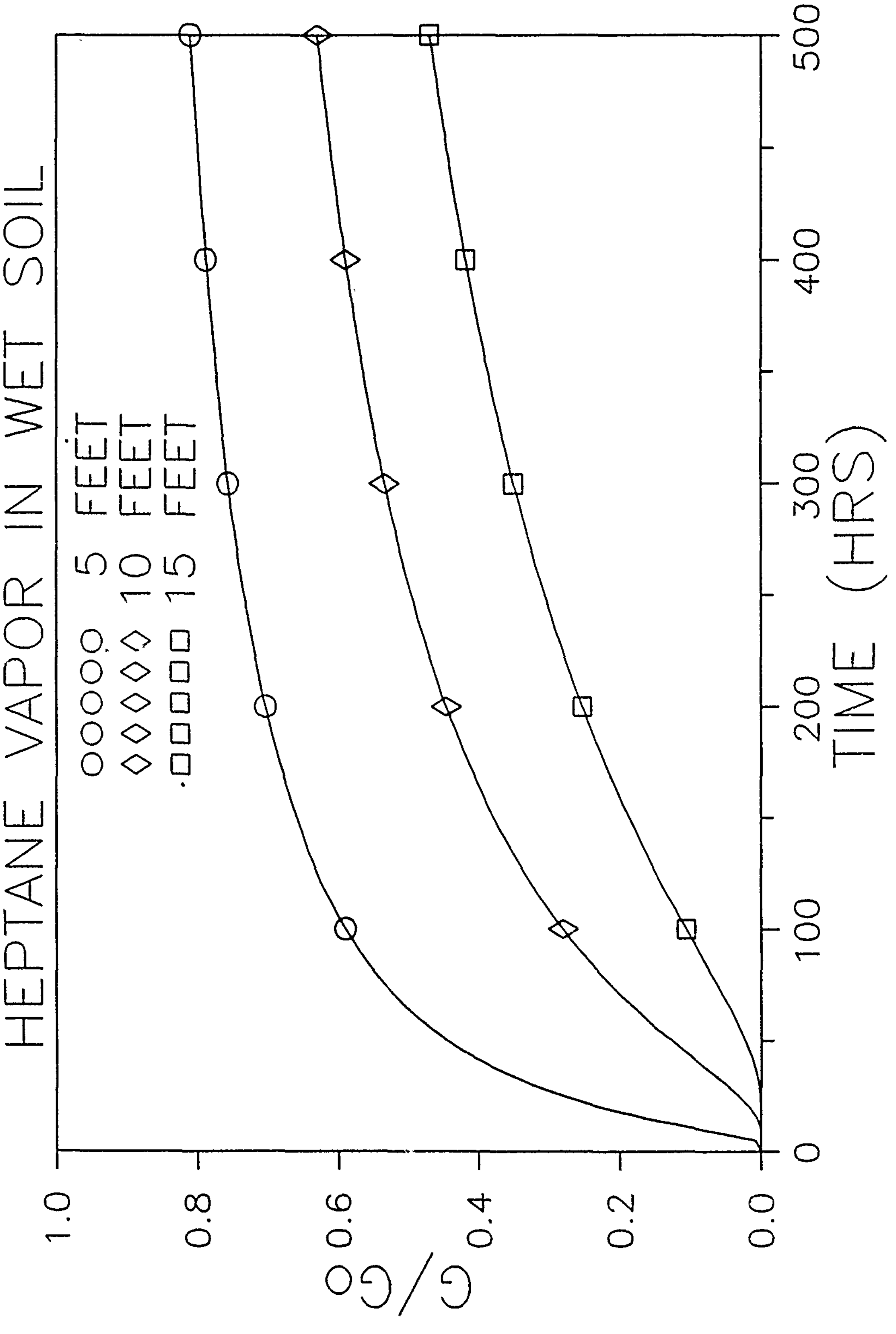
HEPTANE VAPOR IN WET SOIL
○○○○○ 5 FEET
◇◇◇◇◇ 10 FEET
□□□□□ 15 FEET
C/CO
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500
TIME (HRS)

FIGURE M-13

PLATE M -1

AUG 7 1987

UNDERGROUND TANK REGULATIONS

CALIFORNIA ADMINISTRATIVE CODE
TITLE 23 WATERS
SUBCHAPTER 16 UNDERGROUND TANK REGULATIONS

Article 4. Existing Underground Storage Tank Monitoring Standards

2646 Vadose Zone Monitoring
2647 Ground Water Monitoring
2648 General Construction and Sampling Methods

TABLE 4.1 MONITORING ALTERNATIVES*

ALTERNATIVE	METHOD	MONITORING FREQUENCY	REFERENCE SECTION	COMMENTS AND CONDITIONS PROHIBITING USE OF ALTERNATIVE*
1	Tank Testing	Monthly	Section 2643	None .
2	Vapor or Other Vados Zone Monitoring and Ground Water Monitoring and Soils Testing	Continuous or Daily Continuous to Weekly Semi-annual One-Time	Section 2646 Section 2646 Section 2647 Section 2645	1. Must be able to do both vadose and ground water monitoring 2. Ground water should normally be less than 100 feet deep to use this alternative. 3. Minimum number of ground water monitoring wells: a. Ground water equal to or less than 50 feet deep. o Single or multiple tanks (all <1,000 gal, same or closely spaced excavations) - one downgradient well per tank minimum up to three wells. o Single tank (≥1,000 gal) - two wells minimum one of which shall be downgradient. o Two or three tanks (at least one ≥1,000 gal, same or closely spaced excavations) - three wells, minimum at least one of which shall be downgradient. o Four or more tanks (at least one ≥1,000 gal, same or closely spaced excavations) - four wells minimum, at least two of which shall be downgradient and the remainder equally spaced. Pipelines - additional wells, if needed, as determined by the local agency. b. Ground water greater than 50 feet deep. o Single tank -one downgradient well. o Multiple tanks or closely spaced tank excavations - three wells uniformly spaced. unless the ground water gradient can be accurately determined, in which case, one downgradient well. o Pipelines - additional wells, if needed, by the local agency. 4.2a
3	Vapor or Other Vadoze Zone Monitoring and Soils Testing and Tank Testing	Daily/Weekly One-Time Annual	Section 2646 Section 2645 Section 2643	This alternative shall not be used when first ground water is less than 100 feet deep and: 1. First ground water has actual or potential beneficial uses (municipal, domestic, industrial, or agricultural supply); or 2. First ground water is hydraulically connected to ground water which has or potentially has beneficial uses.
4	Ground Water and Soils Testing	Monthly One-Time	Section 2647 Section 2645	1. Use of this alternative shall be limited to the following situations: a. Perennial ground water is normally less than 30 feet deep, and b. The ground water being monitored does not have any actual or potential beneficial uses (municipal, domestic, agricultural, or industrial supply), and c. The ground water being monitored is not hydraulically connected to ground water which has any actual or potential beneficial uses (municipal, domestic, agricultural, industrial supply), and d. The monitoring well can be screened in the area 10 feet above the highest perennial ground water level and 20 feet below the lowest ground water level. 2. Minimum number of ground water monitoring wells-- See Section 3a. of Alternative No. 2. 4.2b

5	Inventory Reconciliation and Tank Testing and Pipeline Leak Detectors	Daily Annual Continuous	Section 2644 Section 2643	1. Must use approved meters for tank inputs and and withdrawals. 2. Inventory reconciliation which exceeds an allowable measurement error plus 0.15 percent of throughput at any time during a 30-day period shall require further investigation: Tank Size — Allowable Measurement Error <4000 — 25 gallons 4000 to <8000 — 50 gallons 8000 to <12000 — 75 gallons 12000 to <16,000 — 100 gallons ≥16000 — 125 gallons 3. Limited to motor vehicle fuels storage tanks.
6	Inventory Reconciliation and Tank Testing and Pipeline Leak Detectors and Soils Testing and Vadose Monitoring and Ground Water Monitoring	~~Daily~~ Weekly/Monthly Annual Continuous One-Time Variable Variable	Section 2644 Section 2643 Section 2645 Section 2646 Section 2647	1. Must use approved meters for tank inputs and withdrawals. 2. Inventory reconciliation which exceeds any of the following shall require further investigation: ~~a. Daily variation + (+/-)100 gallons~~ ~~b~~ a. ~~Weekly~~ 7-day variation -(+/-) 5 percent of throughput or 100 gallons whichever is greater but no greater than 350 gallons ~~c~~ b. Monthly variation - (+/-)0.5 percent of throughput no less than 100 gallons 3. Minimum number of ground water wells--See Alternative No.2. 4. Limited to motor vehicle fuels storage tanks. 4.2c
7	Tank Gauging and Tank Testing	Weekly Annually	Section 2644(d) Section 2643	1. This alternative is limited to use on ~~small~~ tanks that do not have ~~frequent~~ input or withdrawals for a period of 36 hours each week ~~(e.g., standby generator fuel supply)~~ and where the liquid level in the tank can be measured to the accuracy of + or ~~±5~~ -9 gallons. A liquid level difference of ~~1 percent of the tank volume or 5~~ 17 gallons, ~~whichever is less~~ shall be cause for further investigation.
8	Tank Testing and Inventory Reconciliation or Tank Gauging	Annually Daily Daily or Weekly	Section 2643 Section 2644(d) Section 2644	1. This is an interim monitoring alternative that can be implemented for up to three years. 2. Inventory reconciliation shall utilize approved meters for inputs and withdrawals and shall maintain variations within the limits specified in Alternative No. 6. 3. Tank gauging is limited to use on tanks described in Alternative No. 7. ~~and to those tanks that can eliminate inputs and withdrawals three times per week for 12 hours each. A liquid level difference of 1 percent of the tank volume but not greater than 50 gallons shall be cause for futher investigation.~~ 4.2d

9	Inventory Reconciliation	Daily	Section 2644	1. Must use approved meters for tanks inputs and withdrawals (See Section 2644) and an in-tank level measuring device meeting criteria of Section 2641(c)(9)(e). 2. Inventory reconciliation which exceeds the levels specified in Table 4.2 shall require further investigation. 3. Limited to motor vehicle fuels storage tanks.
	and			
	RVC Testing	Weekly/ Bimonthly	Section 2641(c)(9)(D)	
	and			
	Pipeline Leak Detectors	Continuous		
	and			
	Tank Testing	Every 3 Years	Section 2643.	
10	Vadose Monitoring	Monthly/ Annually	Section 2641(c)(10)	This alternative is limited to large tanks over 20,000 gallons
	Ground water Monitoring	Monthly/ Annually	Section 2641(c)(10)	This alternative shall not be used when first ground water is less than 50 feet deep and: 1. First ground water has actual or potential beneficial uses (municipal, domestic, industrial or agricultural supply); or 2. First ground water is hydraulically connected to ground water which has or potentially has beneficial uses.
11	Continuous Leak Detection in wells	Continuous	Section 2641(c)(11)	1. Must be able to do both vadose and ground water monitoring 2. Number and location of wells to be determined by local agency

4.2e

4.2f

2646. Vadose Zone Monitoring

(a) All owners of existing underground storage tanks implementing one of the monitoring alternatives described in Section 2641 of this article ~~WHICH~~ that requires vapor monitoring or another form of vadose zone monitoring shall implement the vadose zone detection monitoring system pursuant to Subsections (b) through (h) of this section and the applicable subsections of Section 2648.

(b) Vadose zone monitoring shall consist of vapor monitoring, soil-pore liquid monitoring, or other forms of vadose zone monitoring. Combinations of these methods may be used.

(c) Wells for vapor monitoring shall be fully perforated except for that portion adjacent to a surface seal and that portion of the bottom of a well where a plugged, blank segment of casing is used as a free liquid trap.

(d) The number, location, and depths of vadose zone monitoring points shall be selected so as to give the earliest possible warning of any unauthorized release from the underground storage tank.

(e) Subsurface vadose zone monitoring systems shall, if possible, be located within the backfill surrounding the underground storage tank.

(f) Vapor monitoring for underground storage tanks shall be used in accordance with the following criteria if the vapor characteristics of the stored product are susceptible to detection:

(1) Before any method of vapor monitoring is approved for a specific site, it shall be demonstrated by an actual on-site demonstration, using an appropriate tracer substance, that vapor would actually be detected by the installed system. This requirement may be waived by the local agency based on a demonstration by the applicant that the proposed monitoring system has been proven to be effective in detecting unauthorized releases from underground storage tanks in equal or less favorable situations. The following factors shall be considered in comparing the demonstration to the actual on-site conditions:

(A) Backfill materials and grain size distribution.

(B) Type and homogenity of native soils.

(C) Range of moisture contents of the backfill and native soils that will be encountered and their effect on vapor migration and detection.

(2) The location and depth at which each sensor is placed relative to the underground storage tank shall be determined according to the

(3) Vapor monitoring wells placed in the backfill shall be constructed so that any unauthorized release that may pond at the horizontal interface between the backfill and natural soils can be detected in the vapor well.

(g) Soil-pore liquid monitoring and other forms of vadose zone monitoring may be approved if the tank owner ~~discharger~~ can clearly show that:

(1) The stored substance is susceptible to detection by the proposed technique.

(2) The stored substance will not attack the materials from which the detector system is constructed or otherwise render the detector system inoperable.

(3) The site and soil characteristics will not prevent detection of an unauthorized release by the monitoring system.

(4) The proposed technique will be effective in providing early detection of underground storage tank leakage.

~~(h) Borings shall be described in accordance with the provisions of the Subsections 2648 (t) and (u) of this article.~~

(h) If vadose zone monitoring indicates that an unauthorized release has occured, the permittee shall report the release pursuant to Article 5 of this subchapter and shall repair or close the underground storage tank pursuant to Article 6 or 7 of this subchapter.

Authority: H&SC 25299.3
Reference: H&SC 25292

2647. Ground Water Monitoring

(a) All owners of existing underground storage tanks implementing one of the monitoring alternatives in Section 2641 of this article which requires ground water monitoring shall implement a ground water monitoring system pursuant to Subsections (b) through (j) of this section and the applicable Subsections of Section 2648.

(b) All ground water monitoring wells shall be located as close as possible to the underground storage tank or the perimeter of the underground storage tank cluster consistent with optimum coverage of potential plumes.

(c) Ground water monitoring wells shall extend at least 20 feet below the lowest anticipated perennial ground water level and at least 15 feet below the underground storage tank bottom. However, wells shall not extend through laterally extensive clay layers that are below the water table and that are at least 5 feet thick. In these situations, the well shall be terminated 1 to 2 feet into this clay layer.

(d) Ground water monitoring well casings shall extend to the bottom of the boring and be factory perforated from a point 1 foot above the bottom of the casing to an elevation ~~which is either~~ 10 feet above the highest anticipated ground water level or to the bottom of the surface seal or to the ground surface, whichever ~~is~~ occurs at the lowest elevation. ~~point above the highest anticipated ground water level~~ A means shall be provided for monitoring any intermittent perched ground water zone that occurs above the main, perennial ground water aquifer.

(e) Ground water monitoring wells shall be designed and constructed as filter-packed wells ~~that will prevent~~ with factory perforated casing such that the migration of the natural soil and filter media into the well will be prevented. ~~and with factory perforated casing that is sized to prevent migration of filter material into the well/~~

(f) All well casings shall have a bottom cap or plug.

(g) Filter packs shall extend at least 2 feet above the top of the perforated zone except where the top 2 feet of the filter pack would provide cross-connection between otherwise isolated zones or where the ground surface is less than 10 feet above the highest anticipated ground water level. If the ground surface is less than 10 feet above the highest anticipated ground water level, ~~in which case this requirement may be waived by~~ the local agency ~~provided~~ may reduce the height of the filter pack so long as the filter pack extends at least to the top of the perforated zone. Under such circumstances, additional precautions shall be taken to prevent plugging of the upper portion of the filter pack by the overlying sealing material.

(h) Ground water monitoring wells shall be constructed with casings having a minimum inside diameter of 2 inches which is installed in a boring whose diameter is at least 4 inches greater than the inside diameter of the casing.

(i) Ground water monitoring wells shall be sealed from the ground surface to the top of the filter pack.

~~(j) Borings shall be destroyed in accordance with the provisions of Sections 2543 (c) and (d) of this article.~~

(j) If groundwater monitoring indicates that an unauthorized release has occurred, the permittee shall report the release pursuant to Article 5 of this subchapter and shall repair or close the underground storage tank pursuant to Article 6 or 7 of this subchapter.

Authority: H&SC 25299.3
Reference: H&SC 25292

2648. General Construction and Sampling Methods

(a) Soil and water sampling equipment and materials used to construct a well shall be compatible with the stored hazardous substance and shall not donate, capture, mask, nor alter the constituents for which analyses will be made.

(b) Representative samples of all imported materials used for filter packs and to construct seals shall be evaluated to determine their acceptability with regard to Subsection (a) of this section.

(c) All drilling tools shall be thoroughly cleaned immediately before a boring is started.

(d) All well casings, casing fittings, screens, and all other components that are installed in the well shall be thoroughly cleaned before installation in the boring.

(e) All soil and water samplers shall be cleaned before each sample is taken.

(f) All exploratory borings and borings used for the installation of monitoring systems shall be drilled and sampled by techniques that do not introduce liquids into the boring and that will allow the accurate detection of perched and saturated zone ground water. If these prerequisites cannot be met using standard drilling techniques, the borings may be completed by any appropriate drilling techniques.

(g) ~~(f)~~ Drilling fluid additives shall be limited to inorganic, non-hazardous materials which conform to the provisions of Subsection (a) of this section. All additives used and the depth ~~in~~ at which they were used shall be accurately recorded in the boring log.

(h) ~~(g)~~ Representative samples of additives, cement, bentonite, and filter media shall be retained for at least 90 days for possible analysis for contaminating or interfering constituents.

(i) ~~(h)~~ All ground water monitoring wells shall be appropriately developed until the discharge water contains less than 10 ppm settleable solids.

(j) ~~(i)~~ Well heads shall be provided with a water-tight cap.

(k) ~~(j)~~ Well heads shall be enclosed in a surface security structure that protects the well from the entry of surface water, accidental damage, unauthorized access, and vandalism. This may be accomplished by providing a locked well cap or by securing the facility within which a well is located.

(l) ~~(k)~~ Pertinent well information including well identification, well type, well depth, well casing diameters if more than one size is used, and perforated intervals shall be permanently afixed to the interior of the surface security structure and the well identification number and well type shall be affixed on the exterior of the surface security structure.

(m) ~~(l)~~ Surface seals for vapor wells that are completed no more than 5 feet below the bottom of the underground storage tank and which are above any free water zones shall be required at the discretion of the local agency on a site-specific basis.

(n) ~~(m)~~ If surface seals for vapor wells that are completed in or below a free water zone are required, the seal shall not extend below the top of the underground storage tank.

(o) ~~(n)~~ Vapor wells constructed wholly within backfill that surrounds the underground storage tank and which extends to the ground surface need not be sealed against infiltration of surface water.

(p) ~~(o)~~ The need for surface seals for other types of vadose zone installations shall be determined on a case-by-case basis.

(q) ~~(p)~~ In order to implement monitoring Alternatives 2, 3, 4, 10 and the ground water monitoring portion of 6, the highest anticipated ground water level and existing ground water level shall be determined. Highest anticipated ground water levels shall be determined by a review of all available water level records for wells within 1 mile of the site. Existing site ground water levels shall be established by either water level measurements taken within the last 2 years in all existing wells, for which records are available, that are within 500 feet of the facility and which are perforated in the zone of interest, or by drilling at least 1 exploratory boring constructed as follows:

(1) The exploratory boring shall be drilled downgradient if possible and as near as possible to the underground storage tank within the boundaries of the property encompassing the facility, but no further than 500 feet from the underground storage tank.

(2) The exploratory boring may be of any diameter capable of allowing the detection of first water.

(3) The exploratory boring shall be drilled to first perennial ground water or to a minimum depth of 100 feet for Alternatives 2, 3, and 6 or to a minimum depth of 30 feet for Alternative 4 or to a minimum depth of 50 feet for Alternative 10.

(4) If ground water is encountered and ground water monitoring is part of the monitoring alternative, the boring shall be converted to a ground water monitoring well consistent with the provisions of this section and Section 2647 of this article.

(5) If ground water is encountered but ground water monitoring is not required or if the exploratory boring does not encounter ground

water and the boring is not used for vadose zone monitoring, it shall be sealed in accordance with the provisions of Subsections 2648 (r) ~~(q)~~ and (t) ~~(s)~~ of this article.

(r) ~~(q)~~ All borings that are not used for ground water or vadose zone monitoring shall be sealed from the ground surface to the bottom of the boring with bentonite grout.

(s) ~~(r)~~ All borings that are converted to vadose zone monitoring wells in which the monitored interval is shallower than the total depth of the boring shall have the portion of the boring which is below the monitored interval sealed with bentonite grout.

(t) ~~(s)~~ All ~~slurry-type grouts~~ sealing materials used to abandon a boring or for well seals shall be emplaced by the tremie method.

(u) ~~(t)~~ All borings shall be described in detail using the Unified Soil Classification System and shall be logged by a professional geologist, civil engineer, or engineering geologist who is registered or certified by the State of California and who is experienced in the use of the Unified Soil Classification System. A technician trained and experienced in the use of the Unified Soil Classification System who is working under the direct supervision of one of the aforementioned professionals shall be deemed qualified to log borings provided the aforementioned professional reviews the logs and assumes responsibility for the accuracy and completeness of the logs.

(v) ~~(u)~~ All wet zones ~~above the free water~~ in the vadose zone shall be noted and accurately logged.

(w) ~~(v)~~ If evidence of contamination is detected by sight, smell, or other field analytical methods, drilling shall be halted until the responsible professional determines if drilling deeper is advisable.

(x) All perforated casing used in the construction of monitoring wells shall be factory perforated.

(y) Ground water levels shall be measured and recorded each time the well is sampled.

Authority: H&SC 25299.3
Reference: H&SC 25292