Use of an Open-path FTIR Sensor to Measure VOCs at the Hanford Site

Prepared for the U.S. Department of Energy
Office of Environmental Restoration and Waste Management

Westinghouse Hanford Company Richland, Washington
Hanford Operations and Engineering Contractor for the
U.S. Department of Energy under Contract DE-AC06-87RL10930

Copyright License. By acceptance of this article, the publisher and/or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper.

Approved for Public Release

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
LEGAL DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced from the best available copy.

Printed in the United States of America

DISCLM.2.CHP (1-91)
Use of an Open-path FTIR Sensor to Measure VOCs at the Hanford Site

R. H. Kagann
MDA Scientific, Inc.

J. D. Fancher
Westinghouse Hanford Company

S. D. Tomich
Pacific Northwest Laboratory

Date Published
January 1994

To be presented at
The 87th Annual Meeting and
Exhibition of the Air and Waste
Management Association
Cincinnati, Ohio
June 19-24, 1994

Prepared for the U.S. Department of Energy
Office of Environmental Restoration and
Waste Management

Hanford Operations and Engineering Contractor for the
U.S. Department of Energy under Contract DE-AC06-87RL10930

Approved for Public Release

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
INTRODUCTION

An Open-path Fourier Transform Infrared (OP-FTIR) instrument was used to measure carbon tetrachloride vapor emitted from contaminated soil and monitoring wells in the 200 West Area of the Hanford Site in southeastern Washington State (see Figure 1). Historical activities at U.S. Department of Energy (DOE) facilities around the United States during World War II, including development of a nuclear deterrent, resulted in the discharge of chemical and radioactive materials to the environment. Beginning in 1955, carbon tetrachloride and other liquid wastes were released to the subsurface along with co-contaminants to three liquid waste disposal facilities. The DOE has now focused a major technical effort on the mitigation of the effects of those discharges through an environmental restoration program. The OP-FTIR was used over the soil surface near the 216-Z-9 Trench (one of the disposal facilities) in the 200 West Area as shown in Figure 2.

Figure 1. Map Showing the Location of the Hanford Site in Southeastern Washington State, near Richland.

The Hanford demonstration of the OP-FTIR was conducted as part of the Volatile Organic Compound-Arid Integrated Demonstration (VOC-Arid ID), which is funded by the U.S. Department of Energy, Office of Technology Development. The mission of the VOC-Arid ID is to identify, develop, and demonstrate new and innovative technologies to support environmental restoration.
Figure 2. The FTIR-RS Measurement Configuration Used at the 216-Z-9 Trench (liquid waste facility) in the 200 West Area. The three dark circles represent the approximate positions of the two monitoring wells.

Over the last few years, the interest in applying OP-FTIR techniques to air quality measurements has accelerated. These techniques have been investigated for different applications, including Superfund remediation monitoring, emergency response, waste water treatment and sludge treatment monitoring, fenceline monitoring, production facility monitoring, measurements in DOE treatment, storage and disposal facilities, and industrial hygiene and other indoor applications. In the present study, OP-FTIR is applied to the measurement of emissions from undisturbed contaminated soil.

The open-path sensor was placed approximately 30 meters west of the vapor extraction facility and the measurement path was chosen to be over a region in which the soil was contaminated with carbon tetrachloride. The measurement path was 149 meters. The measurements were made over a three day period. On the first day, when the barometric pressure decreased, carbon tetrachloride, the main soil contaminant, was detected with path-averaged measurements ranging from 4 to 100 ppb. The path was located near a monitoring well. The infrared beam was moved on the second day, in order to confine the measurements mostly to emissions directly from the soil. In this configuration, with a one-way pathlength of 149 meters and with the beam approximately 1 meter above the contaminated soil, carbon tetrachloride was detected with concentrations in the range of 2 to 5 ppb.

**OP-FTIR MEASUREMENT METHODOLOGY**

The OP-FTIR is used to make integrated-path concentration determinations of the chemical constituents in the infrared beam. The initial spectroscopic data are in the form of single beam spectra, I. According to Beer's law, the concentration-pathlength product, CL, of an absorbing chemical is proportional to the absorbance, A, which is defined as
\[ A(v) = - \log \left( \frac{I(v)}{I_0(v)} \right), \tag{1} \]

where all three quantities here, \( A(v) \), \( I(v) \), and \( I_0(v) \), are spectra and are functions of \( v \), the optical frequency in wave number \((\text{cm}^{-1})\) units. \( I_0(v) \) is the background spectrum taken under identical conditions to \( I(v) \), with the exception that the absorbing chemicals are not present. Beer's law is written as

\[ A(v) = \varepsilon(v) C L, \tag{2} \]

where the proportionality constant, \( \varepsilon(v) \) is the absorption coefficient of the chemical. The absorption coefficient is essentially a spectral shape function and is unique for each molecule. The absorption coefficient gives rise to the unique "fingerprint" shape of the chemical absorption spectrum used in making qualitative identifications. The quantitative determination is made by measuring the absorbance, \( A(v) \), and determining the concentration-pathlength product, \( C L \), of the absorbing chemical.

The concentration-pathlength products of the absorbing chemicals are calculated using the multicomponent classical least-squares technique (CLS) developed by Haaland and Easterling.\(^{13}\) This technique involves performing a least-squares fit of the field spectra to reference spectra (of the absorbing chemical species) using the following set of linear equations, derived from Beer's law,

\[ A_S(v) = a + b \nu + \sum_r \gamma_r A_r(v) + e(v), \tag{3} \]

where \( A_S(v) \) is the total absorbance of the measured atmospheric spectrum, at frequency \( \nu \), \( A_r(v) \) is the absorbance of the \( r \)th reference spectrum and \( \gamma_r \) is the ratio of the concentration-pathlength product for the \( r \)th chemical in the field, to the concentration-pathlength product for the reference spectrum of the \( r \)th chemical. The first two terms, on the right side of the equation, perform a linear correction for baseline error. The range of frequencies, \( \nu \), for the analysis are limited to regions where the target compound actually absorb the radiation. For each region, the sum in the third term is over all species which absorb in that particular region. The final term is the error or residual. The reference spectra are measurements of the pure gases, usually mixed in one atmosphere of dry air or nitrogen. The concentrations of the reference gases were precisely measured in the laboratory.

3. The Open-path FTIR

A recent review describes the use of optical remote sensors, including the OP-FTIR to measure toxic gases.\(^{1}\) The OP-FTIR is configured in a unistatic design, which uses a single transmitter/receiver telescope. Figure 3 shows a simple schematic of the measurement setup. The infrared radiation is modulated by a Michelson interferometer, of a wishbone design, which uses corner-cube retroreflectors. This retroreflector-interferometer design eliminates the need to make field alignment adjustments on the interferometer, with changing temperature. The modulated infrared radiation is collimated by a 12 inch Cassegrain telescope and transmitted through the parcel of atmosphere being measured to a corner-cube retroreflector array. The array reflects the beam back to the single transmitter/receiver telescope, resulting in two passes through the chemical plume. The radiation is then focused on the aperture of a mercury cadmium telluride (MCT) detector. The modulated signal (interferogram) is inverse Fourier transformed to produce a spectrum from 700 cm\(^{-1}\) to 4500 cm\(^{-1}\), with 1 cm\(^{-1}\) resolution.
Figure 3  The Measurement Configuration of the FTIR Remote Sensing System. The FTIR-RS uses a single telescope to both transmit a 12 inch collimated infrared probe beam to the atmosphere, and receive the infrared beam after it traversed a round-trip path through the atmosphere. A 14 inch corner-cube retroreflector array is used to reverse the path of the ir probe beam back to the transmitter / receiver telescope.

MEASUREMENTS

The measurements were made in four sets. At the time of the measurements, the OP-FTIR was setup to make real-time determinations on carbon tetrachloride. Since carbon tetrachloride was expected to be present at some level in the ambient air local to the site, we used a "zero-path" measurement (< 1 meter) as the background spectrum, Io. However, on the third, and last measurement day, the OP-FTIR was moved to a clean desert site about one km west of the contaminated soil site. A 115 volt, 1 KW gasoline generator was used to provide power to the instrumentation at this remote site. We made twelve 5-minute averaged "upwind" measurements. These twelve spectra were co-added to give a one-hour averaged background spectrum (Io). The quality of the absorbance spectra improved considerably over the set with the "zero-path" background. The analysis of these absorbance spectra resulted in detection limits of ~ 10 ppb, path averaged over a 149 meter one-way path. This analysis was used to identify which spectral files of the data sets had little or no carbon tetrachloride absorption. Absorbance spectra were recalculated using some of these spectra as backgrounds. The resulting detection limits were reduced to the range of 1 to 2 ppb, in many of the measurements.

Measurement Set 1

Set 1 consists of 211 Measurements made on July 27, from 1:32 pm to 11:38 pm, P.D.T. The configuration used for these measurements is shown in Figure 2. The beam path was ~ 30 meters west of the vapor extraction facility, and was oriented roughly north-south direction. The distance from the sensor to the retroreflector array was 149 meters, resulting a round-trip pathlength for the infrared radiation of 298 meters. The beam passed, at ~ 1 meter height, over an area which was known to have soil contaminated with carbon tetrachloride. From 1:32 to 11:10 pm, the spectral data was collected in ~ five minute averages. After 11:10 pm higher temporal resolutions were used, order to investigate the short term concentration fluctuations. One minute averages were used from 11:13 to 11:22, ~ 16 second averages were used from 11:22 to 11:32 pm and 6 second averages were used from 11:32 to 11:38 pm.

The single beam spectrum from Measurement # 1110 was used as the background spectrum (Io(v) in Equation 1) to produce absorbance spectra for Set 1. This produced a good match to the interfering
water vapor lines and thus improved the quality of the concentration determinations considerably compared to using spectra prepared with the zero path backgrounds. Figure 4 shows the comparison of the spectrum measured for Measurement # 1143 (Set 1) to the Reference Spectra of water vapor and of Carbon Tetrachloride. The classical least-squares calculation of the path-averaged concentration of carbon tetrachloride was 105.5 (3.3) ppb, where the number in the parentheses, 3.3 ppb, is equal to three time the standard deviation of the least squares fit, propagated to the concentration determination.

![Figure 4](image-url)

Figure 4. Comparison of Field Spectrum of Run 1143 (b.) to Reference Spectra of Water Vapor (a.) and carbon tetrachloride (c.). The measured path-averaged concentration of carbon tetrachloride was 105.5 (3.3) ppb.

The concentrations of carbon tetrachloride measured in Set 1 ranged from 3 to 106 ppb. From 13:12 to 19:23 P.D.T. The concentrations remained in the range of 3 to 10 ppb, with the majority of the measurements below 6 ppb. After 19:23, a large increase occurred in the concentrations, in four separate events at 20:00, 21:10, 22:10 and after 22:45 P.D.T. These four events, which can be seen in the time plot of the measured concentrations shown in Figure 5, are probably due to meteorological events.

![Figure 5](image-url)

Figure 5. Plot of OP-FTIR Measured Carbon Tetrachloride Concentrations versus Time during a four hour period on the evening of July 27 at the 216-Z-9 Trench. Each measurement was averaged for ~ five minutes. The hatches present +/- the 3σ value.
The carbon tetrachloride concentrations varied markedly in very short periods of time. For instance, in a single one minute period starting at 11:26 pm, the concentrations varied from 45.9 ppb to 71.3 ppb to 42.1 ppb to 105.5 ppb. This variability indicated that during the higher concentration events, the majority of the measured carbon tetrachloride was in a relatively small plume, emanating from a small source. A monitoring well close to the infrared beam was suspected to be the main source of the measured carbon tetrachloride in this period.

**Measurement Set 2**

Set 2 consists of 317 measurements made continuously over a 25 hour period starting on July 28, at 1:06 pm. The FTIR sensor and its computer was housed in a six foot high back-packing tent to protect it against rain and dust storms while it operated overnight unattended.

Our goal for Set 2 was to confine the measurements to carbon tetrachloride emissions directly from the soil. To achieve this, the retroreflector was moved laterally to the west by ~10 meters. This removed the beam from the vicinity of the monitoring well. The one-way pathlength was maintained at 149 meters with the beam height 1 meter above the contaminated soil. The path averaged concentrations in this data set ranged from no-detects to measurements from 1.4 to 5.0 ppb. The single beam spectrum from Measurement # 2090, taken at 7:59 pm PDT, July 28, was determined to have zero or negligible absorption due to carbon tetrachloride, and was therefore used as the background spectrum, (Io(v) in Equation 1) to produce absorbance spectra for Set 2. Figure 6 shows the comparison of the spectrum measured for Measurement # 2015 to the reference spectrum of carbon tetrachloride. This was a 5 minute average taken at 2:11 pm, July 28. The classical least-squares calculation of the path-averaged concentration of carbon tetrachloride was 4.6 (1.2) ppb. Figure 7a shows time plots of the OP-FTIR determinations on July 27, before the occurrence of the fluctuations shown in Figure 5, and Figure 7b shows the plots for the determinations on July 28. During these two time periods, the path-averaged concentrations remained in the 2 to 10 ppb range.

![Figure 6](image-url) Comparison of Field Spectrum of Run 2015 (the noisy trace) to the Reference Spectrum of Carbon Tetrachloride (the smooth trace). The measured path-averaged concentration of carbon tetrachloride was 4.6 (1.2) ppb.
Figure 7. Plot of OP-FTIR Path Averaged Concentration Determinations versus Time for the afternoons of (a) July 27 (Set 1) and (b) July 28 (Set 2). Each measurement was averaged for ~ five minutes. The hatches represent the + / - 3 σ values. The open rectangles are the measured detection limits for runs in which the concentrations were below the detection limit of the measurement. The detection limits are affected by humidity and factors which may alter the signal level or the spectral baseline, and thus the detection limits vary with each measurement.

On July 29, after the completion of Measurement Set 2, we set up the sensor in the desert, about 1 mile to the west of the contaminated soil site. The configuration was north-south and parallel to, and ~ 50 meters west, of a road. This area was expected to be free of carbon tetrachloride, so we made 12 ~ 5 minute averaged "upwind" measurements. Upon completion of these, the response of the system was tested by allowing ~ 0.1 ml of carbon tetrachloride to evaporate from a vial, which was placed in the
beam. The evaporation was complete within three minutes. Table 1 shows the results of four successive measurements, each averaged for 2.5 minutes, starting at the time when the vial was opened.

<table>
<thead>
<tr>
<th>File</th>
<th>Time</th>
<th>CCl4 (ppb)</th>
<th>3σ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4001</td>
<td>16:35</td>
<td>3.49</td>
<td>0.45</td>
</tr>
<tr>
<td>4002</td>
<td>16:37</td>
<td>0.82</td>
<td>0.44</td>
</tr>
<tr>
<td>4003</td>
<td>16:40</td>
<td>0.13</td>
<td>0.29</td>
</tr>
<tr>
<td>4004</td>
<td>16:42</td>
<td>0.00</td>
<td>0.30</td>
</tr>
</tbody>
</table>

DISCUSSION

In Set 1 (July 27), the measured concentrations, in the first six hours, were more or less constant at a path-averaged value of 5 ppb. After 7:00 pm, the measured concentrations increased in waves with large variations in short periods of time, as was shown in Figure 5. These fluctuations are most probably due to changes in wind speed and/or direction, and therefore indicate that the carbon tetrachloride plume was very small and thus swept in and out of the ~12 inch infrared beam. There were three monitoring wells in the vicinity of the infrared beam (see Figure 2). These wells were monitored with a photoionization detector on July 27 and were found to be emitting measurable levels of carbon tetrachloride. One of the wells, designated 299-W15-5, was within one meter of the beam, and this was probably the major source of the OP-FTIR measurements above 10 ppb, shown in Figure 5.

On July 28, when the beam was moved away from the well, 299-W15-5, the concentrations were again at the ~5 ppb level and were relatively stable. Figure 7 shows the time plots of the FTIR-RS measurements during the first six measurement hours of July 27 (before the large fluctuations occurred) and during the first seven measurement hours of July 28. During these periods, the path-averaged concentrations remained in the range between 1 and 10 ppb. The large fluctuations, shown in Figure 5, occurred in the period immediately following the plot in Figure 7a (19:00 PDT).* On the second day, there was a gradual lowering of the concentrations over the first seven hour measurement period. After seven hours, the concentrations fell below the detection limit of the FTIR-RS. Previous work at the project site has confirmed the presence of carbon tetrachloride in shallow (~1 m) soil-gas samples in concentrations reaching 45 ppm.14 During the period OP-FTIR data were collected, a series of surface based passive samplers were emplaced. These passive samplers were emplaced for three days in an area that included the FTIR sight path. The samplers contained a sorbent suspended 1 cm above the soil. After retrieval, sorbent analysis revealed carbon tetrachloride concentrations along the beam path from 106.2 to 251.7 ng/m²/min.15 The known presence of carbon tetrachloride in the soil and soil-air interface along the beam path suggests that most of the OP-FTIR measurements taken after the retro-array was moved away from well 299-W15-5 are primarily direct emissions from the contaminated soil.

* The concentration varied from 3 to 70 ppb in the period between 19:00 and 23:38, on July 27. The system was turned off at 23:38 and restarted on the next day.
Figure 8 shows the change in the barometric pressure during the course of the measurements. Previous measurements in the area of the OP-FTIR beam path indicate air moves into and out of the subsurface in response to fluctuations in barometric pressure.\textsuperscript{16,17} During the afternoon and evening of July 27, the barometric pressure was on a steep decline. During this period the highest concentrations of carbon tetrachloride were measured. This suggests that the carbon tetrachloride was "breathing out" from the soil, into the lower pressure surface environment. Table 2 lists the locally measured barometric pressure, wind direction and wind speed during the period of the measurements. There was no clear correlation between the measured concentrations and the wind direction and speed. The meteorological measurements were time-sliced samples taken on the hour, and there may have been a high level of variability in the wind conditions in the periods between the hourly measurements. Figure 9 is a double time plot of the hourly sample of barometric pressure and the hourly averages of the OP-FTIR carbon tetrachloride determinations.

![Graph showing barometric pressure over time](image.png)

Figure 8. Plot of the Barometric Pressure versus Time, over the period of the measurements.

**CONCLUSION**

This feasibility study demonstrated the successful OP-FTIR measurements of emission from undisturbed contaminated soil.
Table 2. Barometric Pressure and Wind Measurements made locally during the OP-FTIR Measurement Period.

<table>
<thead>
<tr>
<th>Date (1993)</th>
<th>Time</th>
<th>Barometric Pressure (in.)</th>
<th>Wind Direction</th>
<th>Wind Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 26</td>
<td>0:00</td>
<td>29.26</td>
<td>300</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>6:00</td>
<td>29.29</td>
<td>280</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>29.26</td>
<td>210</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>18:00</td>
<td>29.17</td>
<td>170</td>
<td>8</td>
</tr>
<tr>
<td>July 27</td>
<td>0:00</td>
<td>29.17</td>
<td>280</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6:00</td>
<td>29.15</td>
<td>270</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>29.08</td>
<td>130</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>13:00</td>
<td>29.06</td>
<td>140</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>29.03</td>
<td>140</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>15:00</td>
<td>29.00</td>
<td>160</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>16:00</td>
<td>28.98</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>28.96</td>
<td>160</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>18:00</td>
<td>28.94</td>
<td>210</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>19:00</td>
<td>28.94</td>
<td>160</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>20:00</td>
<td>28.94</td>
<td>120</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>21:00</td>
<td>28.94</td>
<td>220</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>22:00</td>
<td>28.94</td>
<td>320</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>23:00</td>
<td>28.93</td>
<td>350</td>
<td>8</td>
</tr>
<tr>
<td>July 28</td>
<td>0:00</td>
<td>28.93</td>
<td>280</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2:00</td>
<td>28.92</td>
<td>340</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4:00</td>
<td>28.92</td>
<td>340</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6:00</td>
<td>28.94</td>
<td>310</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>8:00</td>
<td>28.95</td>
<td>290</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10:00</td>
<td>28.94</td>
<td>180</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>28.88</td>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>13:00</td>
<td>28.88</td>
<td>230</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>28.87</td>
<td>210</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>15:00</td>
<td>28.85</td>
<td>280</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>16:00</td>
<td>28.84</td>
<td>290</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>28.84</td>
<td>280</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>18:00</td>
<td>28.85</td>
<td>290</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>19:00</td>
<td>28.87</td>
<td>310</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>20:00</td>
<td>28.90</td>
<td>310</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>21:00</td>
<td>28.96</td>
<td>310</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>22:00</td>
<td>28.98</td>
<td>310</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>23:00</td>
<td>29.00</td>
<td>310</td>
<td>10</td>
</tr>
<tr>
<td>July 29</td>
<td>0:00</td>
<td>29.02</td>
<td>280</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6:00</td>
<td>29.12</td>
<td>270</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>29.14</td>
<td>200</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>18:00</td>
<td>29.16</td>
<td>270</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>24:00</td>
<td>29.33</td>
<td>300</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 9. Double Time Plot: Barometric Pressure on Left Ordinate and Hourly Averages of the Carbon Tetrachloride Measurements on Right Ordinate.

REFERENCES


DISTRIBUTION

Number of copies

OFFSITE

2 U.S. Department of Energy
Ames Laboratory
Iowa State University
Ames, Iowa 50011

- G. Junk

Office of Environmental Restoration
and Waste Management
Washington, D.C. 20585-0002

- D. Biancosino

1 Brookhaven National Laboratory
Building 703M
Upton, New York 11973-5000

- E. Kaplan

1 Colorado Center for Environmental
Management
Building 21, Suite 150
1746 Cole Boulevard
Golden, Colorado 80401

- D. Kaback

1 EG&G Environmental, Inc.
Route 1
Richland, Washington 99352

- G. Dawson

1 Eastman/Cherrington
1640 Old Pecos Trail
Suite H
Santa Fe, New Mexico 87501

- C. Keller

1 Idaho National Engineering Laboratory
P.O. Box 1625, MS 2110
Idaho Falls, Idaho 83401

- W. Downs

2 Lawrence Livermore National Laboratory
P.O. Box 808, L-453
Livermore, California 94551-0099

- P. F. Daley

- J. Shinn

Number of copies

ONSITE

2 U.S. Department of Energy
Richland Operations Office

- L. S. Mamiya K8-50
- D. E. Trader K8-50

11 Pacific Northwest Laboratory

- K. J. Allwine K6-11
- T. M. Brouns P7-35
- J. C. Evans K6-B1
- G. V. Last K6-96
- K. B. Olsen K6-96
- S. D. Tomich (4) K6-08
- C. D. Whiteman K6-11

23 Westinghouse Hanford Company

- J. D. Fancher (10) N3-05
- M. C. Hagood H6-04
- G. C. Henckel H6-04
- K. J. Koepler H6-05
- M. S. Kowalski N3-05
- W. H. Price N3-05
- V. J. Rohay H6-06
- W. S. Thompson N3-05

Document Processing & Distribution L3-15
Information Release Administration H4-17

Distr-1
OFFSITE

1 Los Alamos National Laboratory
   MS F665
   Los Alamos, New Mexico 87545
   N. Rosenberg

1 Oak Ridge National Laboratory
   P.O. Box 2008, MS 6120
   Oak Ridge, Tennessee
   R. A. Jenkins

1 Pacific Northwest Laboratories
   Seattle Research Center
   4000 NE 41st Street
   Seattle, Washington 98105
   S. L. Stein

5 R. H. Kagan
   2895 Bordeaux Boulevard
   Cummings, Georgia 30131
   R. H. Kagan

1 Sandia National Laboratory
   Department 6116
   Albuquerque, New Mexico 87185
   S. Ballard

1 U.S. Geological Survey
   DFC MS964
   P.O. Box 25046
   Denver, Colorado 80225-0046
   G. R. Olhoeft

3 Westinghouse Savannah River Company
   SRTC
   Building 773-42A
   Aiken, South Carolina 29808
   C. Eddy-Dilek
   B. Looney
   J. Rossabi
DATE
FILMED
5/25/94
END