FINAL REPORT

Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling

ESTCP Project ER-200830

July 2014

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14. ABSTRACT

This report documents a demonstration/validation of passive diffusive samplers for assessing soil vapor, indoor air and outdoor air concentrations of volatile organic compounds (VOCs) at sites with potential human health risks attributable to subsurface vapor intrusion to indoor air. The study team was selected to include individuals highly experienced with passive samplers in general and each of the five samplers tested in particular.

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LIST OF ACRONYMS AND ABBREVIATIONS

11DCA	1,1-dichloroethane
11DCE	1,1-dichloroethene
111TCA	1,1,1-trichloroethane
12DCA	1,2-dichloroethane
112TCA	1,1,2-trichloroethane
1122PCA	1,1,2,2-tetrachloroethane
124TMB	1,2,4-trimethylbenzene
$\mu g\ m^{-3}$ or $\mu g/m^3$	Micrograms per cubic meter
ACoE	Army Corps of Engineers
AFB	Air Force base
ASU	Arizona State University
ATD	Automatic Thermal Desorption
BENZ	Benzene
BTEX	Benzene, Toluene, Ethylbenzene, and Xylene
C/Co	concentration in passive sampler/concentration in active sampler
CAS	Columbia Analytical Services
cDCE	cis-1,2-dichloroethene
COC(s)	Compound(s) of Concern
CRREL	Cold Regions Research and Engineering Laboratory
CTET (or CT)	Carbon tetrachloride
DoD	Department of Defense
DoE	Department of Energy
DoN	Department of the Navy
ESTCP	Environmental Security Technology Certification Program
FID	Flame Ionization Detection
GC	Gas Chromatograph
GC/MS	Gas Chromatography / Mass Spectrometry
Geosyntec	Geosyntec Consultants Inc.
ITRC	Interstate Technology and Regulatory Council
Koc	Organic carbon partitioning coefficient
LTPRI	Linear Temperature Programmed Retention Index
MCAS	Marine Corps Air Station
MCAS 137	Marine Corps Air Station Cherry Point Building 137, North Carolina
MCRD	Marine Corps Recruit Depot
MEK	Methylethylketone (or 2-Butanone)
m/s	meters per second
NAPH	Naphthalene
NAS	Naval Air Station
NAS JAX	Naval Air Station Jacksonville, Florida

NESDI	Navy Environmental Sustainability Development to Integration
NHEX	n-Hexane
OTC3	SSC-Pacific Old Town (Campus) Building 3, San Diego, California
OSWER	Office of Solid Waste and Emergency Response
OVM	Organic Vapor Monitor
Pa	Pascal
ppm_v	Parts per million by volume
ppb_v	Parts per billion by volume
PCE	Tetrachloroethene or perchloroethene
PID	Photoionization Detector
PDMS	Polydimethylsiloxane
PSIA	Pounds per Square Inch Absolute
QA/QC	Quality Assurance/Quality Control
RMSV	Recommended Maximum Sample Volume (Supelco, 2013)
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
SIM	Selected Ion Monitoring
SSC Pacific	Space and Naval Warfare Systems Center Pacific
SVOC	Semi-Volatile Organic Compound
tDCE	trans-1,2-dichloroethene
TCE	Trichloroethene
U.S. EPA	United States Environmental Protection Agency
VC	Vinyl chloride
VI	Vapor Intrusion
VOC	Volatile Organic Compound
WMS	Waterloo Membrane Sampler
% RH	Percent Relative Humidity

EXECUTIVE SUMMARY

This report documents a demonstration/validation of passive diffusive samplers for assessing soil vapor, indoor air and outdoor air concentrations of volatile organic compounds (VOCs) at sites with potential human health risks attributable to subsurface vapor intrusion to indoor air. The study team was selected to include individuals highly experienced with passive samplers in general and each of the five samplers tested in particular. The passive samplers tested included: 1) SKC Ultra and Ultra II, 2) Radiello®, 3) Waterloo Membrane Sampler (WMS), 4) Automated Thermal Desorption (ATD) tubes, and 5) 3M OVM 3500.

The program included laboratory testing under controlled conditions for 10 VOCs (including chlorinated ethenes, ethanes, and methanes, aromatic and aliphatic hydrocarbons), spanning a range of properties and including some compounds expected to pose challenges (naphthalene, methyl ethyl ketone). Laboratory tests were done under conditions of different temperature (17 to 30 ^{o}C), relative humidity (30 to 90 % RH), face velocity (0.014 to 0.41 m/s), concentration (1 to 100 parts per billion by volume [ppb_v]) and sample duration (1 to 7 days). These conditions were selected to challenge the samplers across a range of conditions likely to be encountered in indoor and outdoor air field sampling programs. High concentration laboratory tests were also conducted at 1, 10 and 100 parts per million by volume (ppm_v) to evaluate concentrations of interest for soil vapor monitoring using the same 10 VOCs and constant conditions (90% RH, 30 min exposure, 22^{o}C). Inter-laboratory testing was also performed to assess the variance in the analytical results attributable to the differences between several laboratories used in this study.

The program also included field testing of indoor air, outdoor air, sub-slab vapor and deeper soil vapor at several Department of Defense (DoD) facilities. Indoor and outdoor air samples were collected over durations of 3 to 7 days and Summa canisters were collected over the same durations as the passive samples for comparison. Subslab and soil vapor samples were collected with durations ranging from 10 min to 12 days, at depths of about 0.5 (immediately below floor slabs), 4 and 12 feet. Passive samplers were employed with uptake rates ranging from about 0.05 to almost 100 mL/min and analysis by both thermal desorption and solvent extraction. Mathematical modeling was performed to provide theoretical insight into the potential behavior of passive samplers in the subsurface, and to help select those with uptake rates that would minimize the starvation effect (which occurs when a passive sampler with a high uptake rate removes VOC vapors from the surroundings faster than they are replenished, resulting in a low or negative bias in the results). A flow-through cell apparatus was also tested as an option for sampling existing sub-surface probes that are too small to accommodate a passive sampler.

The results of this demonstration show that all of the passive samplers provided data that met the success criteria (defined in Section 3) under some or most conditions. Exceptions were generally attributable to one or more of five possible causes: a) poor retention of analytes on the sampler; b) poor recovery of the analytes from the sorbent; c) starvation effects, d) uncertainty in uptake rate for the specific combination of sampler/compound/conditions, or e) blank contamination.

Poor retention appeared to occur in cases where the product of the uptake rate and the sample duration (termed the "equivalent sample volume") was greater than the recommended maximum sample volume (provided by sorbent suppliers for various combinations of compounds and sorbents), and may therefore be predictable. Starvation appeared to occur in cases where the sampler uptake rate was higher than the rate of delivery of vapors to the face of the sampler, which was particularly problematic for passive soil vapor sampling where the delivery occurs predominantly by diffusion, and especially for wet soils where the rate of diffusion is low. High (or positive) biases were less common than low biases, and attributed either to blank contamination, or to uncertainty in the uptake rates. Most of the passive samplers provided highly reproducible results throughout the demonstrations. This is encouraging because the accuracy can be established using occasional inter-method verification samples (e.g., conventional samples collected beside the passive samples for the same duration), and the field-calibrated uptake rates will be appropriate for other passive samples collected under similar conditions.

The overall cost of monitoring with passive samplers is comparable to or lower than monitoring with conventional methods because of the simplicity of the sampling protocols and reduced shipping charges. Passive samplers are generally easier to use than conventional methods (Summa canisters and active ATD tubes) and minimal training is required for most applications. A modest increase in effort is needed to select the appropriate sampler, sorbent and sample duration for the site-specific chemicals of concern and desired reporting limits compared to Summa canisters and EPA Method TO-15, but the level of effort is not much different than the design process for active ATD tube sampling for analysis by EPA Method TO-17. As the number of samples in a given program increases, the initial cost of sampling design becomes a smaller fraction of the overall total cost, and the passive samplers gain a significant cost advantage. For best results, the selection of the appropriate sampler, sorbent and sample duration for a particular set of target chemicals and reporting limits should be reviewed carefully by an experienced professional.

Further research is needed to demonstrate the performance for a wider range of compounds (particularly those with indoor air risk-based target concentrations less than 0.1 $\mu g/m^3$) and longer sample durations (up to several months) with different sorbents (matched to the target compounds to optimize retention and recovery). Calibration of the uptake rate depends on the sampler, sorbent, target compounds and environmental conditions to some degree, and empirical data for a range of field conditions would be useful if compiled in an accessible repository.

1 INTRODUCTION

This Final Report has been prepared by Geosyntec Consultants, Inc. (Geosyntec) for the Environmental Security Technology Certification Program (ESTCP) review committee and it presents the results of ESTCP project ER-0830: Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air using Quantitative Passive Diffusive Adsorptive Sampling Techniques. The Study Team members are listed in Appendix A. Dr. Samuel Brock of the Air Force Civil Engineering Center (AFCEC) was the Department of Defense (DoD) Liaison and Andrea Leeson of ESTCP was the Contracting Officer's Representative.

Additional funding was provided by the Navy Environmental Sustainability Development to Integration (NESDI) Program conducted as part of Project 424 on "Improved Assessment Strategies for Vapor Intrusion (VI)". Ms. Leslie Karr was the NESDI Program Manager, Ms. Stacey Curtis was the SPAWAR Systems Center Pacific (SSC Pacific) representative in the Technology Development Working Group and Drs. D. Bart Chadwick and Ignacio Rivera-Duarte from SSC Pacific were the project directors.

The ESTCP program involved testing of four different passive samplers under both controlled laboratory conditions and field conditions with conventional active sampling and analysis also conducted for comparison purposes. The four passive samplers were:

- passive automated thermal desorption (ATD) tubes;
- Radiello samplers;
- Waterloo Membrane Samplers (WMS), and;
- Ultra II badge samplers.

The NESDI research program provided funding to add the 3M OVM 3500™ sampler for those components of the research where NESDI funding was used to supplement the ESTCP funding.

Passive samplers provide several potential advantages over passivated canister sampling (the current industry standard method for vapor intrusion assessments), including: 1) simplicity, 2) the ability to collect longer-term integrated samples, 3) smaller size for ease of shipping and handling, and 4) lower overall cost. Prior to this research, each of the five candidate passive sampler technologies had been independently tested by their developers and end-users and proven to be capable of accurately measuring vapor concentrations in indoor and outdoor air for some chemicals under certain conditions (Górecki and Namiesnik 2002, Namiesnik et al., 2005); however, the commercially-available passive samplers had not been rigorously compared with each other. Furthermore, none of the passive samplers were specifically designed for use in soil vapor monitoring, and passive soil vapor sampling has not previously been demonstrated to provide accurate soil vapor concentration data (USEPA, 1998a,b, CalDTSC 2011, ASTM D7758). This demonstration/validation study was conducted to improve knowledge of the capabilities and limitations of the candidate passive samplers and foster regulatory and practitioner familiarity, confidence, and acceptance in the future.

1.1 Background

Subsurface vapor migration to indoor air (vapor intrusion, or VI) has been an important and challenging component of assessing human health risks associated with contaminated soil and groundwater since the late 1990s, during which time regulatory guidance for assessing vapor intrusion has been issued by at least 27 State Agencies, the Interstate Technology and Regulatory Council (ITRC, 2007), and by the US Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER, 2002, which was revised and released as an external review draft in April 2013, but not to be quoted or cited). The DoD and Department of Energy (DoE) and related contractors are collectively responsible for environmental compliance at thousands of sites contaminated with volatile organic compounds (VOCs), and will invariably be asked to assess whether and to what extent vapor intrusion poses a potential health concern. For sites where vapor intrusion is a potential concern, long-term monitoring may also be warranted, which will incur significant costs for responsible parties.

Currently, the most common method for collection and analysis of indoor air and sub-slab or soil vapor samples consists of drawing air or soil gas into an evacuated, passivated stainless steel canister (SilcoTek® or Summa®) with the rate of flow regulated by a flow controller followed by shipment to a laboratory for analysis by EPA Method TO-15 (USEPA 1996) via gas chromatography/mass spectroscopy (GC/MS). This is also referred to as "whole-gas" sampling because the container collects all constituents (i.e., typically ~80% nitrogen, ~20% oxygen, and all compounds present as VOC vapors). The cost for TO-15 analysis of each Summa canister sample is generally in the range of $135 to $180US (depending on the compound list and reporting limit), and includes rental, cleaning and certification for the canister, and flow controller rental in addition to the cost of analysis. Shipping costs are high because of the large size and weight of the canisters. Sampling protocols for canisters are complicated so labor costs for sample collection are relatively high, and complicated protocols increase the risk of inter-operator errors that may cause data bias and variability. For soil vapor sampling and analysis in particular, there are a wide variety of different methods and guidance available (e.g., ASTM D5314-92, ASTM D7663-11, EPRI 2005, API 2005, Geoprobe 2006, ITRC 2007, CCME 2009, CalEPA/DTSC 2012, Hers et al., 2010), but few comparative studies that evaluate the relative performance between various active soil vapor sampling methods (EPA, 2006). Sampling protocols for canisters are complicated because subsurface gas permeability can vary over many orders of magnitude and care is needed to prevent and document the absence of leaks of atmospheric air into the sample train, especially in low-permeability soils (McAlary et al., 2009). Leakage can be evaluated using tracer gas and various forms of pneumatic testing, but the complexity of the sampling protocol increases significantly. There are also differing opinions regarding the volume to be purged prior to sample collection, the flow rate and vacuum that should be applied, and the potential for adsorption/desorption reactions with tubing, fittings and containers, and the duration over which the sample should be collected (summarized by CCME 2009), all of which could potentially be avoided using passive samplers.

The most common alternative to whole-gas sampling is active adsorptive sampling using Automated Thermal Desorption (ATD) tubes (*NB*: one of the passive samplers included in this Final Report also uses ATD tubes in the passive mode, so this document refers to both active and passive ATD tube samples). For active adsorptive sampling, the ATD tubes are filled with a selected adsorbent and gas is drawn through the tube at a controlled flow rate for a measured time, from which the total volume of gas constituting the sample can be calculated. The mass of chemicals adsorbed in the tube is determined by laboratory analysis using US EPA Method TO-17 (USEPA 1999), and the concentration is calculated by dividing the measured mass by the volume of gas drawn through the tube. Pumped ATD tube sampling is very commonly used in industrial hygiene applications and tends to be more popular than Summa canister sampling and whole-gas analysis in Europe.

Active adsorptive sampling also faces several practical challenges. For indoor air sampling, the sample duration is usually limited to 24-hours or less either to reduce the risk of breakthrough (poorly retained VOCs can migrate chromatographically through the sorbent and be lost from the sample) and because the pumps are often powered by rechargeable batteries with a limited service life. Also, some chemicals have very low risk-based target concentrations for the vapor intrusion pathway and thus require very large volumes of gas to be drawn through the adsorptive media to achieve the required reporting limits (even after optimizing the sensitivity via the split ratio in the GC). Large sample volumes may exceed practical limits on the flow rate or sample duration and may not be conducive to good retention of less strongly sorbed analytes (Jia et al., 2007). When collecting active samples in a pumped ATD tube, the potential for breakthrough or poor retention is evaluated by review of the recommended maximum sample volume (RMSV, Supelco, 2013), which is the volume of air that can be drawn through the ATD tube without unacceptable losses via breakthrough of a particular analyte for a particular sorbent. Verification testing for potential breakthrough can be performed using two ATD tubes in series or distributed pairs of samples (high and low volume), with associated increases in the costs of analyses. For soil vapor sampling, the concentrations of chemicals in the gas to be sampled are usually unknown in advance, so there is a risk that the concentrations will be higher than expected and the mass adsorbed may exceed the linear range of calibration during analysis. Soil vapor tends to have a relative humidity near 100%, and moisture can interfere with adsorptive sites for activated carbon-based sorbents. The gas-permeability of soils is highly variable, and it can be challenging to draw a constant flow rate through an ATD tube without imposing excessive vacuum when sampling probes screened in moderate to low-permeability materials. Despite these drawbacks, the active adsorptive methods are accurate and precise when applied under ideal conditions (unrestricted flow, strongly-retained target compounds, sorbed mass within calibrated range). Nevertheless, the design of the sorbent, flow rate, sample duration and analytical method depends on the compounds of interest, target reporting limits and range of anticipated concentrations, so the selection of the sorbent, flow rate and sample duration is more complex than Summa canister sampling. Images of Summa canister and active ATD tube sampling are shown in Figure 1.

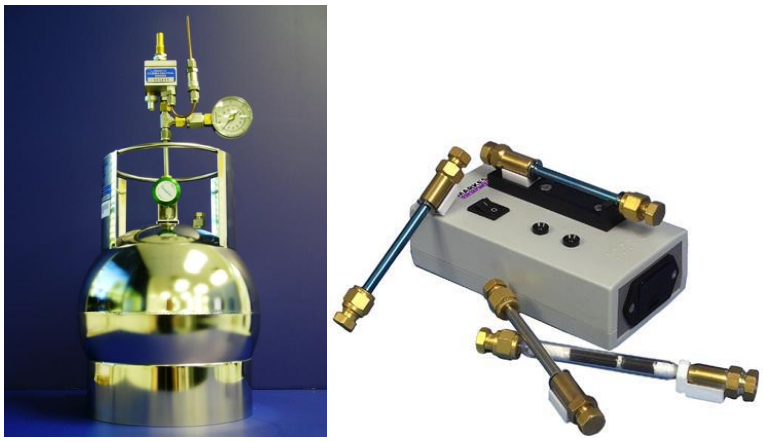


Figure 1: Summa canister and pumped ATD tube equipment (different scales)

At the present time, there are varying opinions regarding the reliability of soil vapor sampling for assessing human health risks posed by VOCs. For example, the ITRC vapor intrusion guidance (ITRC, 2007) states: "Soil gas data are recommended over other data, specifically soil matrix and groundwater data, because soil gas data represent a direct measurement of the contaminant that can potentially migrate into indoor air". However, the empirical database of soil vapor and indoor air concentrations compiled by the USEPA (2012) shows a worse correlation between soil vapor and indoor air concentrations than the corresponding comparison between groundwater and indoor air concentrations. It is not clear what role sampling errors or biases play in the relatively poor correlation between soil vapor and indoor air concentrations. However, protocols using passive sampling devices are considerably simpler than active sampling protocols, and simpler protocols are likely to reduce variability attributable to operator error, which provides an incentive to advance the science of passive soil vapor sampling. Passive samplers provide several potential advantages over conventional whole-gas sampling, including simpler protocols, smaller size for ease of shipping and handling, and lower overall cost (including the labor cost for sample collection).

The passive samplers tested in this study consist of an adsorbent medium that is exposed to gas for a period of time, and mass transfer to the adsorbent occurs without pumps or imposed pressure or vacuum gradients. VOC uptake by passive samplers is assumed to be dominated by diffusion or permeation, but may be influenced by turbulence in high air velocity environments. The trapped mass is quantified using solvent extraction or thermal desorption followed by GC/MS. Calculations are used to determine the time-weighted average concentrations of vapors in the gas to which the sampler is exposed, based on Fick's First Law of diffusion. The concentration is calculated from the sampler sample duration, mass of analyte adsorbed and the uptake rate of the sampler for the compound of interest under the conditions of sampling. Sample duration and the adsorbed mass can be measured very accurately, so the accuracy of the passive sampler concentration measurements depends primarily on the accuracy of the value used for the uptake rate, which is described further in Section 2. For soil vapor sampling, the uptake rate of the sampler may depend on the delivery rate of vapors from the surrounding soil, which is described further in Sections 5.6, 6.7 and 7.4.

Passive sampling is also used for monitoring radon in indoor air. Indoor air concentrations of radon vary in response to several processes, including wind-speed, rainfall, barometric pressure and temperature changes, and building factors and there is no reason to believe that indoor air concentrations of VOCs from vapor intrusion would not show some degree of temporal variability attributable to most of the same processes (radon and VOCs have different distributions, and fate mechanisms, so the temporal trends would not likely be identical). The most common methods of radon sample collection (activated carbon badges and electrets) are passive samplers, primarily because of low cost and simplicity, but also because they can be used to collect samples over time periods long enough to be more representative of long-term average concentrations. Radon samples collected over a period of less than three days are considered less reliable, and samples collected over a period of less than 48 hours are not considered appropriate (www.epa.gov/radon). By contrast, most VOC vapor intrusion guidance documents recommend sample durations of 8-hour (commercial) or 24-hour (residential), mostly because conventional sampling for analysis by EPA Methods TO-15 and TO-17 are not well suited to longer samples. Shorter-term samples will inherently show more temporal variability, which makes the results less useful for assessing long-term average exposures. Such temporal variability can be managed by collecting a greater number of samples to support a statistical calculation of a representative long-term average concentration (e.g., Johnson et al., 2013; Holton et al., 2012; Luo et al., 2012; Kuehster et al., 2004; Folkes et al., 2009; U.S. EPA, 2012, Johnston, 2013; Johnston and Gibson, 2013); however, this increases cost considerably. Passive samplers are better suited to longer sampling intervals (i.e., much greater than 24 hours), which is expected to provide data with less variability compared to conventional shorter duration sampling methods.

The OSWER 2002 Draft Vapor Intrusion Guidance (EPA, 2002) lists 114 chemicals that are known or suspected to be volatile and toxic enough to potentially pose a risk via vapor intrusion. This list includes VOCs, semi-VOCs (SVOCs), pesticides, and metals. The California Department of Toxic Substances Control (CalEPA/DTSC, 2011) added a few polychlorinated biphenyls (PCBs). Of the 114 compounds on the OSWER list, only about 46 compounds are included on the standard EPA Method TO-15 analyte list, and of these, the target indoor air concentrations for an incremental cancer risk of 1 in 1 million are lower than typical analytical reporting limits for several compounds. Method TO-15 is the most commonly used method for vapor intrusion assessments, and at most sites is the only method used, leaving 70 or more potential compounds of concern for vapor intrusion unquantified. Analysis of an additional 18 polynuclear aromatic hydrocarbons (PAHs) can be accomplished by EPA Method TO-13A, 7 pesticides by EPA Method TO-4A, and 85 VOCs and SVOCs by TO-17/8270; however, these methods all require different sampling media and analytical methods, so it becomes prohibitively expensive to conduct a comprehensive analysis using current methods. Passive samplers can potentially assess a wide range of compounds using sorbents selected to provide optimal retention and recovery for selected ranges of compounds (stronger sorbents for low boiling point compounds, and vice-versa). This research tested the applicability of passive samplers for a list of 10 common VOCs with a wide range of properties affecting their potential for passive sampling (primarily diffusion coefficient and adsorptive affinity); however, SVOCs, PAHs, PCBs and other very high boiling point compounds were not tested in this program.

1.2 Objectives of the Demonstration/Validation

The objectives of the program were to identify whether and under what conditions passive diffusive samplers provide a good quality measurement of VOC vapor concentrations and to document the study findings so that regulatory agencies have strong scientific support for accepting less-expensive alternatives to conventional monitoring methods where applicable. Five different passive samplers were compared to conventional sampling methods to demonstrate the advantages and disadvantages of each under both controlled laboratory conditions and field conditions. None of these passive samplers were specifically designed for soil gas monitoring; however, this is a very useful capability for vapor intrusion investigations, so the research included development and testing of quantitative passive soil vapor sampling and analysis.

1.3 Regulatory Drivers

Regulatory guidance for assessment and management of risks associated with vapor intrusion has been issued by at least 27 States, the USEPA, and the Interstate Technology and Regulatory Consortium (ITRC). In most jurisdictions, these documents are only guidance, and are not statutory requirements; however, there are statutory requirements to assess potential human health risks, and this possibility exists where VOCs are present in the subsurface near occupied buildings. Therefore, a screening level assessment is often required, and some amount of indoor air and soil vapor sampling and analysis is typically expected as a primary line of evidence. Vapor intrusion assessments are also a routine component of 5-year reviews under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and No Further Action letters have been rescinded to require vapor intrusion investigations. Furthermore, brownfield redevelopments are required to assess the potential for vapor intrusion (OSWER, 2002; ASTM E2600-10), so economic benefits from redevelopment of underutilized properties will provide motivation for vapor intrusion investigations. For sites where there is unacceptable vapor intrusion, a long-term monitoring program may be required, to demonstrate the effectiveness of mitigation measures, verify the absence of concerns around the perimeter of the mitigation area, or provide a basis for closure upon completion of mitigation activities. There is also an increasing awareness that temporal variability in indoor air concentrations attributable to vapor intrusion poses a risk of a false-negative conclusion (concluding vapor intrusion poses no unacceptable risk, when the opposite is the true condition) where sampling is conducted over a relatively short time (e.g., one or a few 24-hour samples over the course of a year or so). Alternatives to the conventional methods are needed.

1.4 Study Team

This research was conducted by a team of experts listed in the table below (contact information is in Appendix A). Dr. Sacco was a developer of the Radiello sampler. Dr. Crump has extensive experience with the ATD tube passive sampler. Drs. Gorecki and Seethapathy developed the Waterloo Membrane Sampler. Drs. Hayes and Tuday are leading analytical chemists with commercial laboratories that analyze passive samplers. Dr. Schumacher was the EPA liaison (with Dr. Nocerino until his untimely death). All of the above were co-principal investigators. Mr. McAlary and Ms. Groenevelt of Geosyntec were the lead principal

investigators. Dr. Johnson was the academic liaison. Drs. Brock and Leeson were the DOD liaisons.

Name	Organization	Role
Todd McAlary and Hester Groenevelt	Geosyntec Consultants, Inc.	LEAD PI
Dr. Brian Schumacher and Dr. John Nocerino	US EPA (Las Vegas)	CO-PI
Dr. Derrick Crump	Cranfield University (UK)	CO-PI
Dr. Tadeusz Gorecki and Dr. Suresh Seethapathy	University of Waterloo (Canada)	CO-PI
Dr. Paolo Sacco	Fondazione Salvatore Maugeri (Italy)	CO-PI
Dr. Michael Tuday	Columbia Analytical Services (Simi Valley, CA)	CO-PI
Dr. Heidi Hayes	Air Toxics (Folsom, CA)	CO-PI
Dr. Paul Johnson	Arizona State University (Tempe, AZ)	Peer Reviewer
Dr. Sam Brock and Dr. Andrea Leeson	HQ AFCEE/TDN and ESTCP	DOD Liaisons

2 TECHNOLOGY

2.1 Technology Description

Quantitative passive sampling can be defined as the collection of vapors by diffusion or permeation in response to concentration gradients (rather than pressure gradients, as are used by Summa canisters and pumped ATD tubes) at a known and controlled uptake rate, such that the time-weighted average concentration can be calculated from the mass of each analyte collected over a given period of time. The passive sampler acts as a sink for the analytes, which establishes the concentration gradients, so no external power source is required (hence the sampling is termed "passive"). There are several different commercially available quantitative passive samplers with different sizes, shapes, materials of construction, sorbents and protocols. This section describes the quantitative samplers' operating principles, varieties, capabilities and limitations.

2.1.1 Basic Principles of Quantitative Passive Sampling

The basic principles of operation for all 5 passive samplers tested in this program are similar. Each device is supplied by the vendor or laboratory as certified clean and sealed in air-tight packing. The sampler is exposed to the air or gas being investigated for a measured amount of time (t), during which VOCs diffuse or permeate into the device from the surrounding gas or atmosphere and a certain mass (M) of VOCs will be trapped on the adsorptive medium within the device. The device is re-packed in an air-tight container and returned to the laboratory, where the mass adsorbed is quantified. Once the adsorbed mass has been quantified, the time-weighted average (TWA) concentration of a particular analyte in the medium being sampled can be calculated as follows:

$$C_o = \frac{M}{(UR)(t)} \qquad (1)$$

where:

C_o = TWA concentration in the sampled air ($\mu g/m^3$)
M = mass of analyte on the sorbent (picograms)
UR = uptake rate (mL/min)
t = sampling time (min)
(Note: there are two offsetting conversion factors from pg to µg and mL to m^3)

The mass adsorbed and sample duration are both measured very accurately, so the uptake rate is the key factor controlling the accuracy of the concentration measurement. Note that the uptake rate has units of mL/min, similar to a flow rate, despite the fact that the samplers operate by diffusion or permeation, and there is ideally no net fluid flow into or through the samplers (the uptake rate is equal to the flow rate that would be required for a pumped sorbent tube to adsorb the same mass over the same sample duration when exposed to the same concentration).

The candidate passive diffusive samplers included in this study are all designed to control the uptake rate of chemicals in a quantifiable way, which distinguishes these devices from semi-quantitative passive samplers (e.g., Gore-Sorber® or Gore® Modules, Beacon B-Sure Sample Collection Kits™, EMFLUX® Passive Soil Gas Investigation System, Petrex tubes and similar devices), which quantify the mass adsorbed, but have uncertain uptake rates, so the concentrations are less certain (Hodny et al, 2009; Odencrantz and O'Neill, 2009). The geometry of each of the candidate samplers included in this study is fixed to allow exposure over a measured cross-sectional area and diffusion or permeation through a medium where the diffusion coefficient or permeation constant for the chemicals of interest is known. This is necessary for a reproducible uptake rate, which is needed to convert the mass measured on the adsorptive media to a TWA concentration at the face of the sampler. The ability to quantify concentrations is an important improvement over semi-quantitative passive sampling because concentrations are needed for comparison to risk-based target concentrations when assessing human health risks via vapor intrusion.

Uptake rates are typically measured in controlled laboratory chamber tests, where the VOC concentrations are also independently measured using another method. Equation (1) is then rearranged to solve for the uptake rate. The uptake rate varies somewhat between compounds, and the chamber tests are invariably limited to a fixed number of analytes, so there are cases where the uptake rate is not known for a particular analyte at a given site. If the uptake rate is controlled by diffusion through air, the uptake rate can be estimated from other compounds by interpolation based on the free-air diffusion coefficient. For one of the candidate samplers in this study, the uptake rate is controlled by partitioning into and permeation across a membrane, and the uptake rate can be estimated by interpolation based on the linear temperature-programmed retention index, another property that is generally available in the scientific literature, or can be determined from the elution time in a gas chromatogram (Seethapathy and Gorecki, 2010). The uptake rate for any compound and any passive sampler in any setting can also be determined using inter-method duplicate samples (a second sample collected using a different method at essentially the same location over the same duration), which can be useful in certain circumstances where the environmental conditions (temperature, humidity, wind-speed, concentration, duration, etc.) may be different than the conditions under which the uptake rates were calibrated. The inter-method duplicate samples can be used to derive "field-calibrated" uptake rates, specific to the site conditions.

2.1.2 Varieties of Passive Samplers

Most of the passive samplers are available in more than one variety. For example, the uptake rate of a passive sampler can be increased or decreased by design. High uptake rates allow lower concentrations to be quantified for a given sample duration, which can be an advantage for compounds with very low risk-based screening levels. Lower uptake rates reduce the risk of the "starvation effect", which occurs when the rate-limiting step during sampling is transport of chemicals to the face of the sampler instead of the uptake rate of the sampler itself. This situation results in a reduction in vapor concentrations near the sampler, and a low (or negative) bias in the calculated passive sampler concentrations compared to ideal conditions under which

passive sampler uptake rates are typically calibrated. Advection from wind and ventilation during indoor and outdoor air sampling is often sufficient to minimize the starvation effect for all but the highest uptake rate samplers. For soil gas sampling, advection is likely to be minimal and the rate of contaminant vapor replenishment in the gas-filled void space surrounding the sampler is likely to be limited to diffusive transport only, so a much lower uptake rate is required to minimize the starvation effect (this is the focus of the mathematical models presented in Section 6.7.1).

Many of the passive samplers can also be used with more than one type of sorbent. There are two general classes of sorbents, suited either to thermal desorption or solvent extraction as the sample preparation method. Analysis by thermal desorption is typically performed using a method like EPA Method TO-17 where the ATD tube is heated and flushed with nitrogen or helium into the GC. This provides very good sensitivity because all of the mass adsorbed by the sampler is injected into the GC, although there is typically a split at the interface between the injector and the column, so some of the sample may not run through the GC column. Analysis by solvent extraction is typically performed using carbon disulfide (CS_2) to extract the target VOCs from the adsorbent; however, only a small aliquot of the total CS_2 used is subsequently injected into the GC (e.g., 1 μL injected of 1 mL used for extraction). Consequently, the sampler may need to be exposed for a longer period of time or have a higher uptake rate to achieve comparable reporting limits. Thermal desorption is typically used with weaker adsorbent media (e.g., Tenax TA, Carbopack B), so the retention of lighter VOCs may be low, especially over longer time periods or in areas of high concentrations. In such cases the total mass of all VOCs adsorbed becomes large enough that competition for adsorptive sites becomes an issue, and the less adsorptive compounds may be lost. Solvent extraction is usually used with stronger adsorbents (Anasorb 747, activated carbon or charcoal), and is less likely to show poor retention, but may show low recovery (i.e., less than 100% desorption) for very strongly adsorbed compounds. Several of the passive samplers can be used with different adsorbents and analyzed using either solvent extraction or thermal desorption to provide flexibility for a range of target compounds, reporting limits and expected concentrations (which can range over many orders of magnitude). In pumped ATD tube samples, multi-bed sorbents are common (weaker to stronger sorbents are used in the direction of flow during sampling) to help retain weakly-sorbed compounds without risking poor recovery of strongly-sorbed compounds; however, multi-bed designs are not typically used in passive sampling and therefore, were not attempted in this program.

2.1.3 Selection of Sorbent and Sample duration

Different chemicals have different adsorption properties, and a variety of adsorbent media are available, so there are a wide range of options for selection of the appropriate adsorbent media for a particular compound or list of compounds of interest. The goal is to provide a high degree of retention during sampling and good recovery during analysis. Weakly sorbed compounds (vinyl chloride, chloromethane and other low molecular weight, low boiling point compounds) require a strong sorbent to be effectively retained during sampling, especially for longer sampling intervals. Strongly sorbed compounds (e.g., naphthalene, PAHs, PCBs, and other

high molecular weight, high boiling point compounds) do not require a strong sorbent to be effectively retained, and may not be effectively recovered unless a weaker sorbent is used. It may not be practical to select a single sorbent suitable for the range of compounds of potential interest for vapor intrusion investigations, in which case two or more samplers are an option. Several publications are available that provide information regarding the effectiveness of various sorbents with various VOCs (Supelco, 2013; ASTM D6196, 2009; CEN EN 13528-3, 2003; CEN EN 14412, 2004). For active adsorptive sampling (where air is pumped through a tube of sorbent media), there are recommended maximum sampling volumes (RMSVs) for combinations of compounds and adsorbents beyond which, a low (or negative) bias in the reported concentrations is commonly seen, which is attributable to poor retention by the sampler. For passive sampling, there is no specified volume of gas drawn through the adsorbent, but poor retention can still result in low biases by competition for adsorptive sites (more strongly sorbed compounds can displace less strongly sorbed compounds) causing back-diffusion (diffusion away from the sampler, rather than toward it). The selection of the optimum sorbent for a particular set of target compounds can be complicated and should be done in consultation with an experienced analytical chemist.

The reportable concentration for a passive sample is inversely proportional to the sample duration and the sample duration must be long enough to achieve a reporting limit as low as the risk-based target concentrations or lower for each of the target analytes. However, long deployment periods increase the risk of saturation of the adsorptive sites on the sorbent if concentrations are high and poor retention if weaker sorbents are used (Bates et al, 1997). The risk of saturation can be managed with some advance information about expected concentrations, and usually readings with a portable instrument such as a photoionization detector (PID) are sufficient to identify appropriate limits on the sample duration to avoid saturation (the linear range of analysis for most methods is at least two orders of magnitude, so there is a fair margin for uncertainty in the expected concentrations). Low biases attributable to poor retention will be most problematic for long sample durations and combinations of sorbents/compounds that have limited sorptive capacity (indicated by low RMSVs).

2.1.4 Candidate Passive Samplers Used in this Study

The following samplers and configurations were used in this study:

SKC Ultra™ and Ultra II™ (http://www.skcinc.com/prod/590-100.asp) is a badge-type sampler with option for thermal desorption or solvent extraction, which operates by diffusion through either a plastic cap with ~300 holes, or a low-uptake rate cap with 12 holes (Figure 2a). These devices have been used for industrial hygiene applications for many years (Harper and Guild 1996, US DOL/OSHA 2003), and can provide quantitative VOC analysis of indoor air samples at the ppb_v level (Coyne, et. al. 2002; Hendricks, et. al. 2002; Hendricks 2003, Bergemalm-Rynell et al. 2008; SKC 2004, 2008, 2012). In the Ultra II sampler, the adsorbent is shipped separately in a sealed vial to retain purity; however, this requires manual transfer of the sorbent from the vial to the sampler and back in the field as well as transfer from the vial into an ATD tube in the laboratory prior to analysis, all of which adds potential for bias and

variability. The sampler body establishes a 1-dimensional diffusion profile through a known length and cross-section. Depending on the compounds of interest, this device is commercially available with various types of sorbent media: Carbopack X, Chromosorb 106, Carbograph 5 and Anasorb GCB1. Columbia Analytical Services (CAS) in Simi Valley, CA is specifically listed by SKC as a specialty provider of the analyses of these devices, and was used for these analyses.



Figure 2a: SKC Ultra sampler with regular (white) and low-uptake cap (green)

Radiello® This sampler has a 2-dimensional (radial) geometry, which has a large cross-sectional area and increases the uptake rate for greater sensitivity (lower reporting limits for a given sample duration) compared to most of the other samplers (Cocheo et al. 1994, Cocheo et al. 2009). The sampler is made of two concentric cylinders; the inner cylinder is a cartridge that contains an adsorbent medium surrounded by a stainless steel mesh. The outer cylinder is made of microporous sintered polyethylene, through which the vapors diffuse. Two different outer cylinders (white and yellow, Figure 2b) are available, which are manufactured with different wall-thickness for adjusting the uptake rates. Calibration constants for the sampler have been determined experimentally and are reported in the user manual for many analytes, or they can be estimated from the uptake rates of similar compounds by comparison of the diffusion or permeation coefficients of the analytes. The inner cylinder can be filled with different sorbents suitable for either solvent extraction or thermal desorption. The cylinders and housings are all the same sizes, so they are interchangeable, and all four combinations (low and high uptake rate, solvent and thermal desorption) are possible. Radiello is patented by Fondazione Salvatore Maugeri-IRCCS, Centro di Ricerche Ambientali, in Italy. The Radiello sampler was used successfully in the Monitoring of Atmospheric Concentration of Benzene in European Towns and Homes (MACBETH) Study, which consisted of sampling and analysis of 3,600 samples, each representative of 5-day exposures, collected on six occasions from about 100 locations in each of 6 European cities (http://www.fsm.it/padova/homepage.html).

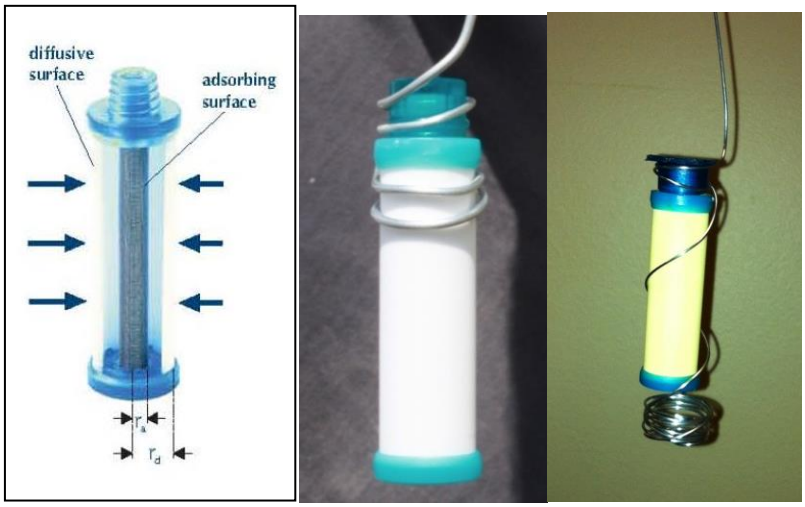


Figure 2b: Radiello sampler with regular (white) and low-uptake rate (yellow) bodies

3M OVM 3500™ - This device is a badge style sampler originally developed for industrial hygiene monitoring (Chung et al. 1999, Purdham et al. 1994; Mukerjee et al., 2004). The plastic body snaps together, and holds a white porous plastic outer layer (diffusive barrier) at a fixed distance from a thin film coated with activated carbon (Figure 2c). Diffusion occurs across the porous barrier and through air to the activated carbon. Solvent extraction of the carbon after a period of exposure is used as the sample preparation, and an aliquot of the extract is injected to a GC/MS to quantify the adsorbed mass of each analyte. The large surface area provides a high uptake rate, which yields a good sensitivity with practical sample durations. Conversely, this may exacerbate the starvation effect for passive sampling in low face velocity settings, such as passive soil gas sampling. This sampler is also the largest of the candidate samplers, which is a disadvantage for fitting in passive soil gas probes and flow-through cells. No low-uptake option or thermal desorption option was available at the time of this research.

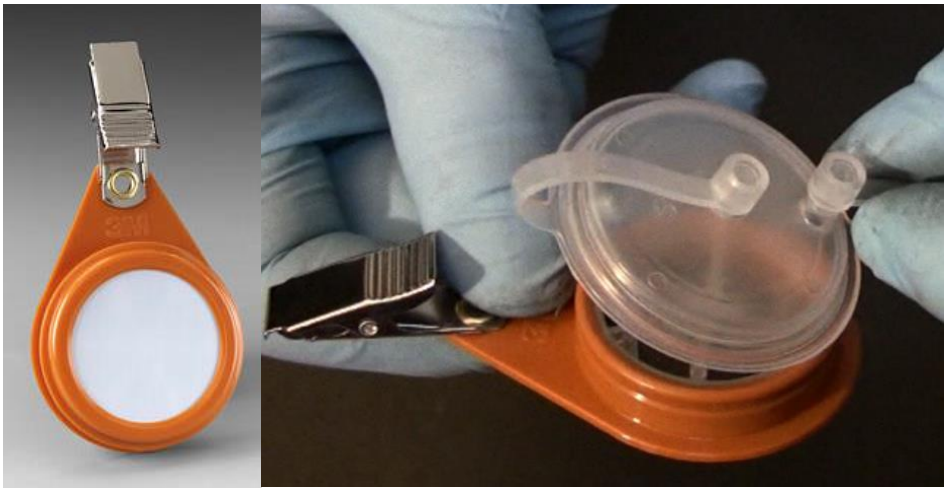


Figure 2c: 3M OVM 3500 sampler and solid plastic cap used to replace the porous plastic sheet after sampling

Waterloo Membrane Sampler™ The WMS sampler is unique because VOC uptake occurs through a membrane of polydimethylsiloxane (PDMS). VOCs dissolve into the membrane and permeate across it. The membrane excludes water vapor (which can compete for adsorptive sites on some sorbents and interfere with laboratory instruments) and prevents advective uptake by turbulence (so sampling can occur in high air velocity environments without a high or positive bias). The uptake rate is proportional to the linear temperature programmed retention index (LTPRI, which is a diagnostic property of chemicals reported in the scientific literature), so the uptake rate can be calculated with reasonable accuracy for compounds similar to those for which it has been measured in controlled chamber experiments (Zabiegala et al., 2006; Seethapathy and Górecki, 2010a,b). The WMS sampler is available in either a 1.8 mL vial (**WMS™**) with an exposed membrane surface of about 0.24 cm^2 or a 0.8 mL vial with a smaller membrane area (0.079 cm^2) and proportionately lower-uptake rates (**WMS-LU™**), both shown in Figure 2d. The WMS sampler was used with either solvent extraction (Anasorb 747) or thermal desorption (Carbopack B).

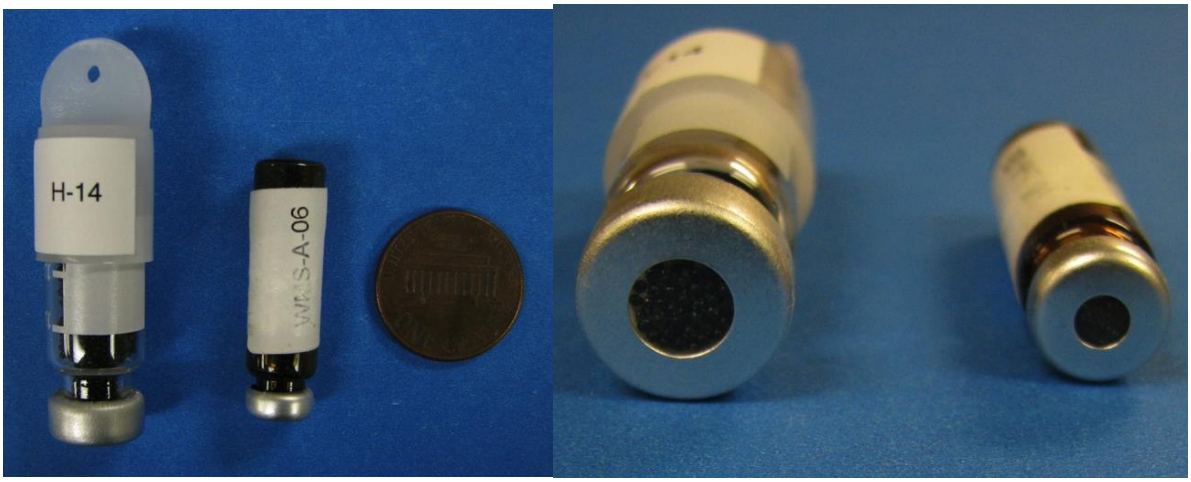


Figure 2d: Waterloo Membrane Sampler (WMS) and close-up of membrane and adsorbent.

Passive ATD tube samplers (from various manufacturers). This sampler consists of a standard Automated Thermal Desorption (ATD) tube that can be used with a wide variety of adsorbents, depending on the compounds of concern and the target reporting limits and sample durations (Cox et al., 1984; Batterman et al., 2002; Brown, Crump and Gardiner, 1992; Brown, Crump and Yu, 1993; Brown and Crump, 1998; Crump, 2001; Crump, 2009; Crump et. al., 2004; Sweitzer et al., 2006; Thomas et al., 2011). The ATD tube is shipped with compression-fit end caps and Teflon ferrules on both ends to prevent uptake during shipping. The ATD tube facilitates sample preparation because it can be placed directly on an auto-sampler of a thermal desorption unit for GC/MS analysis by EPA Method TO-17 or equivalent. Therefore, the ATD tube sampler is used almost exclusively with thermally desorbable sorbents (e.g., Tenax TA and Carbopack B). This sampler has either a stainless steel dust screen (regular uptake) or a cap with a smaller diameter opening (low uptake), as shown in Figure 2e.



Figure 2e: ATD tube sampler and regular and low-uptake rate caps

2.2 Technology Development

Passive samplers have been used for industrial hygiene monitoring for decades (Palmes and Gunnison 1973; Brown et al. 1981; Cox and Brown 1984; Lewis et al. 1985; Cassinelli et al. 1987; Moore 1987; Brown, 1993, 1999 and 2000, Begerow et al., 1999; NIOSH Method 4000, Harper and Guild, 1996, Guild et al., 1992, Harper and Purnell, 1987; ISO, 2000; OSHA, 2008), and their application to the low concentrations of interest for vapor intrusion has been more recently evaluated (Górecki and Namiesnik, 2002; Seethapathy et al. 2008, Gordon et al., 1999; Namieśnik et al., 2005). Furthermore, no passive samplers have previously been demonstrated to provide quantitative soil vapor concentration measurement (USEPA 1998a, 1998b; CalEPA/DTSC, 2011; ASTM D7663-11). International standards are available describing the sampling procedure and the sampler performance assessment (MDHS 70; MDHS 27; MDHS 80; MDHS, 88;ANSI/ISEA 104; ASTM D 6306-98; ASTM D6246; ASTM D4597; CEN 1995, 2002a, 2002b, 2003, 2004, 2004). The method for quantification of VOCs in indoor, ambient and workplace air is described in international standard EN ISO 16017-2 (International Organization for Standardization, ISO, 2003). This standard provides guidance on the selection of appropriate sorbents for particular purposes where key considerations are the properties of the target analytes, the concentration of interest and the required averaging time of the measurement. The selection of an appropriate sorbent relates predominantly to the volatility of the target analyte(s) and there is a requirement for the sorbent – analyte interaction to be appropriate to allow effective retention of the analyte, but also as efficient release as possible when heat is applied in a flow of gas in the thermal desorber.

EN ISO 16017-2 summarizes the published validation data (available in 2003), as a list of determined diffusive uptake rates for specific sorbent and analyte combinations, identifying the level of validation undertaken. By far most of the validations are for tests appropriate for workplace, with typical concentrations in air near the occupational exposure limit, and exposure

periods of 8 hours. The EN ISO 16017-2 standard provides the diffusive uptake rate for passive ATD tubes with over 50 VOCs determined for workplace monitoring including a note on the level of validation of the method. There is also a summary of studies that determined uptake rates for indoor and ambient concentrations using sample periods of between 1 and 4 weeks, with most of the data referring to benzene, toluene, ethylbenzene, and xylene (BTEX), which are volatile aromatic compounds typically found in petroleum, and also data for trimethylbenzene, decane and undecane. The ISO standard also recommends conditions for the thermal desorption of the different sorbents by ATD tubes and GC/MS.

The uptake rate of a passive sampler may be subject to biases due to environmental factors. The stronger sorbents such as charcoal tend to also adsorb water (Qi et al., 2000 and Abiko et al., 2010), which can be a problem in the analysis and can be limiting for some applications. Weaker adsorbents such as Tenax retain less water, but more volatile compounds are not strongly retained and may be lost from the sampling tube by back diffusion, especially for long sample durations. These types of processes can result in non-ideal behavior of the samplers, where the performance of the sampler in the field may deviate from that expected on the basis of the dimensions of the sampler and the rate of diffusion of the analyte in air. When selecting a method, users often accept compromises on performance, particularly for the study of mixtures of compounds. For example, the sorbent Carbopack B may be optimal for benzene, but if the intention is to monitor a low volatility compound at the same time (without the additional cost of using a separate sampler) then Tenax may be the preferred choice. This is because while Tenax's performance for determining benzene is compromised to some extent due to back diffusion losses from the tube, giving a lower effective diffusive uptake rate, it can also be used at the same time to determine compounds that would be poorly recovered on heating when using a stronger sorbent, such as Carbopack B.

The EN ISO 16017-2 standard also discusses the impact on sampler performance of environmental conditions, such as humidity, air velocity, temperature, pressure, and occurrence of transient concentrations. Assuming the correct sorbent is selected, the standard advises that in practical use the three main considerations are air velocity, protection from precipitation and security. For example, the ATD tube sampler has been shown to perform as designed in locations with low air movement (e.g., wind speed of 5 cm/s), but if placed outdoors an appropriate shelter should be used because precipitation, direct solar heating and high wind velocities may adversely affect performance. ISO (2007) and MADEP (2002, 2011) discuss the strategies for sample locations and options for assessing continuous versus intermittent sources. More information about the impact of environmental factors on the accuracy of the uptake rate for passive samplers is provided by Tolnai et al., 2000 and Bohlin et al., 2007.

The measurement of benzene in ambient air via diffusive sampling is the subject of specific European standards (EN14662-4:2005 for thermal desorption and EN14662-5:2005 for solvent desorption). This standard describes the sampling and analytical procedure and provides performance data in terms of the expected overall uncertainty of the method. The document was prepared under mandate from the European Commission in order to establish a method appropriate for the measuring of benzene in ambient air to check compliance with the Air

Quality Directive. Unfortunately, this same level of extensive validation is not available for other analytes or for other passive samplers in ambient air. This can be managed to some degree by using inter-method verification samples as a QA/QC measure in a sampling program (for example 1 in 10 passive samples may be verified using a Summa canister/TO-15 sample), which will provide information that can be used to derive or check uptake rates for detectable chemicals under the site-specific conditions.

2.3 Advantages and Limitations of Passive Sampling

2.3.1 Advantages

Passive diffusive samplers offer at least four potentially significant advantages to the current industry standard approach of whole-air sampling with Summa canisters and TO-15 analysis, detailed below.

Lower Cost: Summa canisters can cost up to about $1,000 to purchase, and costs are typically passed along to the end user in the form of a canister rental charge. Flow controllers are required for time-averaged sample collection, and a rental charge is also levied to cover their purchase, cleaning and certification. Summa canisters are large and heavy, and courier charges are based on size and weight, so Summa canisters are much more expensive to ship back and forth to a field site than passive samplers. Summa canisters are re-useable, but they must go through a time-consuming cleaning and certification process, with record keeping of each canister's history by serial number to maintain high levels of QA/QC needed for vapor intrusion investigations, all of which is costly.

Most of the passive samplers are disposable items and are intended for one time use, with the exception of ATD tubes and Radiello housings that are cleaned and reused. They are small in size and shipping charges are minimal in comparison to costs for shipping Summa canisters. Less operator training is required and the labor costs for sampler deployment and retrieval are also lower.

Simpler Sampling Protocols: Passive samplers are much easier to deploy than Summa canisters. Indoor air sampling with Summa canisters requires several steps: 1) removal of the dust-cap, 2) attachment of the vacuum gauge, 3) opening and closing of the valve, 4) recording vacuum reading to assess whether the canister leaked during shipment from the laboratory, 5) removal of the vacuum gauge, 6) attachment of the flow controller, 7) opening of the valve, 8) recording time, 9) returning at a later time, 10) closing the valve, 11) removing the flow controller, 12) attaching the vacuum gauge, 13) opening and closing of the valve, 14) recording final vacuum to document whether the canister leaks on the return shipment to the laboratory, and 15) replacing the dust cap. Some laboratories provide integrated vacuum gauges with the flow controllers, which eliminates steps 5, 6, 7, 12 and 13. Soil gas sampling adds additional steps for purging prior to sample collection, and this may be complicated in low permeability soils, where flow rates may not be sufficient for continuous purging and sample collection (McAlary et al., 2009). Where tracers are used to assess potential leaks, the level of effort in the field sampling activity increases dramatically. By contrast, the passive samplers are

considerably simpler, typically shipped clean and sealed in air-tight containers which are opened, placed in appropriate locations, left for a specified period, resealed, labeled and returned to the laboratory. For passive soil vapor sampling, a hole must be drilled, and a seal must be placed for the sample duration, or a probe must be installed; however, similar actions are required for active soil vapor sampling. For soil gas sampling, it may not be necessary to purge when using passive samplers, which simplifies the sampling process compared to active sampling. The Radiello and SKC Ultra II samplers require an additional step of placing the sorbent into the housing at the start and removing it at the end of the sampling period. For indoor air monitoring, the passive VOC samplers are very similar to devices currently used for monitoring radon, which are often deployed, retrieved and shipped by homeowners (i.e., not by technical personnel), so much less training is required. Simplicity may help minimize bias and variability attributable to inter-operator errors (differences in the sampling results attributable to operators implementing sampling procedures in different ways).

Longer-Term Samples: Passive samplers can be used to collect samples over much longer periods than conventional Summa canister or active ATD tube samplers, which will result in measured concentrations that represent a time-weighted average of conditions over the sample collection duration, and minimize short-term temporal variability associated with changes in weather conditions, building ventilation and occupant's activities. EPA recommends a sample duration of 72-hours or longer for radon in indoor air (www.epa.gov/radon), and refers to 30-day sample durations as "short-term" samples. Considering the degree of temporal variability in short-term samples (Johnson et al., 2013; Schumacher et al., 2013), it may be necessary to use longer-term passive sampling to minimize the risk of failing to identify short-term peaks in VOC vapor concentrations that can dominate the average exposure but can easily be missed by shorter-term intermittent samples. For vapor intrusion investigations, target concentrations based on 25 to 30 year average exposures are typically the basis for decision-making. Sampling and analytical methods that are affected by short-term temporal variability are undesirable because they either increase uncertainty, or require additional sampling and analysis to characterize the expected degree of variability and support statistical calculations of long-term average concentrations. Summa canisters and active ATD tubes are not well-suited for sampling over periods longer than 24 hours.

Less Obtrusive: Passive diffusive samplers are small enough to be held in the palm of a hand, and look fairly simple and unobtrusive (Figure 2f). Summa canisters are much larger (indoor and outdoor air samples typically require a 6 L canister, which is about the size of a bowling ball), and are therefore much more obtrusive. Individuals unfamiliar with Summa canisters have sometimes mistaken them for compressed gas cylinders or explosive devices, which can impose challenges in monitoring within highly-occupied structures or communities or if Summa canisters are to be shipped across international borders.



Figure 2f: Photo of two 6L Summa canisters and a 3M OVM 3500 sampler (upper right)

2.3.2 Limitations

Passive diffusive samplers have the following potential limitations:

Starvation Effect: If the velocity of air to which the sampler is exposed is very low (less than about 0.1 to 0.001 m/s depending on the uptake rate of the sampler; Brown, 1993, Harper and Purnell, 1987), then the sampler may remove VOC vapors from the air faster than they are replenished, in which case, the sampler itself imposes a localized reduction in the VOC vapor concentrations. This results in a low (or negative) bias in the reported concentrations, which is referred to as the "starvation effect." In indoor and outdoor air sampling, the face velocity is usually high enough to minimize starvation, except perhaps for very high uptake rate samplers. In soil gas sampling, particularly in low-permeability materials, the flow rate of soil gas will be very low or nil and VOC transport to the sampler will often be limited to diffusive flux, which increases the risk of low bias via starvation. Mathematical modeling and sampling using samplers with different uptake rates were including in this study to assess the starvation effect.

Saturation, Competition and Poor Retention: If passive samplers are exposed to high analyte concentrations for extended periods of time, then the adsorptive sites on the adsorbent media may become occupied with VOCs and the adsorbent performance may diminish (referred to as saturation). If multiple VOCs are present, then more strongly adsorbed compounds may displace less strongly adsorbed compounds, which could impose a low bias on the concentration measurements for the less strongly sorbed compounds (referred to as competition). If long deployment periods are used with weak sorbents, there may also be losses from the sorbent by back-diffusion (referred to as poor retention). All three cases have the same net effect of a low bias in the reported concentrations.

Matching to Target Compounds: The sampler type and sorbent must be selected with consideration of the compounds of interest and the desired reporting limits. This is similar to challenges of conventional active sampling methods that employ active (pumped) ATD tubes, such as EPA Method TO-17. For example, vinyl chloride is weakly retained by adsorbents, and may pose a greater challenge to the samplers than other VOCs. If a very strong adsorbent is used to retain vinyl chloride, then more strongly adsorbed compounds (such as naphthalene) may not be effectively recovered from the sorbent during desorption prior to analysis. In many cases, the compounds of concern for DoD facilities are limited to a select number of chlorinated ethenes, ethanes, and methanes, many of which are included in the laboratory testing component of this study, so the suitability of the candidate samplers for the compounds of most interest to the DoD can be evaluated.

Unplanned Uptake of Chemicals: The passive samplers can become contaminated by unplanned exposure to chemicals during shipping and storage. The risk is reduced by carefully packing the samplers in clean containers that are impermeable to VOC vapors. The potential can also be evaluated and documented by including field blanks (a.k.a. trip blanks), which are samplers that travel continuously with the investigative samples, but are not used to collect a sample. Trip blanks are also a standard QA/QC component of air monitoring programs using EPA Method TO-17. Field blanks are not required with Summa canisters, because the integrity of the canister during shipping is verified with vacuum measurements before and after each leg of the journey.

3 PERFORMANCE OBJECTIVES

The performance of the passive samplers is primarily defined by their accuracy and precision for VOC vapour concentration measurements. Cost is also an important factor. These three factors are quantitative. Ease of use relative to conventional sampling methods is a qualitative parameter that is also of practical importance. These objectives and the metrics and criteria for evaluating them are described in more detail in the subsections below and summarized in tabular form at the end of this section.

3.1 Accuracy of VOC Vapor Concentrations

The accuracy of the passive samplers was evaluated by comparing the concentrations of VOCs in indoor air, outdoor air, and soil gas to the results of samples taken by conventional, currently accepted methods (Summa canister sampling and analysis by EPA Method TO-15, as well as pumped ATD tube sampling and analysis by EPA Method TO-17). The two values were compared using the relative percent difference (RPD), which is defined as:

$$RPD = \frac{\text{difference between two numbers}}{\text{average of the two numbers}} \times 100\%$$

The generally accepted RPD for TO-15 analysis is <25% for two analyses of the same sample within the same laboratory. An additional margin was added to account for the fact that the passive and active samples were analyzed by different methods and typically at different laboratories than the conventional samples (the average RPD in the inter-laboratory testing program conducted in this study and described in Section 6.2 was about 26%). Therefore, the success criteria for indoor and outdoor air samples was RPD < 45%. Soil vapor sampling generally shows more variability than indoor air sampling because the vapor distribution in the subsurface is not as well-mixed, so the criteria for soil vapor samples and the high concentration laboratory tests was relaxed to RPD < 50%.

The concentrations of VOCs were tested over a very wide range so the results were generally presented as normalized or relative concentrations:

$$C/Co = \frac{\text{passive sampler concentration}}{\text{active sampler concentration}}$$

It should be noted that an RPD of +/-45% corresponds to C/Co values between 0.63 and 1.58 and an RPD of +/- 50% corresponds to C/Co values between 0.5 and 1.67.

Conventional sampling methods for VOC concentrations in indoor air (TO-15 and TO-17) are generally limited to sample durations of 24-hours or less, and available data indicates that 24-hour samples often show temporal variability of up to 10 times compared to long-term average indoor air concentrations (McAlary et al., 2013; Kurtz and Folkes, 2013). Passive samplers are capable of longer sample durations, which can reduce the temporal variability inherent in the data compared to 24-hour samples (Steck, 2013). Therefore, passive samplers may provide a

better representation of long-term average exposure point concentrations than conventional methods even if the accuracy is not within the success criteria.

3.2 Precision

Precision is a measure of the variation that may be expected within a group of measurements. U.S.EPA Method TO-15 specifies a target of < 30% relative standard deviation (RSD, which is also known as the coefficient of variation [COV] and is equal to the standard deviation divided by the mean) for instrument calibration. The success criteria was therefore set to be a COV < 30% for indoor and outdoor air samples. For soil vapor sampling, the criterion was to have COV for the passive samples similar to the COV of conventional samples (i.e., samples collected and analyzed according to EPA Methods TO-15 or TO-17) and <30% where practical.

3.3 Cost

The cost comparison was based on the cost for passive sampler purchase and shipping, laboratory analysis and time spent by trained professionals to deploy and collect a sample. It is also important to consider the extra costs for regulatory agencies to approve sampling with passive samplers as an acceptable investigation method. Regulatory acceptance of new technologies typically requires some comparison to conventional methods until sufficient comparisons are available to provide the agencies with adequate assurance of the performance of the new method. Therefore, the cost estimate for passive sampling included inter-method verification samples using conventional Summa canisters at a frequency of 1 in 10 for all media (indoor and outdoor air and soil vapor). This strategy also provides data to derive field-calibrated uptake rates for the passive samplers under the specific conditions of the sampling event, which would improve the accuracy of the uptake rates compared to vendor-supplied values from chamber tests under potentially different conditions; therefore, it may be a good practice even if not required for regulatory approval.

3.4 Ease of Use

Ease of use was evaluated based on a comparison of the passive samplers to the conventional sampling methods, including observations for each sampler type and each sampling medium.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Accuracy of VOC vapor concentration quantitation in soil gas, indoor air and outdoor air.	Concentration measurements using each of the candidate passive samplers and Summa canisters as control, with sufficient samples to assess the effects of the key factors	Assessed using Relative Percent Difference (RPD) compared to a "standard" (e.g., passive sampler compared to Summa canister). Within a single method and lab, an RPD <25% is typically considered acceptable, and this is usually easily achieved. The passive samplers were analyzed using different methods and in different laboratories than the Summa canisters, so an additional margin is needed for the criteria. The inter-laboratory test showed an average RPD of 26% between labs. Therefore, passive sampler concentrations with RPD <45% of the corresponding active sample concentrations are considered successful for indoor and outdoor air. For soil gas sampling, spatial variability tends to be greater than in indoor or outdoor air sampling, so an RPD <50% is considered successful.	The accuracy was comparable to conventional methods in most comparisons. Some compounds showed notable biases with certain samplers, which was usually attributable to uncertainty in the uptake rate, starvation, poor recovery or poor retention. Accuracy issues can be minimized by employing occasional duplicate samples analyzed by conventional methods to calculate "field-calibrated" uptake rates, by selecting samplers with uptake rates that are low compared to the face velocity or diffusive delivery rate to minimize starvation and by careful selection of sorbents and sample durations to assure retention and recovery.
Precision	Replicate sampling to allow calculation of the mean, standard deviation and coefficient of variation (COV, standard deviation divided by the mean)	Precision: a coefficient of variation (COV) of <30% is considered acceptable for EPA Method TO-15 for instrument calibration. Therefore, COV <30% is considered successful for indoor and outdoor air. For soil vapor sampling, the COV for the passive samplers should be similar to the COV for conventional active samples.	The COV for the passive samplers met the success criteria in most comparisons. Some compounds (MEK, NAPH) and samplers (SKC in low concentration lab tests) showed greater variability than others, but the precision was generally comparable to conventional sampling methods for most VOCs tested.
Cost	Professional time required for sampling, analytical fees for analysis, material costs and shipping charges	Cost reduction compared to conventional methods that is sufficient to justify potential costs associated with additional QA/QC that may be needed to support regulatory acceptance of the passive samplers.	Simpler protocols and lower shipping costs result in savings. The savings are sufficient to off-set the cost of inter-method calibration samples and effort required to select an appropriate sampler, sorbent and sample duration for a particular application.
Qualitative Performance Objectives			
Ease of use	Feedback from field personnel with practical experience on usability of technology and time required	Limited training required for obtaining high quality data. Indoor air sampling no more difficult than a Summa canister. Soil vapor sampling no more difficult than active soil vapor sample collection.	SKC Ultra II samples showed some challenges associated with sorbent transfer, otherwise field sampling and analytical methods are easy. Some additional effort is needed to select the sampler, sorbent and sample duration for a given application compared to conventional methods.

4 SITE DESCRIPTION

The field sampling events were conducted at a total of five locations, some of which were not amenable to sampling of all three media (indoor air, outdoor air and soil gas). A brief summary of key conditions at each site is provided in this section and the scope of work performed at each site is described in Section 5.

4.1 Old Town Campus Building 3 (OTC3), San Diego, CA

The Annex to Building 3 at SPAWAR Systems Center Pacific (SSC-Pac) Old Town Campus (OTC3, Figure 3) was used for the first field sampling event in March 2010. Processes inside the building are suspected to have produced waste oils, paint sludge, spent acids, plating materials, and degreasing solvents. Previous site assessments (CDM, 2009) identified the presence of VOCs in groundwater and soil vapor samples near the north end of Building 3. This site was developed using dredged bay sediments as backfill and 95% of the site is covered with buildings or pavement. The water table is a few feet below ground surface, consistent with the close proximity to the Pacific Ocean.

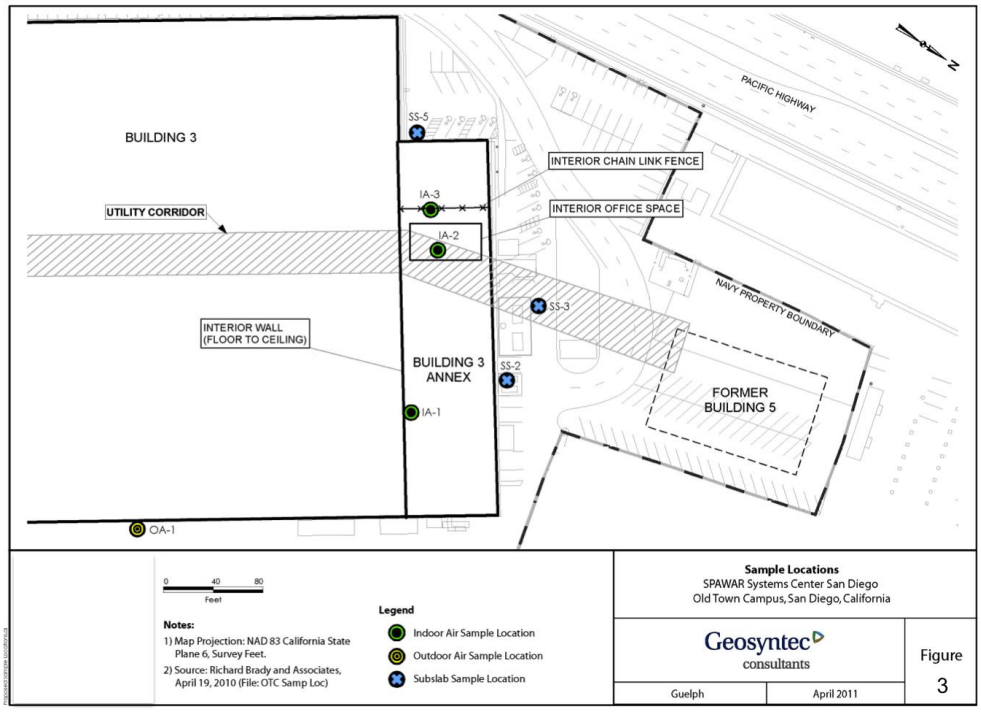


Figure 3: SSC-Pac OTC3 layout and sample locations

As an initial verification of the suitability of the site for passive sampler testing, three (3) indoor samples and one (1) outdoor air sample were collected using Waterloo Membrane Samplers (WMS) between December 17, 2009 and January 4, 2010. Trichloroethene (TCE) was detected at concentrations ranging between 3.3 micrograms per cubic meter (µg/m^3) and 4.6 µg/m^3 in the three indoor air samples and was not detected above the laboratory reporting limit (0.59 µg/m^3) in the outdoor sample.

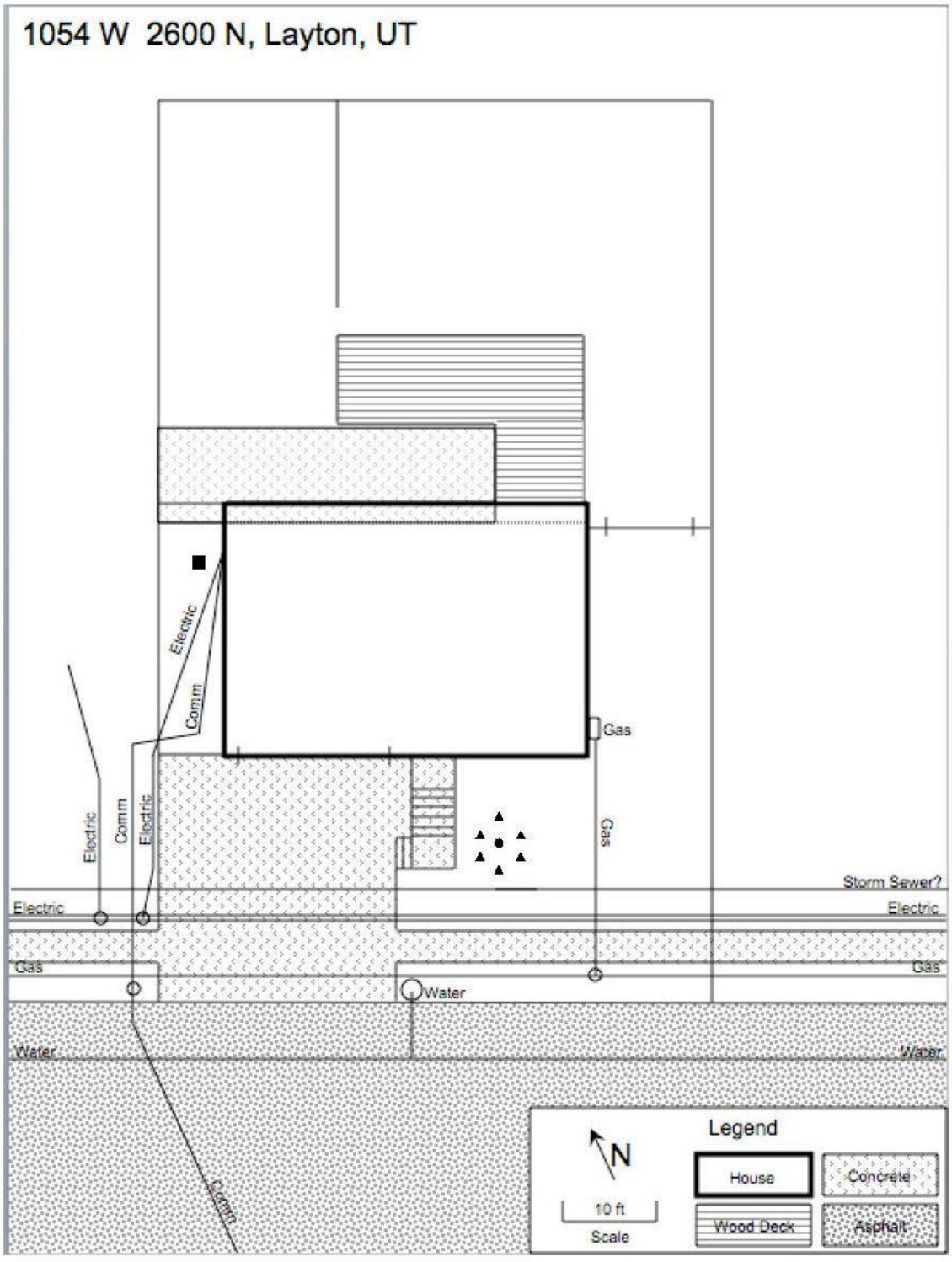
4.2 SERDP Research House near Hill Air Force Base, Layton, UT

The second field sampling event occurred in July and August 2010 at a residential property currently owned by Arizona State University (ASU) in Layton, Utah, near Hill Air Force Base (Hill AFB) which is being used for vapor intrusion research as part of the Strategic Environmental Research and Development Program (SERDP), project 1686. For brevity, this is referred to as the Layton house or the Hill AFB site; even though it is actually located hydraulically downgradient of Hill AFB. The building is a single story dwelling with a partially below-grade basement (Figure 4). Dissolved TCE and 11DCE are present in groundwater below the building and ASU has confirmed that vapor intrusion of these compounds into the building is occurring (Johnson et al., 2013). The building is currently uninhabited and is being used for vapor intrusion research. Soil gas data showed a range of VOCs present at concentrations up to 300 $\mu g/m^3$ prior to selection of this test site. Passive and active soil gas samples were collected from an array of probes installed in the front yard (Figure 5).

The geology of this site and surrounding communities, including Layton, consists of a thin fine sand and silt overburden layer on top of a thick clay layer (Roginske, 2010). This clay layer prevents vertical movement of groundwater and any associated contaminants. The municipal water supplies for the surrounding communities are provided by deep aquifers that are shielded from the shallow contamination by this clay layer and have not reported any issues with water quality related to VOC contamination. Since 1993, investigations have determined that the base's industrial complex had contaminated a large area of groundwater along the southwest boundary and into the communities of Clearfield and Layton (Roginske, 2010). The primary VOCs are TCE and 11DCE. TCE is the most widespread contaminant and occurs in the greatest concentrations.



Figure 4: Front view of ASU vapor research house in Layton, UT



● conventional soil gas probe location

▲ passive soil gas probe locations

Figure 5: Locations of passive soil vapor samples at the Layton house

4.3 USACoE Cold Regions Research and Engineering Lab, Hanover, NH

The main Laboratory and Laboratory Addition at the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) facility in Hanover, New Hampshire (Figure 6) was the site of the third field sampling event in November 2010. CRREL was established in 1961 by the U.S. Army Corps of Engineers to research and develop equipment and procedures for applications in cold regions.

The CRREL site is located in the Connecticut River basin, which is approximately 500 ft wide near the site and fluctuates from 380 to 385 ft above mean sea level (Shoop and Gatto, 1992). Groundwater flow at the site is controlled by a high permeability esker along the Connecticut River. This esker is surrounded by an area of less permeable lake sediments and the entire area is underlain by irregularly fractured bedrock composed of schistphyllite (Shoop and Gatto, 1992). The hydraulic conductivity of the esker material based on *in-situ* pumping tests is approximately 283 ft/day, while that of the lake sediments is 57 ft/day (Shoop and Gatto, 1992).

TCE was used on the site as a refrigerant during the 1960s until the late 1980s. In 1970 a 10,000 gallon underground storage tank (UST) containing TCE near the main laboratory building and laboratory addition released liquid TCE. CRREL has been operating under a New Hampshire Department of Environmental Services (NHDES) Groundwater Management Permit (GMP) since July 9, 2004. CRREL currently has air strippers at four of its five groundwater production wells, used for non-contact cooling, to treat the water before use in the facility. Previous sampling indicated TCE in indoor air at concentrations ranging from about 10 to about 100 $\mu g/m^3$ and in soil gas samples at concentrations several orders of magnitude higher. These concentrations are well within the detection ranges for the candidate passive samplers, therefore making CRREL a viable candidate site for the research conducted, which included indoor and outdoor air monitoring and sub-slab soil vapor sampling in a flow-through cell.



Figure 6: CRREL facility layout and laboratory location

4.4 Marine Corps Air Station (MCAS), Cherry Point, NC

Building 137 at MCAS Cherry Point (Figure 7) was used for the fourth field sampling event in January, 2011. Building 137 is part of Operable Unit (OU) 1 and is referred to as Site 51 under the Federal Facilities Agreement. OU1 is an industrial area in the southern portion of the base and the former plating operations in Building 137 are suspected to have contributed to the OU1 Central Groundwater Plume (a combination of 6 source sites).

The geology of MCAS Cherry Point is primarily composed of Coastal Plain sediments and unconsolidated marine sediments of alternating sands and clays with occasional shell beds and phosphatic sands (Miller and Xia, 1996). Bedrock is encountered at approximately 200 ft below ground surface, while the water table is generally consistent with mean sea level (approximately 15 to 30 ft bgs). The hydraulic conductivity of the clay/silt layers ranges from 0.01 to 0.001 ft/day while that of the sand layers range from 10 to 300 ft/day (Miller and Xia, 1996).

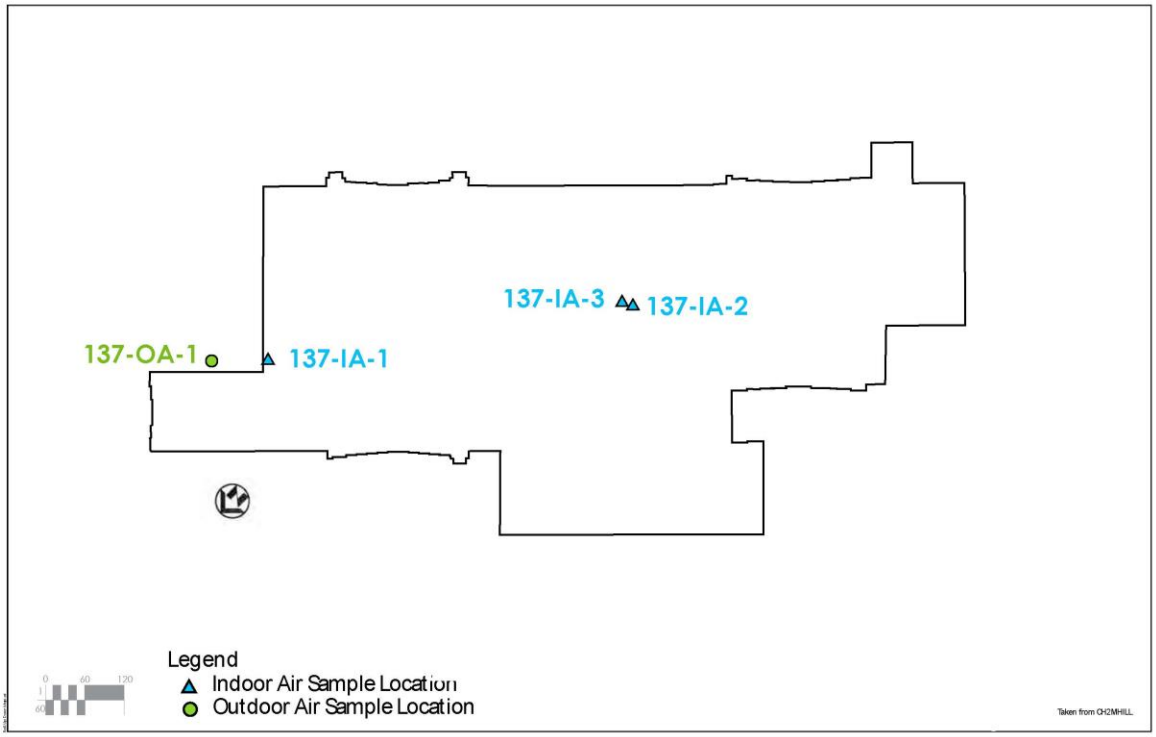


Figure 7: MCAS Cherry Point Building 137 and locations of indoor and outdoor air samples

Soil and groundwater contamination under Building 137 are primarily attributable to source areas around the building. The most prevalent VOCs with the Central Groundwater plume include TCE, VC, cDCE, 11DCA, and 11DCE and less prevalent compounds include PCE, 111TCA, 1122PCA, and 12DCA (CH2M Hill, 2010). There are three distinct plumes of TCE present in OU1 and one is located under Building 137. The plume extends from the upper superficial aquifer to the lower surficial aquifer down gradient from Building 137, where it mixes with another TCE plume (CH2M Hill, 2010).

VOCs were previously detected in soil vapor and groundwater samples during on-going remedial investigations being conducted by the Navy. Two (2) indoor air samples were collected for verification of VOC concentrations using 3M OVM 3500™ samplers between November 3 and 4, 2010 in the northern area of Building 137. TCE, 111TCA, 11DCA, benzene, toluene and xylenes were detected at concentrations ranging between 1.8 to 40 µg/m^3 in the two indoor air samples. Based on these results, the northern corner of Building 137 was identified as a viable field demonstration site for the collection of indoor air samples. No sub-slab or soil vapor samples were collected.

4.5 Naval Air Station (NAS), Jacksonville, FL

Naval Air Station Jacksonville (NAS JAX), located in Jacksonville, Florida was used for the fifth field sampling event in January 2011. The Five-Year review (Tetra Tech, 2005) describes Operable Unit (OU) 3 as a 134-acre site with a former dry cleaner operation. The majority of OU3 was recently re-paved. OU3 is underlain by inter-bedded layers of sand, clayey sand, and clay. The water table at OU3 is located within a few feet of ground surface. Groundwater Services Inc. (GSI, 2009) performed an assessment of soil vapor concentrations and reported elevated VOC concentrations within soil and groundwater in the vicinity of Building 103. The primary contaminants of concern (COCs) are PCE, TCE, and related degradation products (cDCE and VC).



Figure 8: Southwest corner of Building 103, NAS JAX

The demonstration was conducted inside and immediately outside the southwest corner of Building 103 (Figure 8). Exterior soil gas samples were collected from three probes and one temporary uncased hole within 10 feet (3 m) of the southern corner of the building and within a few feet of the west wall. Sub-slab samples were collected near locations SS-1, SS-2 and SS-3 in Figure 9. No indoor or outdoor air comparison testing was performed. The building is slab-on-grade with a concrete foundation and was constructed in stages beginning in the 1940s. The investigation focused on the southwest corner, which is closest to the areas of TCE, PCE, and degradation products in soil and groundwater. A diagram of NAS JAX Building 103 with sampling locations from a previous assessment by GSI (2009) is shown in Figure 9.

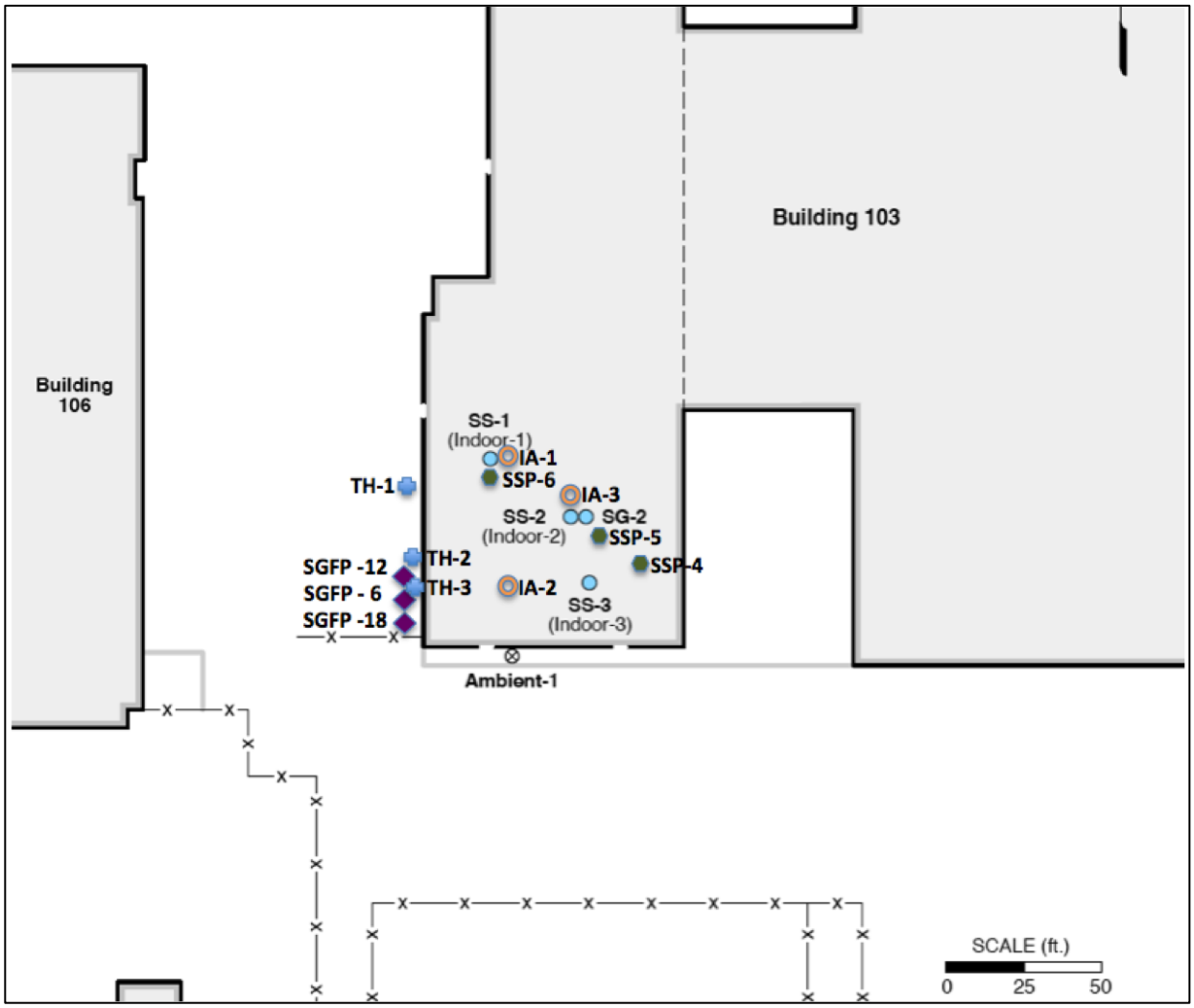


Figure 9: NAS JAX Building 103 plan showing locations of previous sub-slab (SS-1, 2, and 3) and soil gas probes (SG-2) installed by GSI, as well as new passive sub-slab probes (SS-4, 5 and 6), passive soil gas probes (SGFP-6, 12 and 18) and temporary holes (TH-1, 2 and 3) (modified from GSI, 2009)

5 EXPERIMENTAL DESIGN AND METHODS

The research program included laboratory and field-testing to provide data under both controlled conditions and "real-world" sampling conditions. Laboratory testing was divided into low concentration tests (1 to 100 ppb_v range), which were intended to represent the typical range for indoor air monitoring, and high concentration tests (1 to 100 ppmv range) to represent the typical range of interest for soil vapor monitoring. Field testing was conducted at the five sites described in Section 4, and included indoor and outdoor air testing at 3 sites (OTC3, CRREL and MCAS137) and sub-slab and/or soil gas sampling at 4 sites (OTC3, Layton, CRREL and NAS JAX). Soil gas sampling included passive sampling and sampling using passive samplers in a flow-through cell, which may be useful for monitoring existing subslab or soil vapor probes with a diameter too small to accommodate a passive sampler in the subsurface. Each of these tests is described in the subsections below.

5.1 List of VOCs Included in Laboratory Testing

The list of VOCs included in both the low concentration and high concentration laboratory tests was selected to represent common VOCs and span a range of properties (Table 1). The list includes chlorinated ethenes, ethanes, methanes, and aromatics, as well as benzene, naphthalene, hexane, and 2-butanone (or methyl ethyl ketone, MEK). Many other compounds pose a potential concern for vapor intrusion; however, most have properties (vapor pressure, solubility and solid phase partitioning) within the range represented by these 10 compounds, which makes this list representative for comparison testing purposes. The supply gas mixtures were custom-fabricated by Air Liquide America Specialty Gases LLC of Santa Fe Springs, CA, by blending the target analytes in a compressed gas cylinder with balance of high purity air.

Table 1: Compounds tested and their key properties

Analyte	Koc (mL/g)	Henry's Constant @ 25 °C (unitless)	Vapor pressure (atm)	Free Air Diffusion Coefficient (cm^2/s)	Water solubility (g/L)
1,1,1-Trichloroethane (111TCA)	135*	0.70	0.16	0.078	1.3
1,2,4-Trimethylbenzene (124TMB)	614	0.25	0.0020	0.061	0.057
1,2-Dichloroethane (12DCA)	38*	0.048	0.11	0.104	8.6
2-Butanone (MEK)	4.5	0.0023	0.10	0.081	220
Benzene (BENZ)	61*	0.23	0.13	0.088	1.8
Carbon tetrachloride (CTET)	152*	1.1	0.15	0.078	0.79
Naphthalene (NAPH)	1540	0.18	0.00012	0.059	0.031
n-Hexane (NHEX)	132	74	0.20	0.20	0.0095
Tetrachloroethene (PCE)	265*	0.72	0.024	0.072	0.21
Trichloroethene (TCE)	94*	0.40	0.095	0.079	1.3

*Values drawn from: http://www.epa.gov/superfund/health/conmedia/soil/pdfs/appd_k.pdf
All other values from http://www.epa.gov/region8/r8risk/vi.html

5.2 Varieties of Passive Samplers Used

Several varieties of each type of passive sampler were used during the field events. Table 2 shows the varieties of each passive sampler used at each of the field sites for each of the media tested, including the number of replicates, the sorbent, and the uptake rate (where more than one uptake rate was available). After each stage of research, the data were reviewed to assess whether there were indications of data bias or variability attributable to the sorbent selection or choice of uptake rate configurations. In some cases, multiple sorbent types were tested to assess their relative performance (e.g., passive ATD tube samplers were used with both Tenax TA and Carbopack B in both the low concentration laboratory tests and passive soil vapor samples at the Layton house).

The passive sampler uptake rates were based on vendor-specified values, where available. In some cases, the vendors do not have published uptake rates for a particular VOC. In these instances, an uptake rate was estimated from vendor-specified values for similar compounds. Table 3 provides the uptake rates used and identifies which were supplied by the vendors of the passive samplers, and which were calculated for this study. It should be noted that uptake rates for a particular compound and sampler can vary by sorbent type, sample duration and air velocity (ISO 16017; Hendricks, 2003), which varied among the laboratory and field experiments. In most of the samplers, the uptake rate depends on the free-air diffusion coefficient (EPA, 2013), which is closely related to the molecular weight. For these samplers, uptake rates were estimated by linear interpolation from the nearest heavier and lighter molecular weight compounds with vendor-supplied uptake rates. For the WMS sampler, the uptake rate depends on two factors: 1) the distribution coefficient for the compound between air and PDMS (the membrane material), and the permeation rate through PDMS, and has been shown to be strongly correlated with the linear temperature programmed retention index (LTPRI) (Zabiegala et al. 2006; Seethapathy and Górecki, 2010a,b). Where needed, uptake rates were calculated from the linear regressions and the compound-specific retention indices.

Four of the five passive samplers tested were available with regular and low-uptake rate varieties. The SKC Ultra uses a 12-hole cap to cover the normal 300-hole cover over the sorbent chamber, which was assumed to reduce the uptake rate by a factor of 25 (300/12). The Radiello with the low-uptake yellow body (designed for thermal desorption with Carbograph) has published uptake rates for many compounds and where values were not available, they were calculated using the same interpolation approach as described above for the higher uptake (white body) sampler. The ATD tube sampler can be fitted with a cap that has a small diameter opening (provided courtesy of Nicola Watson of Markes International), but no published uptake rates were available; therefore, they were estimated by dividing the regular uptake rates by a ratio of the inner diameter of the tube versus the opening of the cap (1/10). A few versions of low-uptake WMS samplers were tested with an aluminum shield covering the PDMS membrane with various diameter holes drilled in it, but the fabrication was challenging, so the low-uptake variety was ultimately designed using a smaller vial and crimp-cap (i.e., a 0.8 mL vial instead of the standard 1.8 mL vial, both shown in Figure 2d). In some cases, knowledge gained during the conduct of the research led to some fine-tuning of uptake rates for some samplers (shown as double entries in Table 3).

Table 2: Number and varieties of samplers and sorbents used in the field-sampling program

Sampler	Uptake Rate	Sorbent	Laboratory Desorption Method	Navy OTC3, San Diego, CA			Hill AFB, Layton, UT	CRREL, Hanover, NH			MCAS, Cherry Point, NC		NAS Jacksonville, FL		
				Indoor Air	Outdoor Air	Passive Sub Slab	Passive Soil Vapor	Indoor Air	Outdoor Air	Flow-Through Sub Slab	Indoor Air	Outdoor Air	Passive Soil Vapor	Temporary Soil Vapor	Passive Sub Slab
Summa Canister	na	na	TO-15	3 x 3	1 x 3	2 x 1	1 x 9**	3 x 3^	1 x 3^	1 x 36	3 x 3	1 x 1	2 x 10 & 1 x 15		3 x 1
3M OVM 3500™	Regular	Charcoal	Solvent	3 x 3	1 x 3	2 x 1		3 x 3	1 x 3	1 x 7	3 x 3	1 x 1	2 x 2 & 1 x 3		NS
ATD Tube	Regular	Chromosorb 106	Thermal	3 x 3	1 x 3	2 x 1									
		Tenax TA	Thermal				6 x 1								
		Carbopack B	Thermal				6 x 1	3 x 3	1 x 3	1 x 7	3 x 3	1 x 1	2 x 2 & 1 x 3		
	Low uptake rate	Carbopack B	Thermal												3 x 1
WMS™	Regular	Anasorb 747	Solvent	3 x 3	1 x 3	2 x 1	6 x 1	3 x 3		1 x 7					
		Carbopack B	Thermal						1 x 3		3 x 3	1 x 1			
	Low uptake rate	Anasorb 747	Solvent										2 x 2 & 1 x 3	1 x 6	3 x 1
SKC Ultra II™	Regular	Charcoal	Solvent					1 x 3; 1 x 2		1 x 1					
		Chromosorb 106	Thermal	3 x 3	1 x 3	2 x 1									
		Carbopack X	Thermal												
		Carbograph 5	Thermal					1 x 1; 1 x 3	1 x 3	1 x 6	3 x 3	1 x 1			
	Low uptake rate	Carbopack X	Thermal												
		Charcoal	Solvent				6 x 1								
		Carbograph 5	Thermal										2 x 2 & 1 x 3		NS
Radiello™	Regular	Charcoal	Solvent	3 x 3	1 x 3	2 x 1	6 x 1			1 x 7					
		Carbograph 4	Thermal					3 x 3	1 x 3						
	Low uptake rate	Carbograph 4	Thermal								3 x 3	1 x 1			
		Charcoal	Solvent										2 x 2 & 1 x 3		3 x 1

Notes:

Each cell contains information on the number of locations and number of samples in each location (i.e., 1 x 3 means one location with three samples and 3 x 1 means three locations with one sample each)

na - not applicable

** - conventional active samples included Summa canister/TO-15 analysis and on-site analysis with the Hapsite portable GC/MS

NS - No sample: several attempts were made to core 2-inch diameter holes (large enough to accommodate these samplers), but they were not successful, so these samples were not deployed

^ - Flow controllers were set higher than specified, so additional Summa canisters were needed to span the sample period, the results were composited to make triplicate samples

Table 3: Uptake rates for the passive samplers (regular and low uptake varieties)

Analyte	Uptake Rate (mL/min)									
	WMS[1]		Radiello[2]		SKC Ultra[3]			ATD Tube[4]		OVM 3500[5]
	Regular	Low Uptake - Amber Vial	Regular (white)	Low Uptake (yellow)	Regular	Regular - Zero Velocity	Low Uptake	Regular	Low Uptake	Regular
1,1,1-Trichloroethane	1.3		62	20	13; 14	9.4	0.71	0.50		31
1,2,4-Trimethylbenzene	13		50		13	9.9		0.62		
1,2-Dichloroethane	2.6		77	23	13	12		0.50		33
2-Butanone (MEK)	1.3		79		17	6.3		0.50		
Benzene	2.2		80	28	16	11		0.35		36
Carbon Tetrachloride	1.5		67		13	10		0.50		
n-Hexane	1.3		66		14	9.6		0.50		
Naphthalene	26		25		13	--		0.50		
Tetrachloroethene	5.4	1.1	59	25	13	10	0.55	0.41	0.041	28
Trichloroethene	3.3	0.88	69	27	15	11	0.58	0.50	0.050	31
cis-1,2-Dichloroethene	1.9	0.90; 0.53	64	32	15			0.47; 0.51	0.050	29; 35
trans-1,2-Dichloroethene	1.3	0.62; 0.51	62	32	15			0.45; 0.51	0.050	28; 35
Vinyl chloride	0.48									42
1,1-Dichloroethene	0.82		79	32	12		1.3	0.57		35; 33
1,1,2-Trichloroethane	3.3			20	13			0.50		30
1,1-Dichloroethane	1.2			23	12			0.50		33
Toluene	2.0; 4.2			30	15			0.32	0.032	31
Ethylbenzene	6.6			26	13			0.30		27
m,p-Xylene	6.3			27	13			0.30		27
o-Xylene	6.2			25	12			0.30		27
Black - published value Red - calculated value										

Sources:
1 – Seethapathy and Górecki, 2010a,b
2 – Radiello, 2006
3 – SKC, 2008, 2012 or pers. comm. with Linda Coyne of SKC
4 - Subramanian, 1995; ISO 16017-2, ASTM D6196-03 or pers. comm. Derrick Crump of CU
5 – 3M, 2013a.

5.3 Low-Concentration Laboratory Testing

The low concentration laboratory tests (McAlary et al., 2015) were performed at Air Toxics Limited in Folsom, CA, under the direction and supervision of Geosyntec and with review by the other Principal Investigators. Testing was conducted between April 26 and September 25, 2010. The passive samplers consisted of WMS (either solvent extraction or thermal desorption), SKC Ultra II (with Carbopack X), Radiello (white body and activated charcoal) and two types of ATD tube samplers (one using Carbopack B and the other using Tenax TA to compare the two sorbents). Each of the passive samplers was deployed in triplicate in each chamber test. The active (control) sampling was performed using a pumped ATD tube with a minimum of three (for 1-day tests) and up to 8 samples (for 7-day tests).

5.3.1 Apparatus

The low concentration laboratory testing apparatus consisted of a system to purify, humidify and control the temperature of a supply of up to 40 L/min of air (sufficient for two exposure chambers to operate in parallel at the same time). Activated carbon filtration was used to purify the air inside the laboratory (which was verified by sampling and analysis to contain none of the target VOCs at detectable concentrations) and VOCs were added to the purified air stream from supply gas in compressed gas cylinders. Compressed gas cylinders were prepared by Air Liquide America Specialty Gases LLC of Santa Fe Springs, CA with concentrations of 10 ppm for all of the compounds listed in Table 1, except 1 ppm for naphthalene, which has a much lower vapor pressure, and was therefore present in the mixture at a concentration 10 times lower than the other compounds to prevent it from condensing in the cylinder. Mass flow controllers were used to deliver the gas from the cylinders and the purified air at flow rates required to achieve the target concentrations of 1, 50 or 100 ppb_v (0.1, 5 and 10 ppb_v for naphthalene). Humidity was controlled by passing a portion of the air stream through a glass vessel containing water and a magnetic stir-bar for agitation. For high humidity conditions, the glass vessel and downstream piping was heated slightly to minimize condensation. Process flow diagrams for the apparatus for both conditions are in Appendix B.

Each exposure chamber consisted of a glass cylinder with removable top and bottom glass end caps to allow the chamber to be disassembled for easy cleaning. Each chamber was approximately 30 cm in diameter to accommodate 15 passive samplers (5 types, each in triplicate) in a circular Teflon manifold designed to be rotated at a constant speed to control the face velocity and allow sufficient distance between the samplers to minimize competition between the samplers. Baffles were installed inside the chambers to promote one-dimensional upward flow of gas to the samplers, and minimize the creation of a rotational gas flow inside the chamber (gas rotation in the chamber would reduce the actual face velocity to which the samplers were exposed). The chamber materials were all passivated using the Siltek process to coat the surfaces with silicon hydrides and make them as inert as practicable to minimize adsorption and desorption of VOC vapors during the experiments. The design details of the chamber are shown in Figure 10. Photographs of the apparatus are provides in Figures 11 and 12.

The VOC-fortified and humidified supply gas was fed into the bottom of the chamber and flowed upward through a stainless steel plate with 3/32-inch holes drilled on ¼-inch centers (staggered) to distribute the flow uniformly through the chamber. The cylinder above the diffuser plate was the main body of the chamber and it had two sampling ports added by a glass-blower; one to allow access for measuring the concentration inside the chamber with active sampling methods (pumped ATD tubes) and a second for monitoring temperature and relative humidity with probes. The chamber also had a removable lid, which had an exit manifold in the form of a glass ring around the top, as well as a hole in the middle of the lid, through which the rotating frame supporting the samplers was hung.

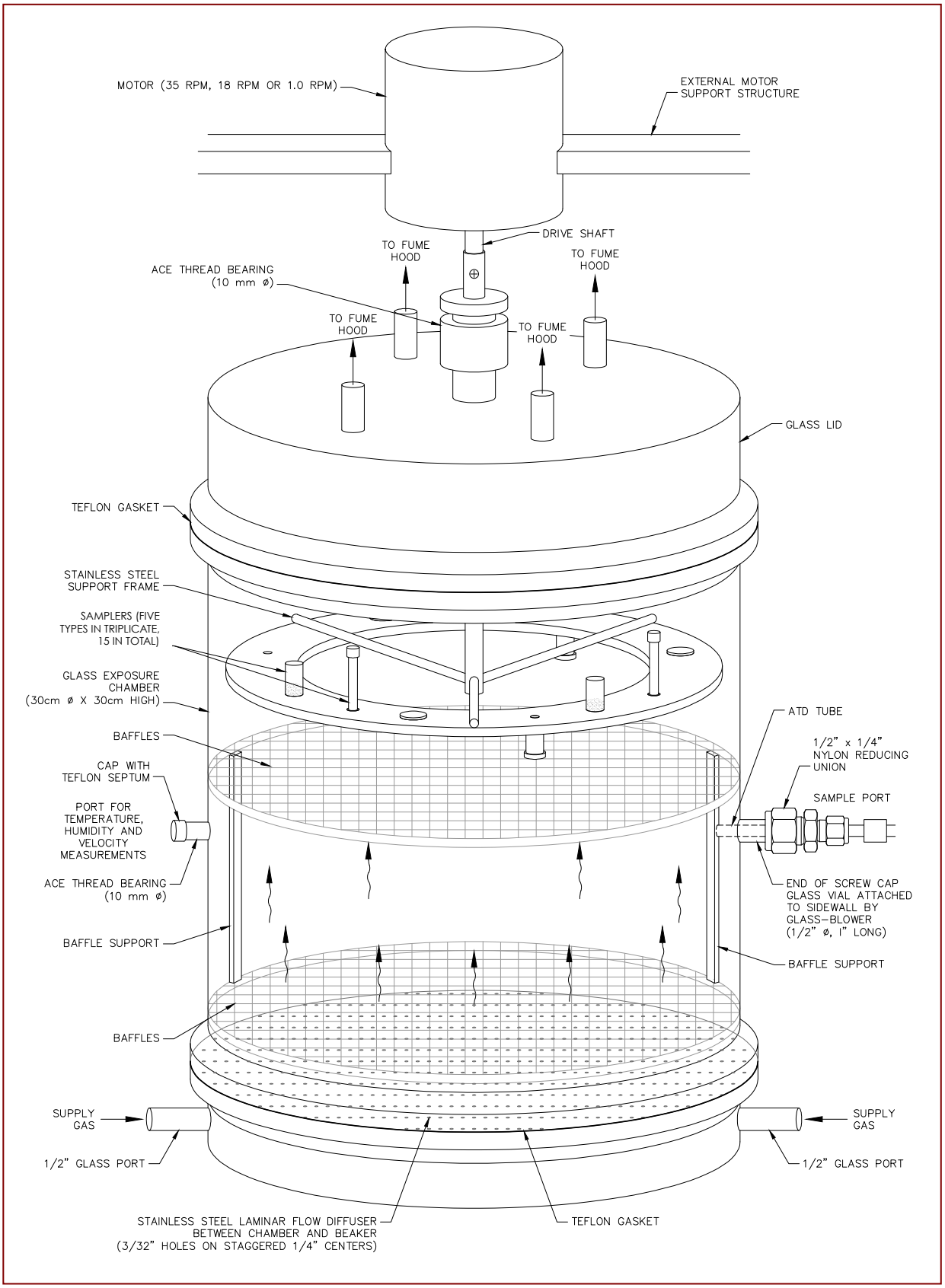


Figure 10: Design details of the exposure chamber for the low concentration tests

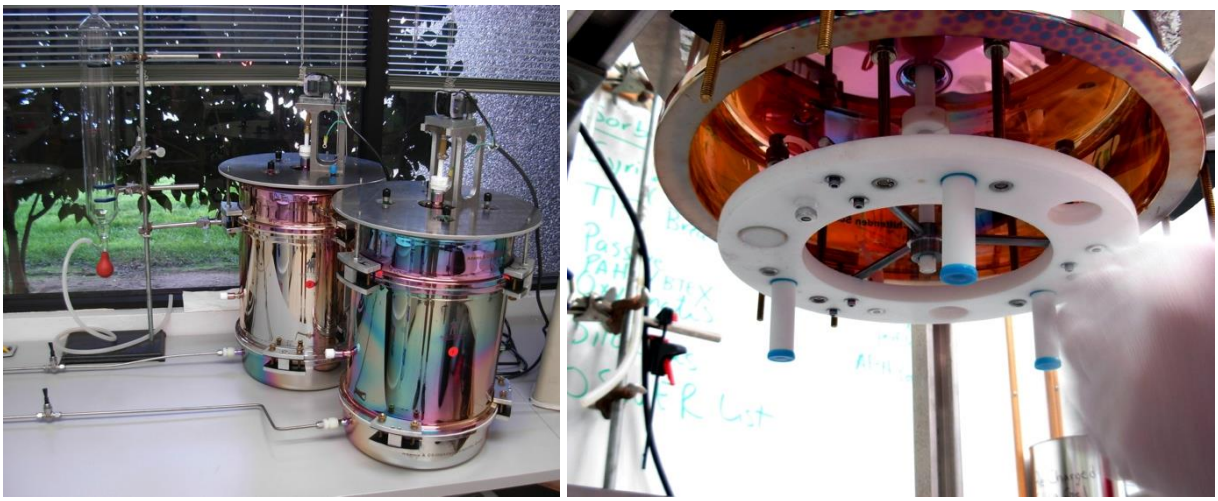


Figure 11: Assembled chambers and close-up of rotating carousel



Figure 12: Low concentration test apparatus, including (left to right: compressed gas cylinders containing 10 VOCs, drum of activated carbon for purifying dilution air, humidification vessel, mass flow controllers, exposure chambers (covered with insulation), constant temperature bath, and discharge lines to fumehood).

The supply gas was fed through the chamber at a rate of about 10 L/min, which was selected to provide sufficient mass flux such that the uptake by the samplers would be negligible compared to the flux through the chamber. This was verified by monitoring concentrations at the influent and effluent end of the chamber during the experiments, which were found to be within about 5%. The corresponding linear velocity of the gas flow was about 0.002 m/s, which was slow enough to be negligible compared to the face velocity generated via the rotating sampler support frame. The samplers were rotated at 1.0, 18 or 35 rpm using one of three rotisserie motors placed on top of the frame to achieve face velocities of 0.014, 0.23, and 0.41 m/s. Each of the five different types of samplers (A, B, C, D and E) were arranged in triplicate in the order of A, B, C, D, E, A, B, C, D, E, A, B, C, D, E for each chamber. One chamber was dedicated to the 1 ppb_v testing, and was not used for testing at higher concentrations to avoid carry-over (desorption of test compounds from the inner surfaces).

5.3.2 Familiarity Testing

Familiarity testing (testing to demonstrate control over the experimental equipment and variables) was performed to assess whether the experimental conditions could be controlled to meet the design values of all of the factors (temperature, humidity, face velocity, concentration and sample duration). The face velocity was controlled by the rotisserie motors and the sample duration (1 to 7 days) was controlled by a stopwatch, both of which were easily controlled with no significant variability or bias. The concentrations were controlled by mass flow controllers on the purified air and supply gas tanks, and also showed minimal variability (less than about 10%), which was verified by comparison of successive samples collected using pumped ATD tubes and analyzed by EPA Method TO-17. The temperature and humidity were more challenging to control, and proved to be interdependent, because condensation occurred in attempt to combine high humidity with low temperature. The temperature and relative humidity were monitored with a Rotronic HygroPalm 1 with a SC05 probe. After completion of several days of testing, the temperature range was adjusted from initial target levels of 10 ^oC to 30 ^oC to a more readily achievable range of 17 ^oC to 28 ^oC. Relative humidity set points were maintained at the initially-planned levels of 30, 60 and 90% RH.

5.3.3 Intra and Inter-Laboratory Testing

Several laboratories were used in this study so inter-laboratory and intra-laboratory variances were evaluated by a two-sample inter-laboratory study (a.k.a., a Youden pair experiment) as described by Wernimont and Spendley (1989) and Miller and Miller (1988). The inter-laboratory testing consisted of exposing two duplicate pairs of each of the five passive samplers to VOCs at the midpoints of concentration (about 50 ppb_v, except for naphthalene at 5 ppb_v), temperature (about 22^oC), humidity (about 60% RH), face velocity (0.23 m/s) and sample duration (4 days) in the exposure chamber. Some of the laboratories in the study team are not set up to analyze all four samplers, so external commercial laboratories were subcontracted as needed (Table 4).

Table 4: Intra and inter-laboratory testing scheme

Sampler Type	Home Laboratory	Secondary Laboratories	# of Samplers to Each Lab
WMS	University of Waterloo	Air Toxics Ltd	2
		Airzone One	
ATD Tubes with Tenax TA	Air Toxics Ltd	Columbia Analytical Services	2
		University of Waterloo	
ATD Tubes with CarboPack B	Air Toxics Ltd	Columbia Analytical Services	2
		University of Waterloo	
SKC Ultra	Columbia Analytical Services	Air Toxics Ltd	2
		Airzone One	
Radiello	Fondazione Salvatore Maugeri	Columbia Analytical Services	2
		Air Toxics Ltd	

5.3.4 Center-point Testing (a.k.a., ANOVA testing)

Six (6) identical chamber tests were performed to assess the intrinsic (random) variability in the concentrations measured by the passive samplers. This test was used to perform a one-way analysis of variance (ANOVA) to determine the variance that is unavoidable, and not caused by changes in the 5 key factors, since all five factors were held constant at the center points of their respective ranges (duration = 4 days, concentration = 50 ppb_v, temperature = 22^oC, humidity = 60% RH and face velocity = 0.23 m/s). Each test included all five candidate samplers in triplicate. The concentrations reported for each of the sampler types were compared to the results of active sampling and analysis by pumped ATD tubes and EPA Method TO-17 to evaluate whether the passive sampler results were statistically different than the active sample controls for each of the 10 compounds and each of the 5 samplers. The data were analyzed to assess precision by calculating the COV among replicate samplers (three per chamber for each type) and accuracy by comparing the passive sampler results to active (pumped ATD tube/TO-17) sampler results.

Two additional chamber tests were performed with all five factors set at the center-points. These two tests were performed after half of the Factorial Testing was conducted, to assess whether the experimental results were reproducible over time. The results of these two tests were compared to the results of the initial six center-point tests and the means were within 25% RSD for all compound and samples (13% on average), so the results of all 8 center-point tests were used together in all subsequent statistical analyses.

5.3.5 Fractional Factorial Testing

A fractional factorial design was used to evaluate the effect of each of the five main factors (temperature, humidity, concentration, face velocity and sample duration). The experimental design was developed with the assistance of Brian Schumacher and the late John Nocerino of EPA Research Labs in Las Vegas, based on the strategies outlined by Deming and Morgan

(1987) and the Stat-Ease group, developers of the Design-Expert 7.1.1. software (www.statease.com).

The design of this test was a $2^{(k-1)}$ fractional factorial design (one-half of a full 2^k full factorial design, where k is the number of controllable factors). This design can be used to assess whether the controllable (main) factors picked for the study (under the conditions specified) have an effect (the main effects) upon the response(s). This design does not resolve interactions between the main effects for the five factors tested. Each analyte relative concentration (passive sampler concentration divided by active sampler concentration, or C/C_o) represents a response. Eighteen (18) different chamber tests were performed by systematically changing the key factors to assess the variability for each of the five samplers attributable to each of the five key factors.

This particular experimental design is economical because it minimizes the number of chamber tests required by changing more than one factor (variable) at a time in a strategic sequence. These tests included low and high levels of the range for each of the 5 key factors, plus two repeats of the mid-point tests to assess whether the ANOVA test results can be pooled with the factorial design results, following the sequence shown in Table 5.

Table 5: Fractional factorial testing run scheme

Run #	Approximate Concentration (ppb_v)	Approximate Temperature (^oC)	Face Velocity (m/s)	Duration (days)	Approximate Humidity (%R.H.)
1	100	17	0.41	1	87
2	1	17	0.014	1	87
3	100	29	0.41	1	33
4	1	29	0.014	1	33
5	100	27	0.41	7	92
6	1	27	0.014	7	92
7	100	17	0.41	7	31
8	1	17	0.014	7	31
9	50	22	0.23	4	63
10	50	22	0.23	4	63
11	100	17	0.014	1	33
12	1	17	0.41	1	33
13	100	17	0.014	7	88
14	1	17	0.41	7	88
15	100	27	0.014	7	32
16	1	27	0.41	7	32
17	100	30	0.014	1	91
18	1	30	0.41	1	91

The data from these tests were compiled and reviewed in real-time as best as possible within the time-frame of shipping and analysis. One observation during the conduct of the tests was a high frequency of non-detect results for the WMS sampler in the short-duration (1 day) and low concentration (1 ppbv) tests, so the sampler was modified to use a thermally-desorbable sorbent for these conditions to increase sensitivity and subsequent low concentration runs provided detectable results.

5.4 High Concentration Laboratory Testing

Controlled experiments were conducted at concentrations of 1, 10 and 100 parts per million by volume (ppm_v) to evaluate the performance of the samplers for concentrations of interest in soil vapor monitoring (McAlary et al., 2014b). Two standard J-size cylinders were custom-filled with the same 10 compounds used in the low concentration lab tests at concentrations of 10 and 100 ppm_v in N_2. These were prepared by Air Liquide America Specialty Gases LLC of Santa Fe Springs, CA. Naphthalene (NAPH) and 1,2,4-trimethylbenzene (124TMB) have much lower vapor pressures than the other compounds, and to avoid potential condensation issues, NAPH was added at a concentration of about 1 ppm_v in the 10 ppm_v supply gas and neither compound was included in the 100 ppm_v supply gas mixture. Therefore, NAPH was tested at 0.1 ppm_v and 1 ppm_v and 124TMB was tested at 1 ppm_v and 10 ppm_v. For the test at 1 ppm_v concentrations, the 10 ppm_v supply gas was diluted 10:1 with ultra pure nitrogen using a mass flow controller to deliver 10 mL/min of the supply gas and a needle-valve to deliver about 90 mL/min of nitrogen (verified periodically with a soap-bubble flowmeter). For the 10 and 100 ppm_v tests, the supply gases were delivered without dilution at a flow rate of about 100 mL/min, controlled using a mass flow controller and verified using a soap-bubble flow meter.

Additional exposure tests were performed using available low uptake rate varieties of the passive samplers. Two tests were performed at the midpoint concentration (10 ppm_v) with the supply gas flow rate held at 100 mL/min for the first test to maintain consistency with the rest of the experiments. The second was performed with the supply gas shut off to assess the performance of the samplers in a setting with no net gas flow ("stagnant" conditions), which is a worst-case condition for low or negative biases attributable to the starvation effect. The SKC low-uptake sampler had no detectable concentrations for either of the first two tests, so a third test was performed at 100 ppm_v under stagnant conditions (only the SKC and ATD tube samplers were used in this test).

The following configurations of passive samplers were used for the high concentration lab tests:

- The SKC Ultra with activated carbon and solvent extraction analysis was used for the 10 and 100 ppm_v tests and the Ultra II with Carbograph 5 and thermal desorption analysis was used for the 1 ppm_v tests and the low uptake rate tests to minimize the risk of non-detect results.

- The Radiello was used with the yellow body, charcoal sorbent and analysis by solvent extraction. This is not a typical configuration for the Radiello. The yellow body which has uptake rates of ~20 to 30 mL/min (2 to 3 times lower than the white body, as shown

in Table 3) and was specifically designed for use with thermally-desorbable sorbents (lower uptake rates reduce the risk of saturation and poor retention). The white body was designed for use with charcoal and analysis by solvent extraction. The yellow body was used with charcoal and solvent extraction in this instance to reduce the risk of a low bias via starvation and avoid saturation of the adsorbent. The uptake rates for the yellow body with charcoal were assumed to be the same as those for the thermal sorbent, which is reasonable if both sorbents act as a zero sink (i.e., the sorbents are strong enough to maintain a vapor concentration near zero in the pore-space of the sorbent throughout the sample duration). The sample duration was only 30 minutes in this study, so the assumption that the sorbent acts as a zero sink is considered reasonable.

- The WMS sampler was used in the regular size (1.8 mL vial) for the tests at 1, 10 and 100 ppm_v, and the low-uptake rate tests were performed using the 0.8 mL vial, both using Anasorb 747 and solvent extraction.

- The ATD tube sampler was used with a dust screen cap for the experiments at 1, 10 and 100 ppm_v, and was fitted with a low-uptake rate cap that has a ~0.8 mm diameter opening that reduces the uptake rates by a factor of about 10 for the additional low-uptake rate tests.

- The OVM3500 is only available in one configuration.

The laboratory apparatus for the high concentration tests consisted of a 1-m long x 5-cm diameter glass cylinder (comparable in dimensions to a borehole cored using a Geoprobe dual tube soil coring device) in order to provide a testing domain similar to what might be used for soil vapor sampling. Three side ports were added by a glass-blower (influent at the bottom, effluent at the top and a sampling port in the middle). The interior surface of the glass cylinder was passivated using a silanization process. The outer wall of the cylinder was wrapped with 1.6 cm diameter Tygon tubing, which was used to circulate water for temperature control. The cylinder and tubing were placed inside a 10 cm diameter clear acetate tube for structural support and mounted to a frame for stability. Two PVC and stainless steel gate valves were secured to the top of the acetate pipe by friction with Teflon™ tape acting as a seal. The gate valves formed an air-lock, to allow samplers to enter and exit the chamber with minimal disruption to the concentrations inside (i.e., the samplers were lowered into the region between the gate valves with the bottom gate closed, then the top gate was closed before the bottom gate was opened, so that the samplers could be placed inside the chamber with minimal loss of the atmosphere inside the chamber). The humidified supply of gas containing known concentrations of selected VOCs was continuously fed through the apparatus. A schematic diagram of the apparatus is shown in Figure 13 and photographs are shown in Figure 14.

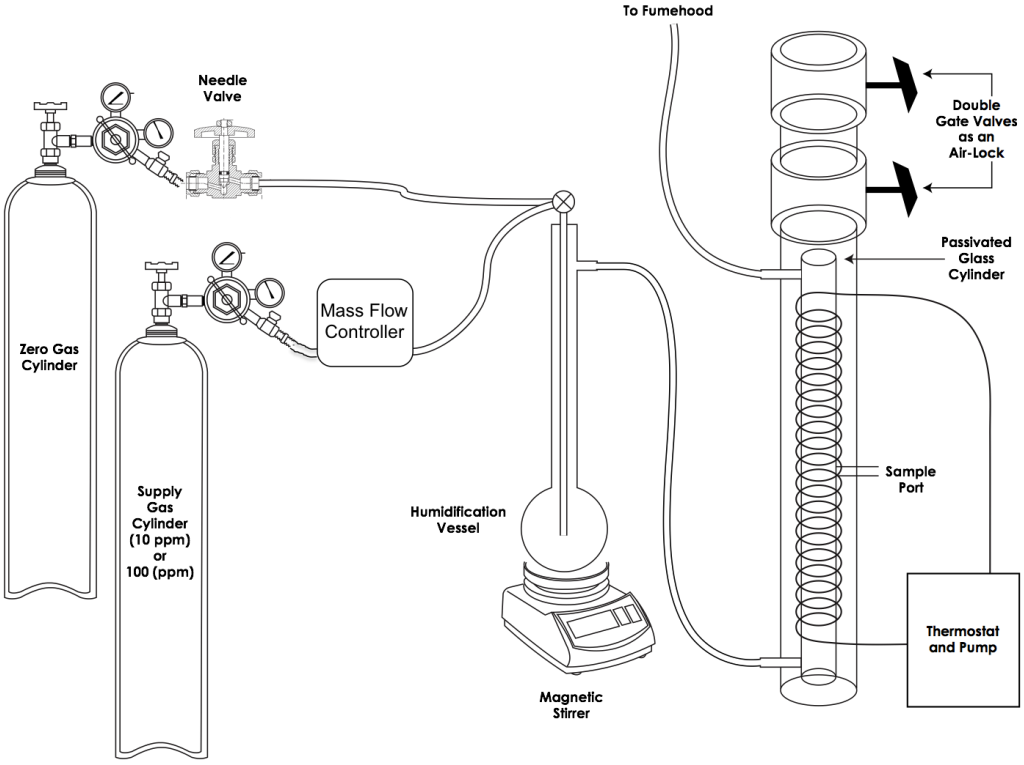


Figure 13: Schematic diagram of high concentration laboratory experimental apparatus



Figure 14: Photograph of high concentration laboratory experimental apparatus, showing (left to right: nitrogen cylinder, cylinders with VOC mix, mass flow controller, humidification vessels, temperature bath (on left) and the exposure chamber (on right))

Stainless steel and nylon tubing were used to deliver the supply gas to the exposure chamber, with compression fitting used at all connections. All fittings were leak-tested by connecting the apparatus to a 100 mL/min flow of pure helium and monitoring all the fittings with a helium meter. Adjustments were made as necessary until there were no measurable helium leaks in the regions immediately outside of the fittings.

Three identical humidification vessels were used (one for each concentration) and the water in each vessel was spiked with a mixture containing each of the 10 neat liquid VOCs mixed in proportions such that after dissolving into the water in the humidification vessel, the water would be approximately in equilibrium with the supply gas according to Henry's Law (Table 6). Each humidification vessel contained about 1 L of distilled, deionized water and a Teflon-coated magnetic stir bar. The stir bars operated continuously and the supply gas was delivered to the bottom of the humidification vessel through 1/4-inch glass tubing with a porous ceramic cup at the bottom to generate a large number of small gas bubbles. This apparatus consistently delivered steady source vapor concentrations with a relative humidity of about 80%.

All three supply-gas systems were set up simultaneously (Figure 13 shows only one for simplicity) and allowed to run continuously for a week at about 100 mL/min. The supply gas was monitored periodically with a MiniRae 1000 photoionization detector (PID) and sampled using an active (pumped) ATD tube filled with Anasorb 747 which was analyzed by solvent extraction GC/MS to document the attainment of stable conditions prior to the experiments. The temperature and relative humidity were monitored using a RHTemp101A datalogger by Madge Tech of Warner, NH.

Table 6: Volumes of pure compounds added to the humidification vessel for the 100 ppm_v test

Compound	Molecular Weight	Gas Phase Concentration corresponding to 100 ppmv in µg/L	Henry's Constant at 22 °C	Aqueous Concentration (µg/L)	Density of pure liquid (g/mL)	Volume (µL) to dose 1000 mL of water
111TCA	133.41	557	0.65	857	1.320	0.649
124TMB	120.2	502	0.2	2508	0.876	2.86
12DCA	98.96	413	0.059	7001	1.253	5.59
MEK	72.11	301	0.004	75244	0.805	93.5
BENZ	78.11	326	0.2	1630	0.877	1.86
CTET	153.8	642	0.99	648	1.587	0.409
NAPH	128.2	54 (for 10 ppm)	0.018	2973	1.140	2.61
NHEX	86.18	360	50	7	0.655	0.011
PCE	165.8	692	0.65	1065	1.622	0.656
TCE	131.4	548	0.39	1406	1.460	0.963

Testing was performed starting with the concentrations at 1 ppm_v, followed by 10 ppm_v and 100 ppm_v to reduce potential effects of carryover from one test to the next. At least 60 hrs were allowed for the chamber to equilibrate with each new concentration. At a flow rate of 100

mL/min, more than 700 times the volume of the test chamber passed through the chamber prior to sampling. The sample port at the mid-point of the column was periodically monitored using a MiniRAE 2000 PID to assess the stability of total ionizable vapor concentrations inside the test chamber. Sampling during the stabilization period prior to exposing the passive samplers was performed via pumped ATD tubes (50 mL/min for 20 min) and solvent extraction GC/MS analysis, which showed NAPH was slower to equilibrate than the other compounds, presumably because of its tendency to adsorb even to relatively inert surfaces.

For the 1 ppm_v test, each of the five passive samplers and the 1 L Summa canister samples were collected over 30 minutes in random order until three replicates of each sampler type were completed. For the 10 ppm_v and 100 ppm_v tests, additional Summa canister samples were collected at the beginning and end for a total of five active samples (denoted "a" through "e"). For the 1 and 10 ppmv tests, samples were deployed for 30 minutes with no lag between them. PID measurements made after the 10 ppm_v tests indicated that some of the samplers may have sufficient uptake to influence the concentrations inside the chamber (e.g., 10% lower PID readings after the sample period compared to before for the samplers with higher uptake rates), so a 5 minute interval was allowed for re-equilibration between samples during the 100 ppm_v tests (roughly enough time to flush the chamber once at 100 mL/min). The difference is discussed further in the results section.

Analyses were performed by the laboratories considered by the study team to be most familiar with the respective samplers: Fondazione Salvatore Maugeri in Padova, Italy analyzed the Radiello samplers, the University of Waterloo analyzed the WMS samplers, AirZone One Ltd of Mississauga, Ontario analyzed the OVM 3500, Columbia Analytical Services of Simi Valley, CA analyzed the SKC Ultra samplers and the Summa canister samples using EPA Method TO-15 (USEPA, 1999), and Air Toxics Ltd. of Folsom, CA analyzed the ATD tube samplers. The Radiello, WMS, OVM and SKC samplers with charcoal were desorbed with carbon disulfide, and the ATD tube samplers and SKC samplers with Carbograph 5 were desorbed thermally. All samples, including the Summa canisters, were analyzed by GC/MS.

5.5 Indoor and Outdoor Air Field Sampling

All indoor and outdoor air samples at each location were collected in reasonably close proximity (i.e., within a few feet, but not so close as to impose interference between them) and about three to five feet above the floor surface (approximately the breathing zone), as shown in Figure 15. The passive samplers were placed on shelves or hung and secured using thin gauge wire, then deployed according to the instructions provided in Appendix C. Summa canisters were placed in close proximity to the passive samplers and operated according to the protocol in Appendix C. The indoor air samples were located in areas that would not be disruptive to building operations and within different sized areas (e.g., enclosed rooms vs. warehouse areas) that would have different building air circulation rates. The outdoor air samples were located in areas that provided some protection from precipitation, high winds, and direct sunlight.

At the Navy OTC3 site, the indoor air samples were collected in three locations (2 in the open warehouse area and one in an interior office) with the four different types of passive samplers

(the OVM 3500 was not included at this stage), each in triplicate at each location. The office was a small room with low (8 foot) ceilings. The warehouse area was chosen for two of the sampling locations because it was a large open area, in contrast to the interior office. Outdoor air samples were collected in triplicate in one location adjacent to the warehouse in an area that provided some protection from precipitation, high winds, and direct sunlight. Samplers were deployed on 9 March 2010 and retrieved on 15 March 2010. The active indoor and outdoor air samples at OTC3 were collected over 6 days using a 3-day flow controller by connecting two 6 L Summa canisters via a stainless steel "T-fitting" provided by the laboratory, which allowed for the continuous collection of a sample over a 6-day period. One Summa canister was individually certified and one canister was batch certified. Only the individual certified Summ canisters were analyzed; the other canister was needed to provide sufficient volume to allow the manifolded pair of canisters to continue drawing gas for 6 days.



Figure 15: Typical layout of indoor air sampling array

At CRREL, indoor air samples were collected in three locations, with five sampler types and 3 replicates in each location (similar to the scope at Navy OTC3, but with the addition of the OVM 3500). One outdoor air location was also tested with each of five sampler types in 3

replicates. Indoor air concentrations at CRREL were expected to be high enough to be detectable with a 3-day deployment of the passive samplers (November 8 to 11, 2010). Outdoor air samples were collected using the 3-day flow controllers and paired Summa canisters (November 9 to 15, 2010), as described for OTC3. Unfortunately, the flow controllers shipped to CRREL allowed a faster flow rate than intended. Additional Summa canisters were acquired on short notice from TestAmerica (Burlington, VT). For the indoor air samples, a total of 23 Summa canisters were used to provide continuous monitoring in triplicate in each of the 3 locations. For the outdoor air samples, two of the paired Summa canister samples were deployed on the first day of the sample period and the third paired set of canisters was deployed on the fourth day in order to obtain outdoor air quality data over the 6 day sampling period (duplicate samples for the first 3 days and a single sample for the next three days). Time-weighted averages of the Summa canister concentrations were then calculated and used as the active control for indoor and outdoor air quality.

At MCAS Cherry Point, indoor air samples were collected in 3 locations with 5 passive sampler types in triplicate in each location. Outdoor air samples were collected in one location with each of five passive sampler types. Outdoor air samples were collected with only one replicate because the results at OTC3 and CRREL were mostly below the limit of detection, and it was not considered a prudent expenditure to continue sampling in triplicate. At MCAS Cherry Point, indoor air samplers were deployed in the break room, warehouse area, and autoclave room. The break room is a small room with low (8 foot) ceilings. The warehouse area was chosen as a sampling location because it is immediately outside the break room and, in contrast to the break room, is a large open area. The autoclave room was chosen as another sampling location because it is a moderately sized space, and is distant from the other two sampling locations. The chosen outdoor air location was beside a one-story shed located immediately outside Building 137. Samplers were deployed on 6 January 2011 and retrieved on 13 January 2011. For the active samplers at MCAS CP, 7-day flow controllers provided by Columbia Analytical Services (CAS; Simi Valley, CA) were connected to individually certified 6 L Summa™ canisters. The 7-day flow controllers yielded somewhat inconsistent flow rates, so some of the Summa canister samples had a residual vacuum after 7 days and some did not, indicating some of the samples were shorter than 7 days by an unknown amount. The results of all Summa canister samples were very similar, so all were used as if they were representative of the 7-day average concentrations.

5.6 Passive Soil Vapor Sampling

Passive soil vapor sampling for VOCs has been conducted for at least two decades, but as recently as 2011, the practice has been considered unreliable for quantifying soil vapor concentrations (CalEPA/DTSC 2011; ASTM D7758). This research included derivation from first principles of the processes and mechanisms influencing the passive sampling process, and verification through field testing.

5.6.1 Conceptualization

Passive soil vapor sampling is usually performed by drilling a hole in the ground, removing soil, placing a passive sampler in the void-space created by drilling, sealing the hole from the atmosphere for the duration of the exposure, then retrieving the sampler and backfilling or grouting the hole. A simple conceptual model of this scenario is as follows:

- Immediately after the hole is drilled and the soil is removed, the void space fills with air. Assuming atmospheric air can enter the void space with less resistance than gas flowing through the surrounding soil, the initial concentration of vapors inside the void space would be expected to be much lower than that in the surrounding soil, and at worst could be assumed to be essentially zero (i.e., atmospheric air is nearly contaminant-free).

- In most cases, passive samplers are placed in the borehole and the space above the sampler is sealed without purging to remove atmospheric air from the void space around the sampler (purging is feasible during passive soil vapor sampling, but not common).

- During the period of exposure, vapors diffuse into the void space from the surrounding soil. If the void space is long relative to its diameter and short enough that the geologic properties and vapor concentrations are relatively uniform over the vertical interval of the void space, then the diffusion will be essentially radially symmetric.

- The rate of diffusive mass transport into the void space over time will depend on the concentration gradient and effective diffusion coefficient, and will gradually diminish as the concentration in the void space approaches equilibrium with the surrounding soil. If a passive sampler is present in the void space, the concentration in the void space may remain somewhat below the concentration in the surrounding soil depending on the uptake rate of the passive sampler and the rate of vapor diffusion from the soil into the void space (i.e., the diffusive delivery rate, or DDR).

- If the uptake rate of the sampler is small relative to the rate of diffusion into the void space (a goal if the starvation effect is to be small), then the steady-state concentration in the void space will be similar to the concentration in the surrounding soil and passive sampling will be able to provide a quantitative measure of the soil vapor concentration with minimal or negligible low bias attributable to the starvation effect.

5.6.2 Mathematical Modeling

Passive soil vapor sampling involves transport of vapors through the soil surrounding the drillhole into the void space in which the sampler is deployed, diffusion through the air inside the void space, and uptake by the sampler. The free-air diffusion coefficient through the air inside the void space will be roughly one to several orders of magnitude higher than the effective diffusion coefficient in the surrounding soil, so vapor transport through the air inside the void space is not expected to be the rate-limiting step. This allows the mathematical

analysis to focus on two components: the rate of vapor diffusion into the void space (the "diffusive delivery rate", or DDR) and the rate of vapor uptake by the passive sampler ("passive sampler uptake rate" or UR). Understanding the rate of diffusion of vapors into the void space is necessary to design an uptake rate for the passive sampler that is low enough to minimize the starvation effect. However, the uptake rate must also be high enough to provide adequate sensitivity (ability to meet target reporting limits with acceptable sample durations).

Two models (transient and steady-state) were used to simulate the passive sampling process, described in the subsections below (see also McAlary et al., 2014a).

Influence of Soil Moisture on the Effective Diffusion Coefficient of VOCs in Soil

The effective diffusion coefficient (D_{eff}) for VOCs in unsaturated porous media was described by Johnson and Ettinger (1991) in their well-known model for assessing the potential for subsurface vapor intrusion to indoor air. Their formulation includes terms for diffusion in both the gas and aqueous phases, assuming the Millington-Quirk (1961) empirical relationship is equally valid for both phases:

$$D_{eff} = D_{air} \frac{\theta_a^{10/3}}{\theta_T^2} + \frac{D_w}{H} \frac{\theta_w^{10/3}}{\theta_T^2} \qquad (2)$$

where the parameters are defined in Table 7. Parameter values used for all calculations in this report were selected to be representative of trichloroethene (TCE), one of the most common VOCs of interest for human health risk assessment associated with contaminated land. Equation (2) was used to calculate D_{eff} for both the transient and steady-state models in this study.

Table 7: Parameter values used in model simulations (representative for TCE)

Parameter name	Symbol	Units	Value
Free air diffusion coefficient	D_{air}	cm^2/s	0.069
Aqueous diffusion coefficient	D_w	cm^2/s	0.00001
Henry's Law Constant	H	µg/L air / µg/L water	0.35
Total porosity	θ_T	Volume of voids / total volume of soil	0.375
Water-filled porosity	θ_w	Volume of water / total volume of soil	0.01 to 0.36
Air-filled porosity	θ_a	$\theta_T - \theta_w$	0.365 to 0.015

D_{eff} depends strongly on the total porosity and water-filled porosity and understanding this relationship is helpful for context in the theory of passive soil gas sampling if diffusion is the main process delivering vapors to the void space in which the sampler is deployed. A series of calculations were performed using Equation (2) and the parameter values in Table 7 to show the relationship between the effective diffusion coefficient and the water-filled porosity. The calculated D_{eff} values span a range from about 0.01 to about 0.00001 cm^2/s over a range of water-filled porosities from 1% to 36% in a soil with 37.5% porosity (Figure 16).

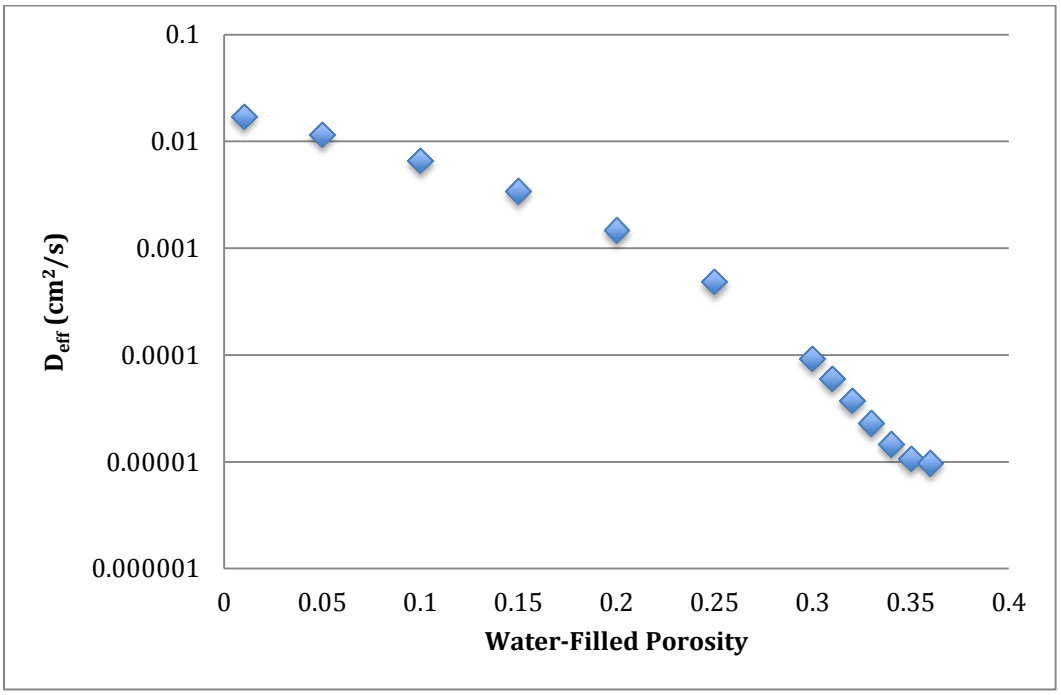


Figure 16: Effective diffusion coefficient versus water-filled porosity for TCE in a soil with 37.5% total porosity, typical of a sandy soil.

The D_{eff} values are indeed much lower than the free-air diffusion coefficient (0.069 cm^2/s), which supports the assumption that diffusion through the void space in which the sampler is deployed is not rate-limiting. Other VOCs have similar diffusion coefficients (see Table 1), so the general trend applies for most VOCs of interest for human health risk assessments.

Transient Model

The conceptualization for a transient mathematical model of radial diffusion of vapors from soil into the void space is shown in Figure 17. The concentrations of VOC vapors in the soil surrounding the void space where the passive sampler is deployed is assumed to be constant (C_s0) from radius r_2 (the radius of the borehole wall) to r_3 (a radius far enough away from the borehole to be unaffected by mass lost to the void space throughout the sampling period) before the borehole is drilled. For simplicity, the transient model simulates an empty void space from r_1 to r_2 (i.e, no passive sampler). This is a reasonable approximation because a passive sampler with an uptake rate low enough to minimize the starvation effect would only start to influence the concentration gradient (and therefore, the diffusive flux) as the concentration inside the void space approached steady-state (i.e., equal to the concentration in the soil). The transient model also assumes the vertical interval of the void space is small enough such that both the soil vapor concentrations and the geologic material are essentially uniform over that interval. After drilling or soil coring, the concentration inside the void space goes to zero, which creates a steep concentration gradient (see line marked t_1 in Figure 17). Over time, the concentration inside the void space increases (see lines marked t_2 and t_3) and converges to C_s0 at steady-state. The derivation of the transient model is provided in Appendix D.

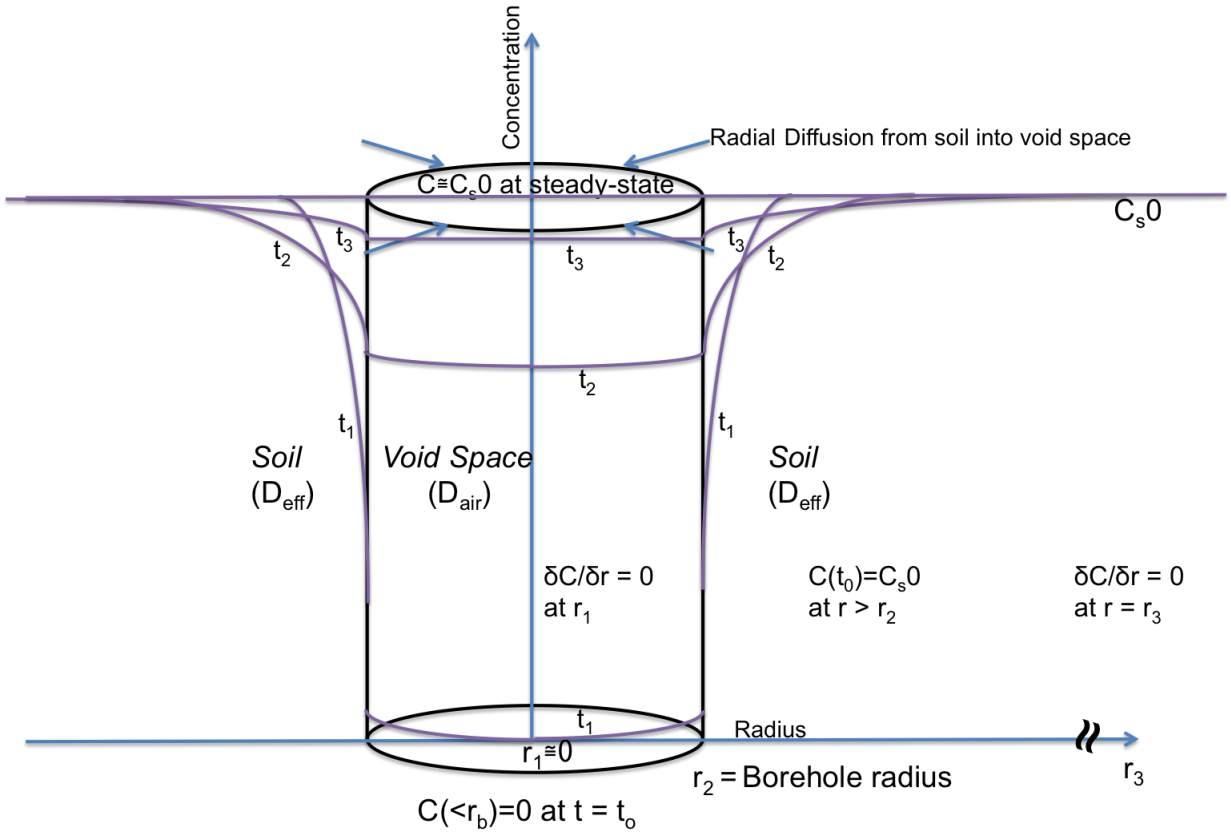


Figure 17: Schematic of transient mathematical model domain for radial diffusion of vapors from soil into a void space

Steady-State Model

If the duration of passive sampling is long compared to the time required for the vapor concentrations in the void space to approach equilibrium with the surrounding soils, then a steady-state model would also provide insight into the passive sampling mechanisms. For this case, the conceptual model is as follows:

- The vapor concentration in the soil gas surrounding the void space (C_{sg}) is uniform beyond the wall of the borehole (i.e., beyond a radial distance of r_2) prior to drilling of borehole and installation of a passive sampler,

- Diffusion occurs in the region between the outer wall of the drillhole (radius = r_2) and a radial distance beyond which vapor concentrations remain unaffected (r_3), through a cylinder of height (h),

- The concentration inside the void space of the borehole (C_{bh}) is lower than C_{sg} by a factor $\delta = C_{bh}/C_{sg}$ (this value should be close to 1.0 in order for the sampler to be exposed to vapor concentrations similar to the surrounding soil),

- Radial diffusion occurs from the soil to the void space at a diffusive delivery rate equal to the passive sampler uptake rate for the majority of the sample deployment intervals (i.e., at steady-state, mass is removed from the void-space by the sampler at a certain rate, which creates a concentration gradient sufficient to drive diffusive transport through the soil toward the void space at essentially the same rate to balance the rate of mass removal by the sampler and sustain a concentration inside the void-space that is very similar to the concentration in the surrounding soil).

The rate of mass transfer of vapors into the borehole via vapor diffusion through the surrounding soil (M1) is given by Carslaw and Jaeger (1959):

$$M1 = \frac{2\pi D_{eff}(C_{sg} - C_{bh})}{\ln(\frac{r_3}{r_2})} \qquad (3)$$

The rate of mass uptake by the sampler (M2) is given by:

$$M2 = C_{bh}\ x\ UR \qquad (4)$$

Setting M1 = M2 gives:

$$UR\left[\frac{mL}{min}\right] = \frac{2\pi h[cm] D_{eff}[\frac{cm^2}{s}](1-\delta)}{\ln(\frac{r_3}{r_2})\delta}\ x\ 60[s/min] \qquad (5)$$

Modeling results are presented in Section 6.7.1.

5.6.3 Passive Sub-Slab and Soil Gas Field Sampling

Navy OTC: passive sub-slab samples were collected in two locations with five passive devices and one active sample (Summa canister with analysis by EPA Method TO-15) in each location. Both locations were outside of a building where a concrete slab was accessible for drilling and coring. Initial screening with a photoionization detector showed total ionizable vapor concentrations of about 0.1 part per million by volume (ppm_v) at location SS-5 and 10 ppm_v at location SS-2. The primary contaminant of concern (COC) was trichloroethene (TCE). Sampler deployment durations were 2 hr at location SS-2 and 15 hr at location SS-5 (longer deployment was required to collect detectable mass of VOCs in the area of lower concentrations). All five passive samplers were used for sub-slab sampling with a configuration (uptake rate and adsorbent) described in Table 2. Samplers were placed in holes drilled or cored (depending on the diameter needed to accommodate the sampler) through the concrete, located in a circle of about 1 m diameter (Figure 18) with the Summa canister sample collected in the center of the circle. Immediately prior to deployment of each passive sampler, soil gas was purged to remove any atmospheric air that may have entered the hole during drilling using a Tedlar bag and vacuum chamber (Figure 19).



Figure 18: Sub-slab probe array (OTC3)



Figure 19: Vacuum chamber used to purge subslab probes prior to passive sampler deployment

The purged gas was monitored for total ionizable vapor concentrations with a Phocheck+™ photoionization detector (PID) from Ionscience of Cambridge, UK, which was field-calibrated

following the manufacturer's instructions. PID readings stabilized (no apparent increasing or decreasing trend) with a total purge volume of about 1 or 2L. Two liters of gas is equivalent to the volume of gas in a 15 cm thick granular fill layer with a 30% gas-filled porosity within a radial distance of about 12 cm from the hole drilled to accommodate the passive sampler, so the purging and sampling was not expected to cause any interaction between sampling locations, which were about 50 cm apart. The passive samplers were fitted with stainless steel wire to prevent contact with soil at the bottom of the cored hole and to create a tether for retrieval and the hole was sealed using a rubber stopper wrapped in aluminum foil and hammered into the concrete with a heavy mallet to provide a flexible and inert plug (Figure 20).



Figure 20: Deployment of a passive ATD tube sample

Layton House: six passive soil gas monitoring probes were installed to a depth of about 3.6 m (12 ft) in a circular pattern with a radius of about 1 m using a 10-cm (4-in) diameter hand-auger. Each probe was constructed of 3 m (10 ft) length of 5 cm (2-in) diameter Schedule 40 PVC pipe, with stilts at the bottom to suspend the pipe 0.6 m (2 ft) above the bottom of the borehole. A gasket wrapped in aluminum foil isolated the region above the void space, and the annulus between the PVC pipe and borehole wall above the gasket was filled with a hydrated bentonite slurry (Figures 21 and 22). The soil consisted of cohesive brown fine sandy silt with trace clay, with moisture content increasing as the depth approached the water table (~4 m depth). The primary COCs were TCE and 1,1-dichloroethene (11DCE) at concentrations of a few hundred µg/m^3. The passive sampler deployment durations ranged from 1 to 11.7 days, with each of six sampler types deployed once in each probe, plus one repeat of the first set of samples (a Latin Square design). Active samples were collected from each probe after purging at least 6 L (one probe volume) using a vacuum chamber and Tedlar bag at the start of each new deployment period and at the end of the last sample event. The reference concentration was take as the average between the concentrations at the start and end of each passive sampler deployment. Field screening was performed using a field-calibrated Phocheck+™ PID to verify steady readings prior to active sample collection. Most of the active samples were analyzed with a Hapsite™ transportable GC/MS (Inficon) via a Tedlar bag and vacuum chamber, and two rounds of active samples were collected in Summa canisters and analyzed by EPA Method TO-15.

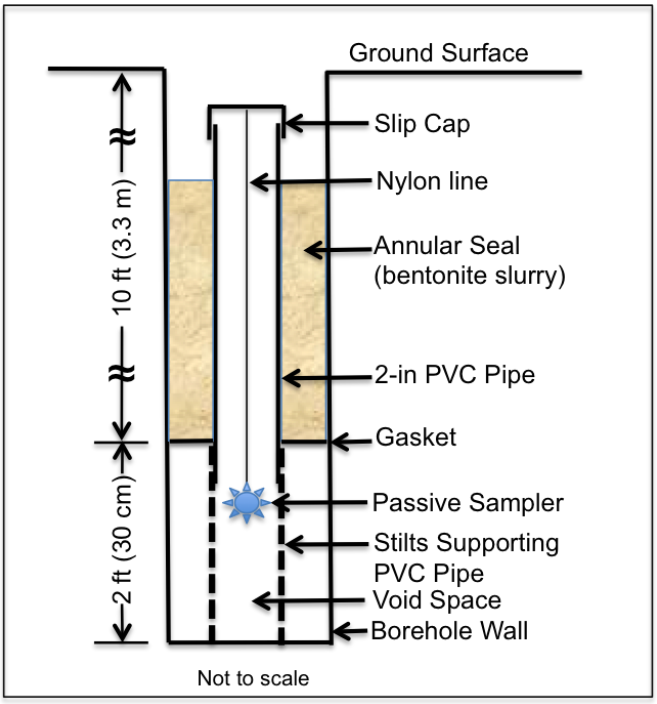


Figure 21: Schematic diagram of the passive soil vapor probe at the Layton house, Utah



Figure 22: Photograph of passive soil vapor probe before installation

The passive samplers used at the Layton House were customized as follows:

- A 12-hole cap was used with the SKC Ultra Sampler to reduce the uptake rate and minimize the starvation effect; charcoal was the sorbent.
- The ATD Tube sampler was used with two different sorbents (Carbopack B and Tenax TA) to assess their relative performance.
- The WMS sampler was also used in two configurations, the regular variety (1.8 mL vial) and an early prototype ultra-low uptake variety for which the membrane was covered with an aluminum shield with a $1/16^{th}$-in diameter hole drilled in it. Results for the ultra-low uptake rate variety were below limits of detection for most analytes, so the data are not presented.

NAS JAX: Three types of samples were collected at NAS JAX: 1) sub-slab samples inside a single-story, slab-on-grade office building, 2) exterior soil gas samples in cased probes similar to those used at the Layton House and, 3) exterior soil gas samples in an uncased hole. The water table was about 1.5 m (5 ft) below ground surface and the vadose zone consisted of a relatively uniform, cohesionless, medium-textured sand. The primary COCs were tetrachloroethene (PCE), TCE, cis-1,2-dichloroethene (cDCE) and trans-1,2-dichloroethene (tDCE).

Exterior passive soil gas samples were collected using three probes, each consisting of 5 cm (2-in) diameter PVC pipe in 10 cm (4-in) diameter hand-augered holes (Figures 23 and 24), spaced about 1 m apart (see Figure 9). The three probes were constructed with void space lengths of about 15, 30 and 45 cm (6, 12 and 18-in) to assess whether the void volume affected the results. The samplers were deployed for 20, 40 and 60 minutes to assess whether the deployment duration affected the results. Each of the 5 passive sampler types (see Table 2) were deployed a total of seven times (short and long durations in each of the large and small void volume probes) and three replicates at the center-points of these factors (40 minutes in the probe with the 30 cm tall void). A total of 35 Summa canister samples were collected for analysis by EPA Method TO-15 (1:1 ratio of passive:Summa samples). This experimental design is a randomized 2-factor, one-half fraction, fractional factorial with triplicates at the center-points, similar to the experimental design used for the low concentration laboratory tests, except with two factors instead of five.

The annular seal was constructed by placing fine sand into the annulus between the 2-in PVC well pipe and the 13 cm (5-in) diameter flexible polyethylene sleeve shown in Figures 24 and tamping the sand with a wooden dowel to cause the plastic sleeve to expand out to the wall of the 10-cm (4-in) diameter borehole. After placing the seal, each probe was purged until PID readings stabilized, then left capped overnight to equilibrate.

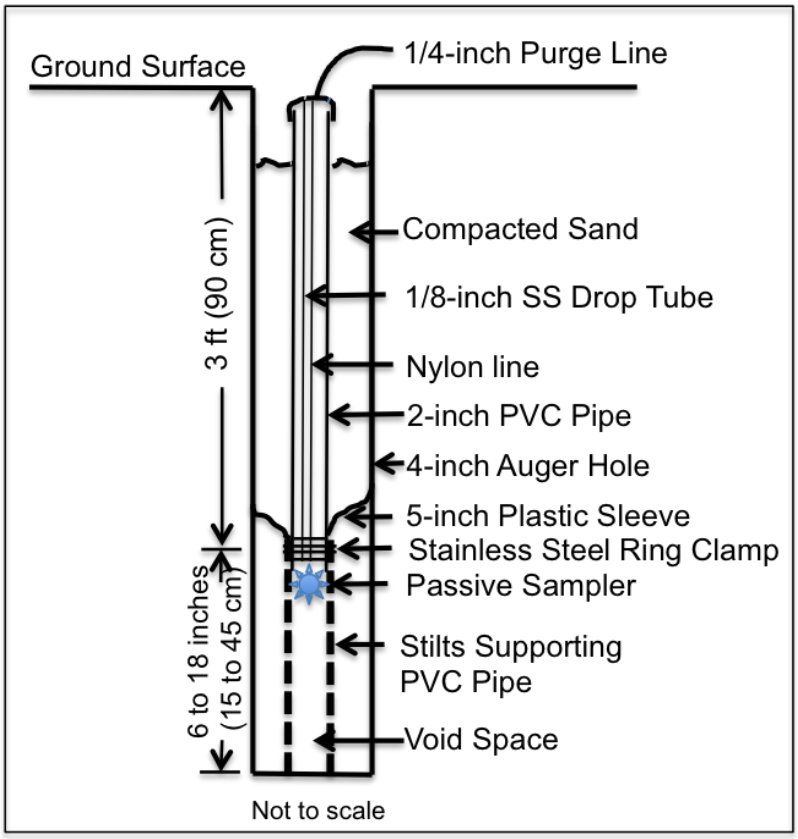


Figure 23: Schematic diagram of the passive soil vapor sampling probes at NAS JAX



Figure 24: Photos of the passive soil vapor probe and hand auger used at NAS JAX



Figure 25: Cap of passive soil gas probe at NAS JAX

Passive soil gas samplers were suspended by nylon lines attached to the bottom of the slip cap and cut to a length just longer than the PVC pipe, so that the samplers were suspended in the open region below the pipe during sampling. Immediately after the passive samplers were deployed and the slip-caps secured, purging was conducted through a 1/4-in compression fitting in the top of the slip-cap (Figure 25) that extended to just below the cap, so the entire column of gas in the probe would be removed during purging. Field screening readings were made by continuously purging each probe and monitoring the effluent with a field-calibrated ppbRAE™ PID by RAE Systems of San Jose, CA. PID readings were consistently within the range of 1.0 to 1.5 ppm_v for all three probes, and generally stabilized within about 20 to 30 seconds. Purge rates were about 3 L/min, so the purge volume was typically about 1 to 1.5 liters, which corresponded to about 1 casing volume for the probe pipe (not including the void space region below the pipe).

Low-uptake varieties of the Radiello sampler (yellow body), SKC Ultra Sampler (12-hole cap) and WMS sampler (WMS-LU - 0.8 mL vial) were used to minimize the starvation effect. The ATD tube sampler already has a relatively low uptake rate and was not modified with a low-uptake cap to avoid having results below the limit of detection. The 3M OVM 3500 does not have a low-uptake variety. Sorbents used for each type of passive sampler are listed on Table 2.

A 1-L Summa canister sample was collected immediately after purging via a 1/8-in stainless steel drop-tube (see Figures 23 and 25) that extended through a compression-fitting in the slip cap to a depth just below the bottom of the PVC pipe (i.e., top of the void space), such that the canister sample was collected from the void space below the PVC pipe. The canister was filled quickly (over about 10 seconds) so that the passive sampler would not be biased by advection

from the active sample collection during most of the passive sampling period. The void volume was about 1L for the 15 cm tall void, 2L for the 30 cm tall void and 3 L for the 45 cm tall void, so the Summa canister sample requirements were met by replenishing 1 to 0.3 times the volume in the void-space, which is expected to have occurred within a few seconds with minimal applied vacuum because the sandy soil was very permeable and posed little resistance to flow. Furthermore, the soil vapor concentrations were consistent throughout the testing period and for all three probes, so the advective sampling was not expected to alter either the pressure or VOC concentrations.

Sub-slab vapor samples were collected from one hole at each of three locations. It was not possible to drill 5 cm diameter holes through the floor (needed to accommodate the 3M OVM and SKC samplers) because steel reinforcing bars were repeatedly encountered and eventually broke the teeth on the concrete hole-saw. The ATD, WMS and Radiello passive samplers were tested through a 1-inch diameter hammer-drill hole in the floor slab. In each of the three locations, one sample was collected with each type of passive sampler (1 h duration) and one Summa canister. Immediately after passive sampler deployment, the hole was purged to remove any atmospheric air entrained during drilling or removal of the prior passive sampler using a lung-box and a 1-L Tedlar bag, which was screened with a field-calibrated ppbRAE® PID by RAE systems, Inc. of San Jose, CA to measure the total VOC vapor concentration. At least two successive purge measurements of 0.5 to 1L each were made to assure stable PID readings, after which the hole was capped using a foil-covered rubber stopper. The passive samplers were surrounded by a stainless steel wire or mesh cage to protect them from direct contact with soil (Figure 26). The low-uptake rate cap was used for the ATD tube in the sub-slab samples. The WMS and Radiello samplers were the same low-uptake rate configurations used for the external soil gas sampling.



Figure 26: Radiello, WMS and ATD Samplers wrapped to protect them from contact with soil



Figure 27: Installation of temporary passive soil vapor probe using hammer-drill and 1-inch diameter, 5-ft long drill bit at NAS JAX.

Temporary passive soil gas samples were also collected at NAS JAX in location TH-3 (see Figure 9), which was an uncased hole drilled to a depth of 1.6 m (5 ft) with a 2.54-cm (1-in) diameter hammer-drill bit (see Figure 27). No PVC pipe was installed in the temporary drilled hole and the sandy soil was sufficiently cohesive to stand open without caving. The low-uptake WMS sampler was deployed for six different sample durations ranging from 1.7 to 18.9 hours (randomized). The hole was sealed during the deployment period using a polyurethane foam plug inside a polyethylene bag of 1-in diameter, which was set to a depth of 1.2 m (4 ft) below ground. The location of the temporary probe was only a few feet from the exterior passive soil gas probes, so the Summa canister data from the nearest exterior passive soil gas probe was used as a baseline for comparison. The field-sampling study is published as McAlary et al., 2014c.

5.7 Flow-Through Cell Sampling

A series of experiments were performed to evaluate the use of quantitative passive samplers for monitoring VOC vapor concentrations in soil gas using a flow-through cell (McAlary et al., 2014d). This is similar in some ways to conventional active sampling using adsorptive tubes; however, with active tube sampling, the flow rate must be precisely measured and controlled to calculate the total volume of gas sampled, which can be challenging because the permeability of subsurface materials can affect the flow rate and the permeability of geologic material can vary over a range of several orders of magnitude. Using passive samplers in a flow-through cell, the flow rate does not need to be known exactly, as long as it is sufficient to purge the cell in a reasonable time and minimize any low bias attributable to the starvation effect. Furthermore, this technique can be used with soil gas or sub slab probes that are too small in diameter to accommodate a passive sampler in the subsurface.

The flow-through cell experiments were conducted at CRREL on November 10 and 11, 2010. Sub-slab soil vapor samples collected in March and June of 2010 at sub-slab probe LB-01 (located just inside the main laboratory building near the former ice well) showed TCE concentrations on the order of 100,000 µg/m^3. At this concentration, the passive samplers are able to provide detectable results with sample durations of a minute or less. In practice, it takes about 10 to 15 seconds to deploy a passive sampler and retrieve it from the flow-through cell, so the minimum sample duration was set to be 10 minutes to minimize the error in the duration of sampler deployment and retrieval relative to the sample duration. The maximum sample duration was set to be 20 minutes in order to avoid saturating the sorbent and exceeding the linear range of the laboratory analytical instruments. The mid-point sample duration was 15 minutes, half-way between the high and low levels for this factor.

The flow rates for the tests were designed to be sufficient to minimize the starvation effect (i.e., the lowest flow rate was greater than the highest uptake rate of any of the samplers). Flow controllers are adjustable, but the adjustments are quite sensitive, so the actual flow rates were somewhat different than the design flow rates. The goal was to have a low flow rate of 100 mL/min, but the flow meter was actually calibrated to about 80 mL/min. The high flow rate was designed to be 1 L/min, which was fast enough to purge the volume of the flow-through cell in about 30 seconds. This was expected to minimize the period of time during which the passive sampler was exposed to an appreciable percentage of indoor air entrained in the flow-through cell during placement of the passive sampler. The actual high flow rate achieved was 930 mL/min. The mid-point flow rate was designed to be exactly half-way between the high and low flow rates (about 550 mL/min), but was actually 670 mL/min. The cross-sectional area of the cell was about 20 cm^2, so these flow rates correspond to average linear flow velocities of 4, 34 and 47 cm/min. The effect of the flow rate and sample duration in the cell was tested in a randomized one-half fraction fractional factorial design with triplicates at the center-points. Table 8 list the five passive samplers used in the flow-through cell test, the sorbent medium used, the lowest reportable mass (in units of ng) and the TCE uptake rates.

Table 8: Summary of passive samplers used for flow-through cell testing

Passive Sampler	ATD Tube	Radiello	3M OVM	WMS	SKC
Type	Regular uptake	white body	3500	1.8 mL Vial	Ultra
Sorbent	Carbopack B	Charcoal	Charcoal	Anasorb 747	Carbograph 5 or Charcoal
TCE Uptake Rate (mL/min)	0.5	69	31	3.3	15
Reporting Limit (ng)	2.7	50	75	50	1000 (charcoal) 50 (Carbograph 5)

The flow-through cell was constructed of transparent acrylic pipe of sufficient length and diameter to fit all of the passive sampler types. The 3M OVM 3500 was the largest passive sampler and mandated a 2-inch diameter of the flow-through cell. The top and bottom of the cell consisted of 2-inch diameter stainless steel threaded caps with compression fittings, which were connected to new ¼-inch Nylaflow™ tubing from sub-slab probe LB-01. Soil gas was drawn through the apparatus using a Gast 1H piston pump downstream of the flow-through cell (Figure 28). Three flow controllers were assembled in series through a header of stainless steel with compression-fit stainless steel ball-valves to allow simple and rapid changes between high, medium and low flow rates.

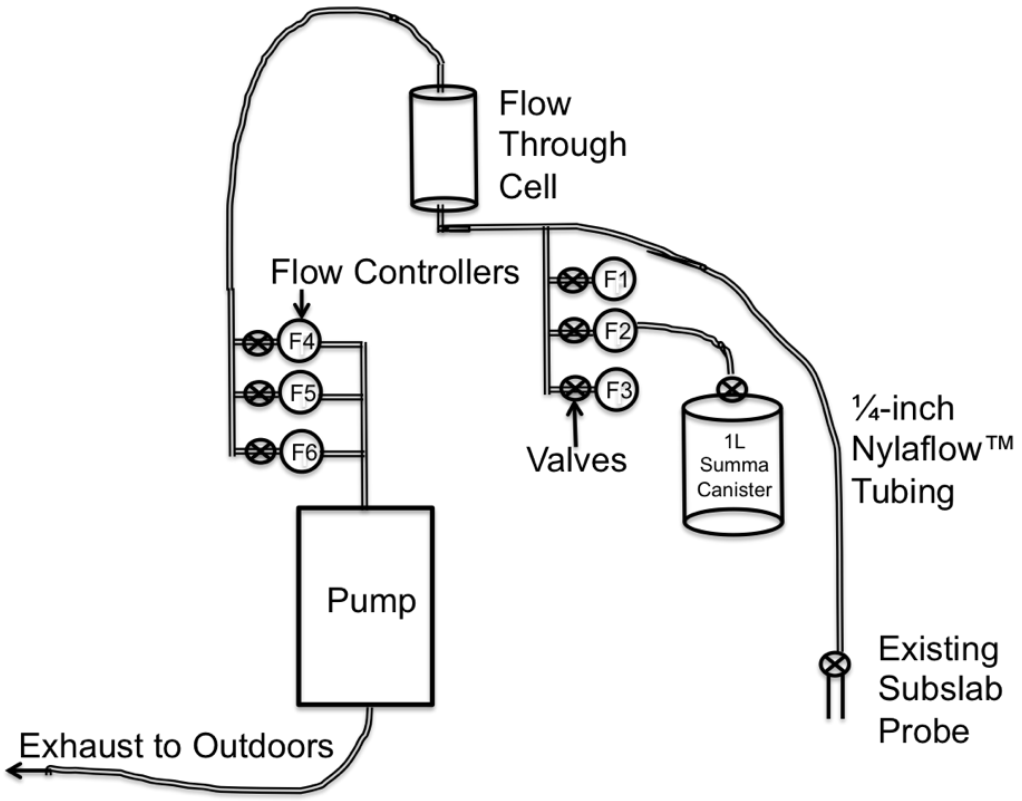


Figure 28: Flow-through cell test apparatus

The sampling procedure consisted of placing one passive sampler in the cell, closing the cell as quickly as possible, drawing sub-slab gas through the cell at the allotted flow rate for the allotted sample duration and removing the passive sampler and replacing with the next sampler to be tested as quickly as possible to minimize the exchange of indoor air with the soil gas in the flow-through cell. Each of the passive samplers was deployed seven times: at all four combinations of high and low levels of sample duration and flow rate, as well as three replicates of the mid-points of the flow rate and sample duration. The order of deployment (sampler type, sample duration and flow rate) was randomized. The flow rate was controlled by drawing gas through one of three flow controllers (F4, F5 and F6 in Figure 28). The duration was monitored using a stopwatch.

Summa canister samples were collected from a "T-fitting" between the sub-slab probe and the flow-through cell using one of three flow controllers (F1, F2 or F3 in Figure 28) designed to fill the 1 L canister over the duration of each particular sample (10, 15 or 20 minutes). One Summa canister sample was collected to coincide exactly with each passive sample (35 canisters in total). One Summa canister showed a notably low concentration (12,000 $\mu g/m^3$), which was considered likely to have had an un-noticed leak at one of the fittings and one Summa canister valve was inadvertently left closed throughout the sample period. In these two instances, the Summa canister concentrations used for calculating relative concentrations (passive/Summa) were the average TCE concentration from the two Summa canister samples collected in the preceding and following sample intervals.

The Summa canister samples were analyzed by USEPA Method TO-15 at Columbia Analytical Services (CAS) of Simi Valley, CA. The 3M OVM 3500 samplers were analyzed by CS_2 extraction and the ATD tubes by thermal desorption, each followed by gas chromatography and mass spectroscopy (GC/MS) and both by Air Toxics Limited of Folsom, CA. The WMS samplers were analyzed by CS_2 extraction and GC/MS at the University of Waterloo. The Radiello samplers were analyzed by CS_2 extraction and GC/MS at the Fondazione Salvatore Maurgeri in Padova, Italy. The SKC samplers were analyzed by CS_2 extraction (except for the low-flow rate and short duration sample, which was analyzed by thermal desorption to improve sensitivity), followed by GC/MS at CAS.

Field screening readings were performed to verify the sub-slab vapor concentrations prior to and periodically during the testing program using a MiniRAE™ 2000 photoionization detector (PID) by RAE Systems of San Jose, CA, which was calibrated daily on-site according to manufacturer's instructions.

5.8 Laboratory Analysis

Summa canister samples were analyzed by EPA Method TO-15 in full scan mode for sub-slab and soil gas samples and EPA Method TO-15 in selected ion monitoring (SIM) mode for all indoor and outdoor air samples. The passive samplers were analyzed by carbon disulfide extraction followed by GC/MS (solvent extraction samplers) or by EPA method TO-17 (thermal desorption samplers).

For the center-point testing, fractional factorial testing, and high concentration laboratory tests, all samples were analyzed by the laboratories considered most familiar with the sampler: FSM for Radiello, ATL for ATD tubes, UW for WMS, and CAS for SKC. For the field sampling activities, the laboratories that performed the analyses are summarized in Table 9.

The charcoal-based passive samplers were analyzed by adding 1 to 2 mL of low-benzene content carbon disulfide in a closed inert vial and allowing 30 minutes on a shaker. An aliquot of approximately 1 to 2 μL was injected via auto-injector into a GC/MS and the mass of analytes were determined using an internal standard calibration technique (Radiello) or external calibration (WMS). The thermally-desorbable sorbents were transferred (if needed) into an automatic thermal desorption (ATD) tube, and the tubes were placed in an auto-injection carousel for analysis by GC/MS using EPA Method TO-17.

One trip blank sample was collected and analyzed for each passive sampler type for each field site. The trip blanks were prepared and shipped with the investigative samples, but were not opened in the field. TCE was detected (23.4 ng) in the SKC blank for the NAS JAX event, while the SKC investigative samples all had values two times or less the value of the trip blank (these samples are discussed further in Section 6). Consequently, the investigative samples were corrected for the blank. All other trip blanks had no detectable or negligible concentrations of target analytes.

The samples were analyzed for the following site-specific target compounds at a minimum:

- **Hill** – TCE, PCE, 111TCA, 11DCE, 11DCA, 12DCA, cDCE, tDCE, VC, carbon tetrachloride, and chloroform.

- **CRREL** – TCE, benzene, toluene, ethylbenzene, mp-xylene, o-xylene, n-hexane, n-heptane, 2,2,4-trimethylpentane, 1,2,4-trimethylbenzene, methylethylketone, acetone, ethanol, methylene chloride and tetrahydrofuran in indoor and outdoor air and TCE in sub-slab samples.

- **OTC3** – TCE, PCE, cDCE, tDCE, 11DCE, and VC.

- **MCAS CP** - TCE, PCE, 111TCA, 112TCA, 11DCA, 11DCE, 12DCA, cDCE, tDCE, benzene, ethyl benzene, toluene, and xylenes; and

- **NAS Jacksonville** – PCE, TCE, cDCE and tDCE.

Table 9: Laboratories that analyzed the passive samplers in the field-testing program

Sampler	Uptake Rate	Sorbent	Laboratory Desorption Method	Navy OTC3, San Diego, CA			Hill AFB, Layton	CRREL, Hanover, NH			MCAS, Cherry Point, NC		NAS Jacksonville, FL		
				Indoor Air	Outdoor Air	Passive Sub Slab	Passive Soil Vapor	Indoor Air	Outdoor Air	Flow-Through Sub Slab	Indoor Air	Outdoor Air	Passive Soil Vapor	Temporary Soil Vapor	Passive Sub Slab
Summa Canister	na	na	TO-15	ATL	ATL	ATL	CAS	ATL & TA	ATL	CAS	ATL	ATL	CAS		CAS
3M OVM 3500™	Regular	Charcoal	Solvent	ATL	ATL	ATL		ATL	ATL	ATL	ATL	ATL	ATL		NS
ATD Tube	Regular	Chromosorb 106	Thermal	ATL	ATL	ATL									
		Tenax TA	Thermal				ATL								
		Carbopack B	Thermal				ATL	ATL	ATL	ATL	ATL	ATL	ATL		
	Low uptake rate	Carbopack B	Thermal												ATL
WMS™	Regular	Anasorb 747	Solvent	ATL	ATL	ATL	UW	UW		UW					
		Carbopack B	Thermal						UW		ATL	ATL			
	Low uptake rate	Anasorb 747	Solvent										ATL	ATL	ATL
SKC Ultra II™	Regular	Charcoal	Solvent					CAS		CAS					
		Chromosorb 106	Thermal	ATL	ATL	ATL									
		Carbopack X	Thermal												
		Carbograph 5	Thermal					CAS	CAS	CAS	ATL	ATL			
	Low uptake rate	Carbopack X	Thermal												
		Charcoal	Solvent				CAS								
		Carbograph 5	Thermal										CAS		NS
Radiello™	Regular	Charcoal	Solvent	ATL	ATL	ATL	FSM			FSM					
		Carbograph 4	Thermal					FSM	FSM						
	Low uptake rate	Carbograph 4	Thermal								ATL	ATL			
		Charcoal	Solvent										FSM		FSM

Notes:
ATL - Air Toxics Ltd, Folsom, CA
TA - TestAmerica, Burlington, VT
FSM - Fondazione Salvatore Maugeri, Padova, Italy
UW - University of Waterloo, Waterloo, Canada
CAS - Columbia Analytical Services, Simi Valley, CA

6 RESULTS

This section provides the results of the laboratory and field-testing activities. In comparisons between passive and active sample results, the duration used for the conventional samples did not necessarily correspond to the duration used for the passive samples. For example, in the controlled laboratory chamber tests active samples were collected as a series of samples; however, the data showed that concentrations were held essentially constant, so the relative concentrations were calculated using average values from the active samples. In the field testing phase, natural variability in vapor concentrations was expected, so the Summa canister samples were deployed over a comparable interval, or sequential Summa canister samples were collected and the passive sampler results were compared to the time-weighted average of the Summa canister data. Some of the active soil vapor samples at the Layton house were analyzed on-site using a Hapsite transportable GC/MS as a supplement to Summa canisters sampling in order to provide real-time data with which to verify that the sample durations would be sufficient to achieve detectable results.

6.1 Familiarity Test Results

During familiarity testing, relative humidity values ranged from about 68 to 54% with a target value of 60%, which is roughly 10% variation from the set-point of 60% RH. Temperature values ranged from about 22.8^{o}C to about 19.2^{o}C, which is a range of 3.6^{o}C and an average slightly below the set-point of 22 ^{o}C. Additional insulation was added to the experimental apparatus after the familiarity testing to provide better control over the humidity and temperature during the fractional factorial and center-point tests.

During the familiarity testing, active samples were collected using the port directly opposite the calibration gas entrance and also immediately below the samplers on the same side as the calibration gas entrance. The concentrations measured at these three sampling ports confirmed uniform vapor concentrations within the chamber with an average relative standard deviation of less than 5%. Additionally, active samples were collected above the chamber carousel at the exhaust port during the 1 ppbv and 100 ppbv chamber tests to verify that the target concentrations were not measurably depleted by the passive samplers. The concentrations measured at the effluent port compared within 5% of the concentrations measured at the side port located below the samplers.

The results of active samples collected from the exposure chamber using Summa canisters and EPA Method TO-15 versus active ATD tubes with a multi-bed sorbent of Tenax GR and Carbopack B analysed by EPA Method TO-17 are shown in Figure 29. The concentrations calculated from the mass flow controller settings were 50 ppb_v for all analytes except naphthalene, which was 5 ppb_v. Both active sampling methods showed a negative or low bias (passive sampler concentrations were lower than expected) for most compounds, likely because the actual concentration in the chamber was lower than planned (~35 to 40 ppbv), which was most likely attributable to imperfect calibration of the mass flow controllers used to blend the stock gas cylinder supply with the purified air. For this reason, all subsequent chamber tests were monitored using active ATD tubes and the passive sampler results were compared to the

active ATD tube results, not concentrations calculated from the supply gas dilution. The RPD between the two methods was within the commonly accepted range for duplicates by the same method (+/-25%), except for NAPH (58%), 124TMB (43%) and HEX (35%). All but NAPH met the success criteria of 45% RPD for samples collected and analysed by different methods, so the TO-15 and TO-17 results are considered comparable.

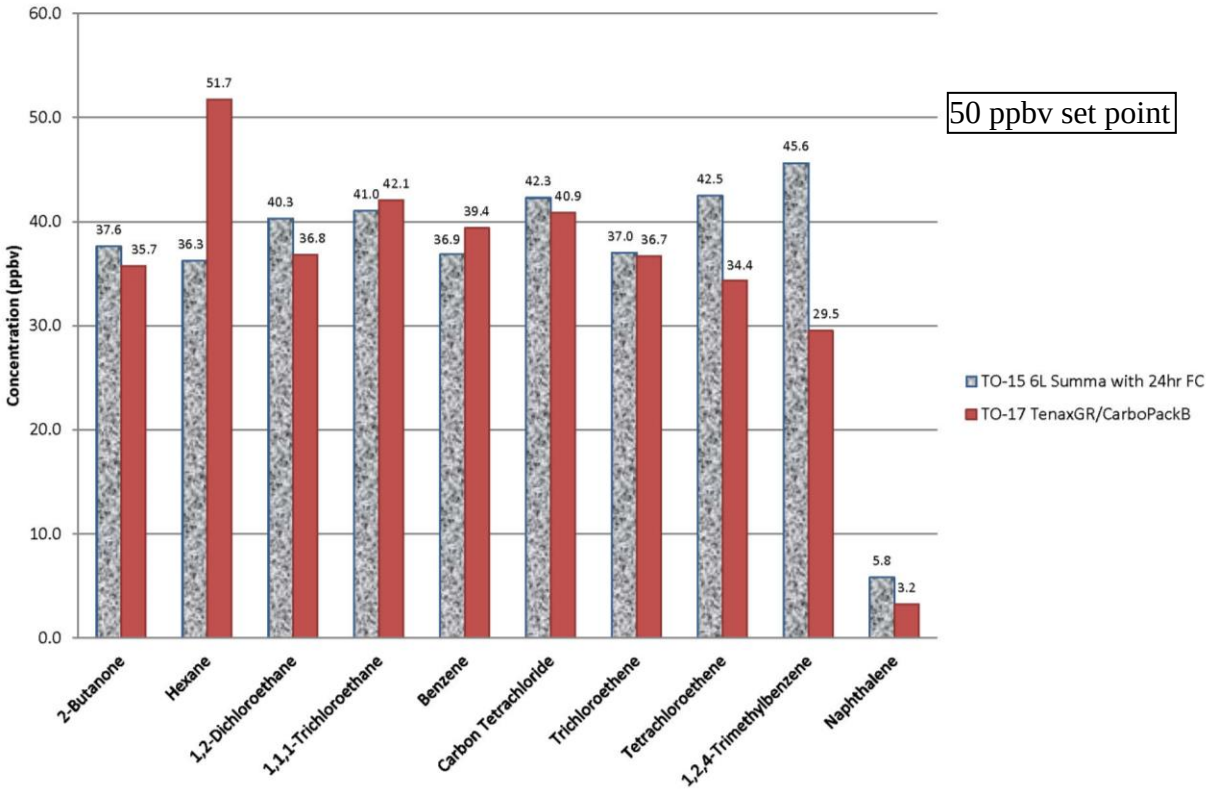


Figure 29: Active sampling TO-15 vs TO-17 during familiarity tests

The results of passive ATD tube sampling inside the exposure chamber during familiarity testing using Carbopack B and Tenax TA are shown in Figure 30. Both samplers provided average concentrations close to the set point (52 ppbv for ATD Carbopack and 50 ppbv for ATD Tenax), excluding naphthalene (which was set 10X lower). The RPD between the two methods averaged 42% and met the success criteria of +/-45% RPD for all but MEK (104%), HEX (49%), 124TMB (53%) and NAPH (70%). Using the uptake rates in Table 3, ATD/Carbopack B showed a high or positive bias (concentrations higher than expected) for benzene and hexane and a low bias for MEK, 124TMB and NAPH. The high bias for benzene is most likely attributable to the uptake rate used (0.35 mL/min from Table 3). ISO 16071-2 and Subramanian, 1995 list various uptake rates for benzene on passive ATD samplers in the range of 0.64 to 1.81 mL/min, depending on the sorbent used and sample duration. None of these values match the exact sorbents and duration of this test, but all values are higher than the value used, so the calculated benzene concentration would have been lower by a factor of about 2 or more, which would be closer to the set point. The ATD/Tenax TA results were similar to the

active (Summa canister and ATD tube) samples, except for benzene, which also showed a high bias, but to a lesser degree. This data demonstrates the sensitivity of the accuracy of the value selected for the uptake rate. The average RPD between the Carbopack B and Tenax samplers was 42%, which was higher than the typical goal for duplicates by the same method (25%), which indicates that even using the same method in the same laboratory, the performance assessment of passive sampling must also consider the effect of sorbent selection.

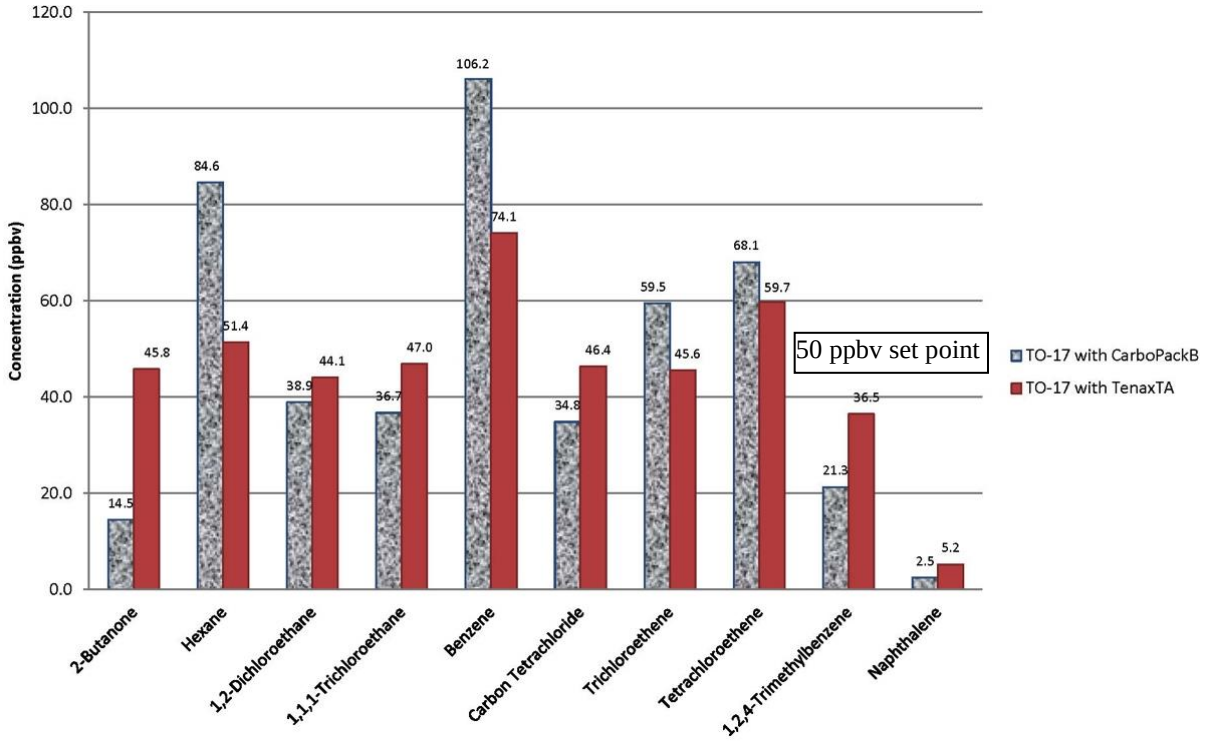


Figure 30: Passive sampling ATD Tenax vs ATD Carbopack B during familiarity tests

6.2 Intra and Inter-Laboratory Test Results

The chamber conditions monitored during the intra and inter-laboratory testing are presented in Table 10. The average flow rates of purified air and supply gas were nearly exactly equal to the set-points of 20 L/min and 100 mL/min, respectively. The average temperature was within 0.2 ^{o}C of the set-point of 22 ^{o}C and the average relative humidity was within 2% RH of the set-point of 60% RH for both chambers and fluctuations were minimal. Active sampler concentrations averaged 99% of the concentrations calculated from dilution of the supply gas with 7% COV. Overall, control over the chamber conditions was excellent.

The VOC concentrations measured with the passive samplers during the intra and inter-laboratory tests are shown in Table 11 and the Youden plots for each VOC are shown in Figure 31 (one plot for each compound). The Youden plots show the results of one duplicate versus the second duplicate sample, where each pair was analyzed by the same sampler, method and laboratory. These data all plotted close to the ideal correlation line (1:1 slope, zero intercept) and showed average RSDs of 3 to 10%, which indicates the intra-laboratory variability was

very low for all compounds and all laboratories. Each Youden plot also shows the average concentration measured using pumped ATD tube (active) samples for reference.

Table 10: Chamber conditions during inter-laboratory testing

ESTCP Interlab Performance Testing Chamber Conditions								
				Chamber #1		Chamber #2		
Date	Time	Air Flow LPM	Cal Flow ccm	Temp deg C	humidity %RH	Temp deg C	humidity %RH	
11-Mar	1726	-	-	22.6	63.6	-	-	
	1830	19.91	101	22.4	64.3	22	65.8	
	1945	19.96	101.5	22	62.2	21.5	64	
12-Mar	610	20.01	101.3	21.9	62.9	21.9	63.3	
	1030	19.95	101.2	21.5	63.1	21.4	63.7	
	1100	19.95	101.1	21.7	62.6	21.7	62.8	
	1130	20	101.3	21.3	63.5	21.2	64	
	1213	20	101.3	21.6	62.3	21.6	62.7	
	1253	19.98	101	21.2	63.6	21.1	64.2	
	1339	20.01	101	21.5	62.6	21.5	63	
	1410	19.95	100.8	21.4	62.5	21	64.3	
	1527	19.93	100.7	21.5	62.5	21.3	63.1	
	1648	19.93	101	21.3	62.7	20.7	64.7	
	1753	19.93	101.1	21.2	62.6	21.1	62.9	
13-Mar	954	20.02	101.3	21.8	65.2	21.6	66.1	
	1209	20.15	101.5	21.6	63.5	21.5	64	
	1428	20.04	101.3	21.8	63.2	21.4	64.8	
14-Mar	939	20	101.1	22.2	61.9	22	62.7	
	1227	19.97	101.3	22.1	67	21.8	68.3	*
	1249	19.96	101.3	22.4	61.5	22.4	61.9	
	1608	19.8	100.5	23.4	59.8	23	61.3	
	1720	19.77	100.5	23.5	58.4	23.4	58.9	
	1815	19.8	100.5	23.2	58.5	23.1	59.2	
	2020	19.94	101.3	22.6	59.1	22.5	59.4	
15-Mar	615	20.03	101.1	21.9	60.9	21.7	61.9	
	710	19.98	101.3	22.1	60.7	21.9	61.5	
	825	20.04	101.1	22.4	59.4	22.4	59.9	
	1017	20.05	101.4	21.9	59.9	21.4	61.7	
	1121	20.03	101.3	22.1	59.5	21.1	59.8	
	1214	20.02	101.4	22	60.3	21.9	61.1	
	1306	19.93	101.1	22.8	59	22.7	59.6	
	1632	19.83	101.1	23.2	58.5	23	59.5	
	Average	19.96	101.12	22.07	61.79	21.83	62.58	

*Power outage on 3/14 at 1115 for a period of less than a minute
Calibration Cylinder: CC316536

Some compounds showed high or low bias compared to the active controls, especially naphthalene and MEK (both of which were expected to be challenging compounds because of their low volatility and high solubility, respectively). Hexane showed a high bias at UW compared to CAS and ATL, which was subsequently attributed to laboratory blank contamination. On average for all compounds, the passive samplers showed relative concentrations (C/Co) of 66% to 80% relative to active sample results, which indicates a low or negative bias on average.

Table 11: Concentrations measured during inter-laboratory testing

Analyte	Sampler Type	Analytical Laboratory	Sampler #1 ID	Sampler #1 Concentration (ppbv)	Sampler #2 ID	Sampler #2 Concentration (ppbv)
MEK	WMS	UW	PS-C61	46.3	PS-C64	45.2
		ATL	PS-C65	23.3	PS-C66	22.8
		AirZOne	PS-C63	54.6	PS-C62	52.7
	SKC Ultra	CAS	SKC B#2	26.4	SKC B#4	24.8
		ATL	SKC Badge #1	25.0	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	10.6	Carbopack B (Chamber 2)	11.1
		CAS	Carbopack B Chamber 1	4.5	Carbopack B Chamber 2	3.3
		UW	Carbopack B (Chamber 1)	3.6	Carbopack B (Chamber 2)	7.2
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	29.2	Tenax TA (Chamber 2)	29.2
		CAS	Tenax TA Chamber 1	30.2	Tenax TA Chamber 2	30.4
		UW	Tenax TA (Chamber 1)	42.0	Tenax TA (Chamber 2)	40.8
	Radiello	FSM	RAD130 #3	13.1	RAD130 #5	12.0
		ATL	RAD130 #1	11.8	RAD130 #6	11.1
		CAS	RAD130 #2	13.6	RAD130 #4	13.3
n-Hexane	WMS	UW	PS-C61	58.9	PS-C64	57.0
		ATL	PS-C65	55.9	PS-C66	52.1
		AirZOne	PS-C63	79.7	PS-C62	60.7
	SKC Ultra	CAS	SKC B#2	44.2	SKC B#4	42.9
		ATL	SKC Badge #1	59.3	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	57.6	Carbopack B (Chamber 2)	56.6
		CAS	Carbopack B Chamber 1	43.3	Carbopack B Chamber 2	41.7
		UW	Carbopack B (Chamber 1)	82.9	Carbopack B (Chamber 2)	83.9
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	31.2	Tenax TA (Chamber 2)	31.2
		CAS	Tenax TA Chamber 1	26.0	Tenax TA Chamber 2	25.8
		UW	Tenax TA (Chamber 1)	41.9	Tenax TA (Chamber 2)	41.9
	Radiello	FSM	RAD130 #3	42.8	RAD130 #5	44.7
		ATL	RAD130 #1	48.8	RAD130 #6	43.6
		CAS	RAD130 #2	65.5	RAD130 #4	62.0
1,2-DCA	WMS	UW	PS-C61	41.5	PS-C64	41.0
		ATL	PS-C65	37.9	PS-C66	37.9
		AirZOne	PS-C63	38.9	PS-C62	38.4
	SKC Ultra	CAS	SKC B#2	37.1	SKC B#4	35.3
		ATL	SKC Badge #1	42.5	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	26.4	Carbopack B (Chamber 2)	27.2
		CAS	Carbopack B Chamber 1	22.9	Carbopack B Chamber 2	22.8
		UW	Carbopack B (Chamber 1)	28.9	Carbopack B (Chamber 2)	32.3
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	28.1	Tenax TA (Chamber 2)	28.9
		CAS	Tenax TA Chamber 1	28.5	Tenax TA Chamber 2	28.4
		UW	Tenax TA (Chamber 1)	31.4	Tenax TA (Chamber 2)	31.4
	Radiello	FSM	RAD130 #3	34.0	RAD130 #5	35.6
		ATL	RAD130 #1	40.8	RAD130 #6	36.4
		CAS	RAD130 #2	47.3	RAD130 #4	49.6
1,1,1-TCA	WMS	UW	PS-C61	51.6	PS-C64	50.4
		ATL	PS-C65	47.2	PS-C66	44.6
		AirZOne	PS-C63	55.4	PS-C62	48.9
	SKC Ultra	CAS	SKC B#2	29.0	SKC B#4	27.6
		ATL	SKC Badge #1	34.0	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	30.3	Carbopack B (Chamber 2)	30.9
		CAS	Carbopack B Chamber 1	26.8	Carbopack B Chamber 2	25.5
		UW	Carbopack B (Chamber 1)	20.2	Carbopack B (Chamber 2)	23.3
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	32.8	Tenax TA (Chamber 2)	32.8
		CAS	Tenax TA Chamber 1	26.7	Tenax TA Chamber 2	26.4
		UW	Tenax TA (Chamber 1)	44.7	Tenax TA (Chamber 2)	42.8
	Radiello	FSM	RAD130 #3	39.1	RAD130 #5	41.3
		ATL	RAD130 #1	47.8	RAD130 #6	43.2
		CAS	RAD130 #2	67.2	RAD130 #4	71.8
Benzene	WMS	UW	PS-C61	48.6	PS-C64	48.8
		ATL	PS-C65	40.1	PS-C66	40.0
		AirZOne	PS-C63	44.6	PS-C62	40.3
	SKC Ultra	CAS	SKC B#2	40.3	SKC B#4	38.2
		ATL	SKC Badge #1	47.1	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	67.7	Carbopack B (Chamber 2)	67.7
		CAS	Carbopack B Chamber 1	62.4	Carbopack B Chamber 2	58.9
		UW	Carbopack B (Chamber 1)	98.4	Carbopack B (Chamber 2)	103.0
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	43.1	Tenax TA (Chamber 2)	43.1
		CAS	Tenax TA Chamber 1	43.0	Tenax TA Chamber 2	42.5
		UW	Tenax TA (Chamber 1)	55.3	Tenax TA (Chamber 2)	53.8
	Radiello	FSM	RAD130 #3	40.2	RAD130 #5	42.2
		ATL	RAD130 #1	38.4	RAD130 #6	35.0
		CAS	RAD130 #2	48.8	RAD130 #4	50.6

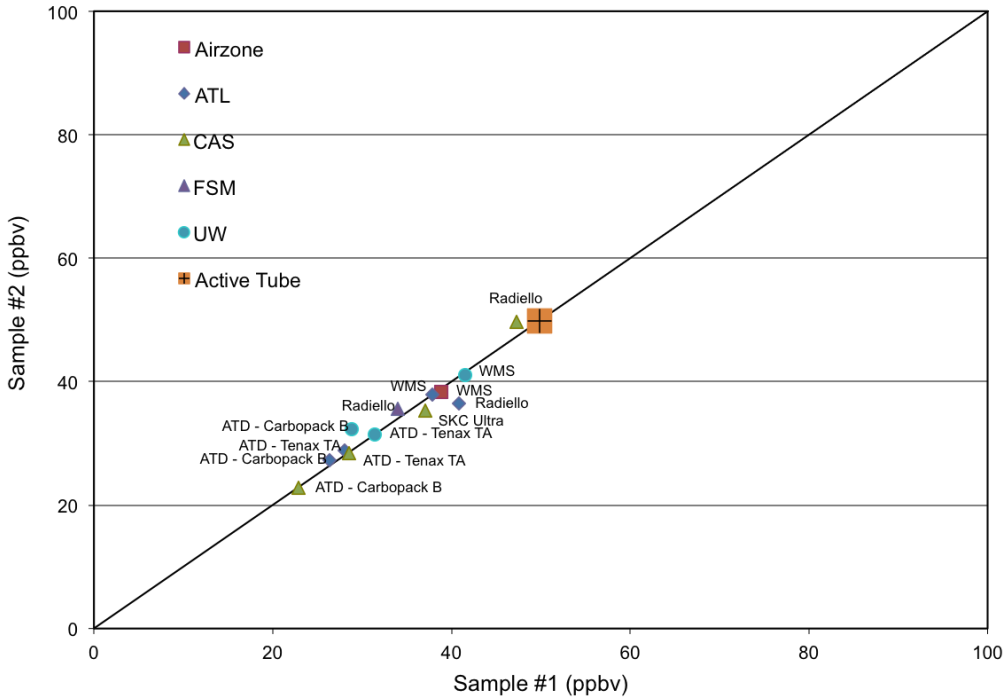
Analyte	Sampler Type	Analytical Laboratory	Sampler #1 ID	Sampler #1 Concentration (ppbv)	Sampler #2 ID	Sampler #2 Concentration (ppbv)
Carbon Tetrachloride	WMS	UW	PS-C61	54.8	PS-C64	53.8
		ATL	PS-C65	44.8	PS-C66	44.8
		AirZOne	PS-C63	54.4	PS-C62	49.5
	SKC Ultra	CAS	SKC B#2	37.6	SKC B#4	35.7
		ATL	SKC Badge #1	47.2	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	36.8	Carbopack B (Chamber 2)	36.8
		CAS	Carbopack B Chamber 1	33.2	Carbopack B Chamber 2	32.4
		UW	Carbopack B (Chamber 1)	43.2	Carbopack B (Chamber 2)	37.4
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	35.7	Tenax TA (Chamber 2)	36.3
		CAS	Tenax TA Chamber 1	29.6	Tenax TA Chamber 2	29.1
		UW	Tenax TA (Chamber 1)	48.5	Tenax TA (Chamber 2)	46.8
	Radiello	FSM	RAD130 #3	37.1	RAD130 #5	39.3
		ATL	RAD130 #1	43.6	RAD130 #6	39.7
		CAS	RAD130 #2	57.5	RAD130 #4	59.3
TCE	WMS	UW	PS-C61	37.8	PS-C64	38.0
		ATL	PS-C65	38.1	PS-C66	37.1
		AirZOne	PS-C63	31.6	PS-C62	29.3
	SKC Ultra	CAS	SKC B#2	36.9	SKC B#4	34.7
		ATL	SKC Badge #1	44.8	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	50.0	Carbopack B (Chamber 2)	50.0
		CAS	Carbopack B Chamber 1	45.7	Carbopack B Chamber 2	44.0
		UW	Carbopack B (Chamber 1)	64.0	Carbopack B (Chamber 2)	67.1
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	37.5	Tenax TA (Chamber 2)	38.3
		CAS	Tenax TA Chamber 1	35.9	Tenax TA Chamber 2	35.5
		UW	Tenax TA (Chamber 1)	42.1	Tenax TA (Chamber 2)	39.0
	Radiello	FSM	RAD130 #3	39.6	RAD130 #5	41.4
		ATL	RAD130 #1	45.0	RAD130 #6	40.8
		CAS	RAD130 #2	52.4	RAD130 #4	56.0
PCE	WMS	UW	PS-C61	32.5	PS-C64	33.6
		ATL	PS-C65	35.6	PS-C66	33.6
		AirZOne	PS-C63	23.8	PS-C62	21.9
	SKC Ultra	CAS	SKC B#2	42.2	SKC B#4	42.1
		ATL	SKC Badge #1	46.8	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	40.6	Carbopack B (Chamber 2)	39.1
		CAS	Carbopack B Chamber 1	39.0	Carbopack B Chamber 2	35.9
		UW	Carbopack B (Chamber 1)	50.7	Carbopack B (Chamber 2)	55.8
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	35.5	Tenax TA (Chamber 2)	35.0
		CAS	Tenax TA Chamber 1	33.0	Tenax TA Chamber 2	31.8
		UW	Tenax TA (Chamber 1)	39.0	Tenax TA (Chamber 2)	36.5
	Radiello	FSM	RAD130 #3	43.0	RAD130 #5	45.5
		ATL	RAD130 #1	51.6	RAD130 #6	43.0
		CAS	RAD130 #2	51.3	RAD130 #4	54.3
1,2,4-TMB	WMS	UW	PS-C61	19.9	PS-C64	21.3
		ATL	PS-C65	23.5	PS-C66	21.0
		AirZOne	PS-C63	16.8	PS-C62	16.8
	SKC Ultra	CAS	SKC B#2	25.0	SKC B#4	26.0
		ATL	SKC Badge #1	14.3	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	29.9	Carbopack B (Chamber 2)	28.2
		CAS	Carbopack B Chamber 1	26.3	Carbopack B Chamber 2	25.7
		UW	Carbopack B (Chamber 1)	41.2	Carbopack B (Chamber 2)	42.3
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	32.2	Tenax TA (Chamber 2)	31.0
		CAS	Tenax TA Chamber 1	26.6	Tenax TA Chamber 2	26.2
		UW	Tenax TA (Chamber 1)	37.8	Tenax TA (Chamber 2)	35.0
	Radiello	FSM	RAD130 #3	47.9	RAD130 #5	48.7
		ATL	RAD130 #1	46.9	RAD130 #6	42.0
		CAS	RAD130 #2	55.2	RAD130 #4	56.2
Naphthalene	WMS	UW	PS-C61	0.24	PS-C64	0.25
		ATL	PS-C65	0.26	PS-C66	0.22
		AirZOne	PS-C63	0.31	PS-C62	0.31
	SKC Ultra	CAS	SKC B#2	0.93	SKC B#4	0.62
		ATL	SKC Badge #1	0.00	SKC Badge #5	-
		AirZOne	SKC Badge #3	--	SKC Badge #6	--
	ATD - CarbopackB	ATL	Carbopack B (Chamber 1)	3.8	Carbopack B (Chamber 2)	3.5
		CAS	Carbopack B Chamber 1	2.6	Carbopack B Chamber 2	2.7
		UW	Carbopack B (Chamber 1)	1.8	Carbopack B (Chamber 2)	1.2
	ATD - Tenax TA	ATL	Tenax TA (Chamber 1)	4.9	Tenax TA (Chamber 2)	4.5
		CAS	Tenax TA Chamber 1	3.0	Tenax TA Chamber 2	3.2
		UW	Tenax TA (Chamber 1)	5.6	Tenax TA (Chamber 2)	5.4
	Radiello	FSM	RAD130 #3	9.5	RAD130 #5	9.0
		ATL	RAD130 #1	1.4	RAD130 #6	1.3
		CAS	RAD130 #2	2.6 U	RAD130 #4	2.6 U

Notes:

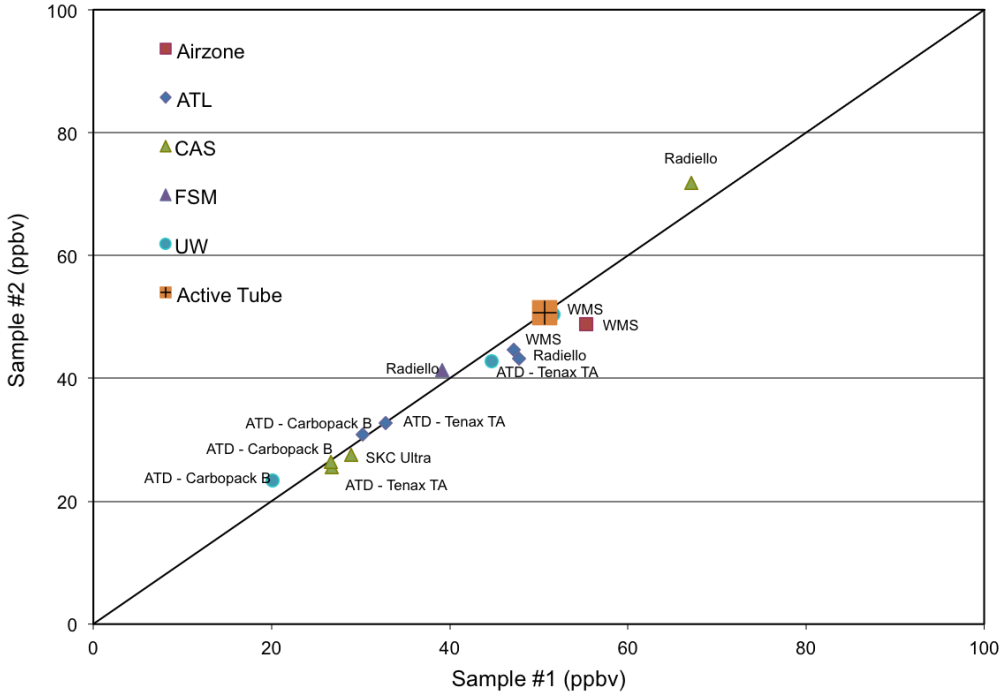
- - results unusable due to unacceptable internal standard reccovery

-- - results not quantifiable as mass far exceeded calibration range

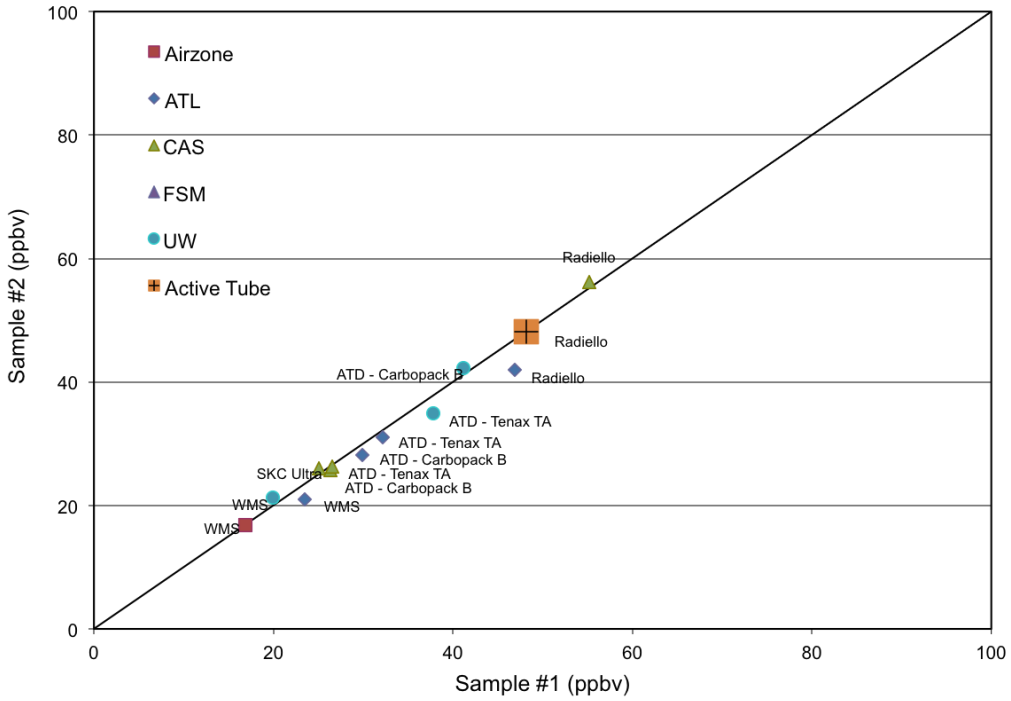
Youden Plot - 1,2-Dichloroethane



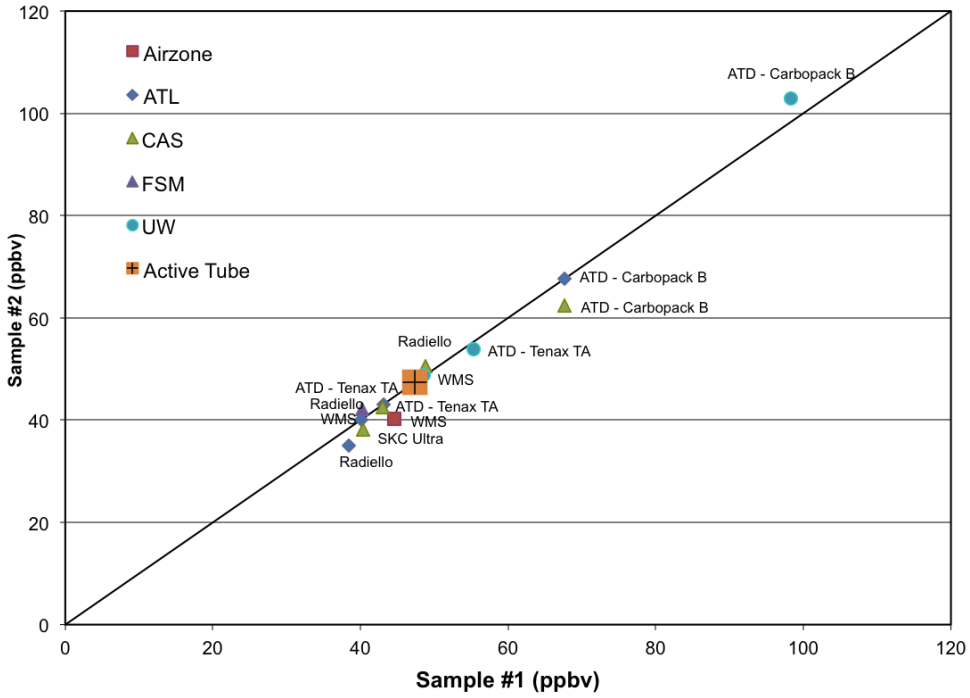
Youden Plot - 1,1,1-Trichloroethane



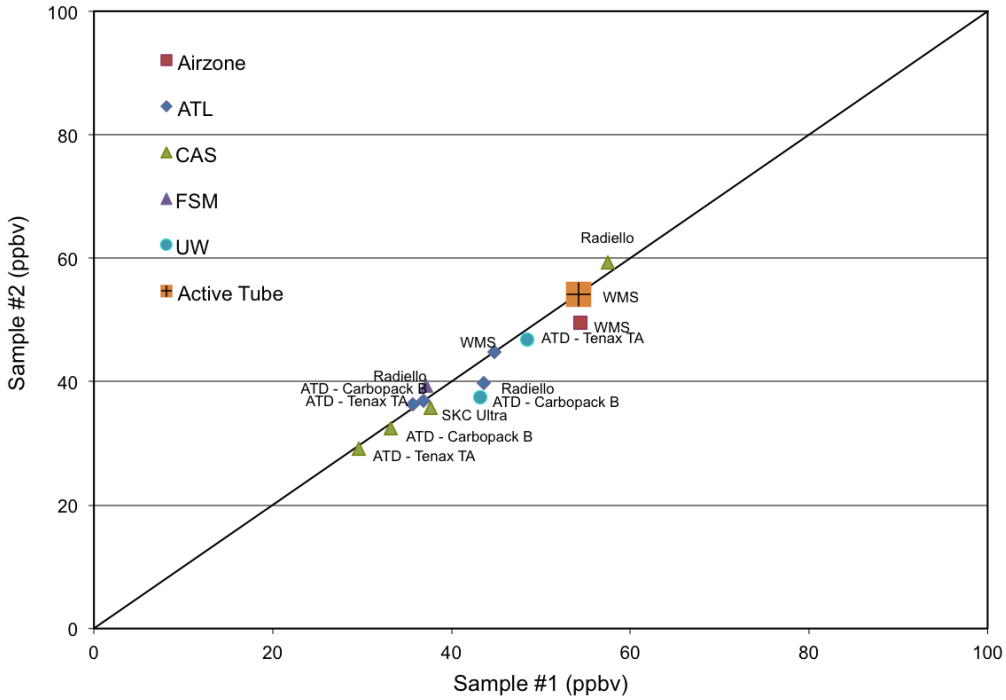
Youden Plot - 1,2,4-Trimethylbenzene



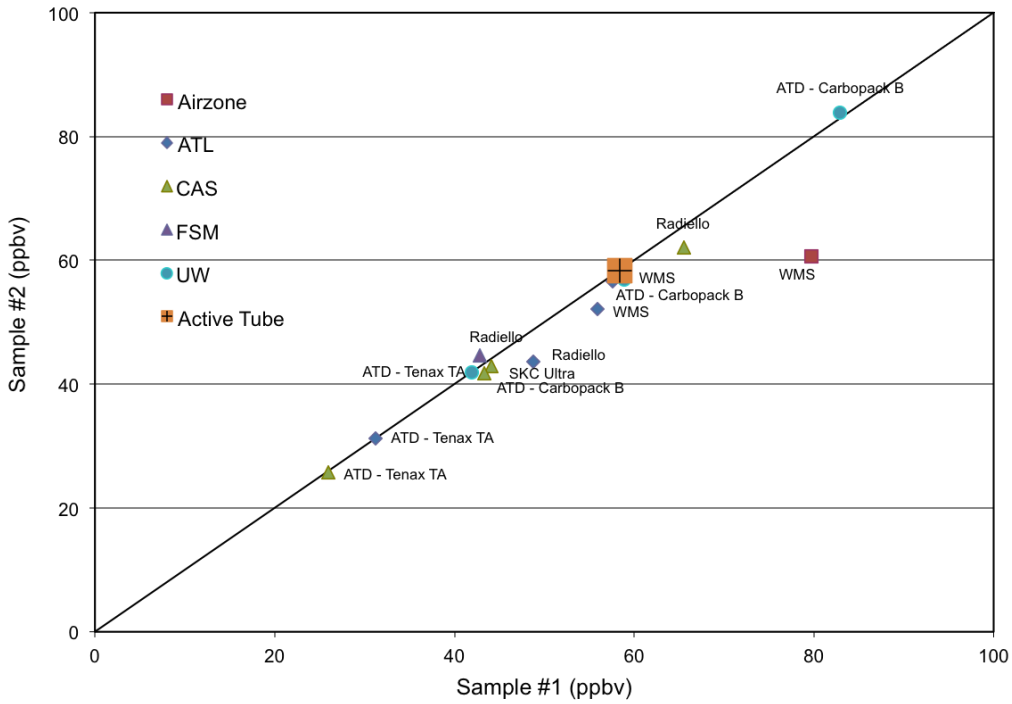
Youden Plot - Benzene



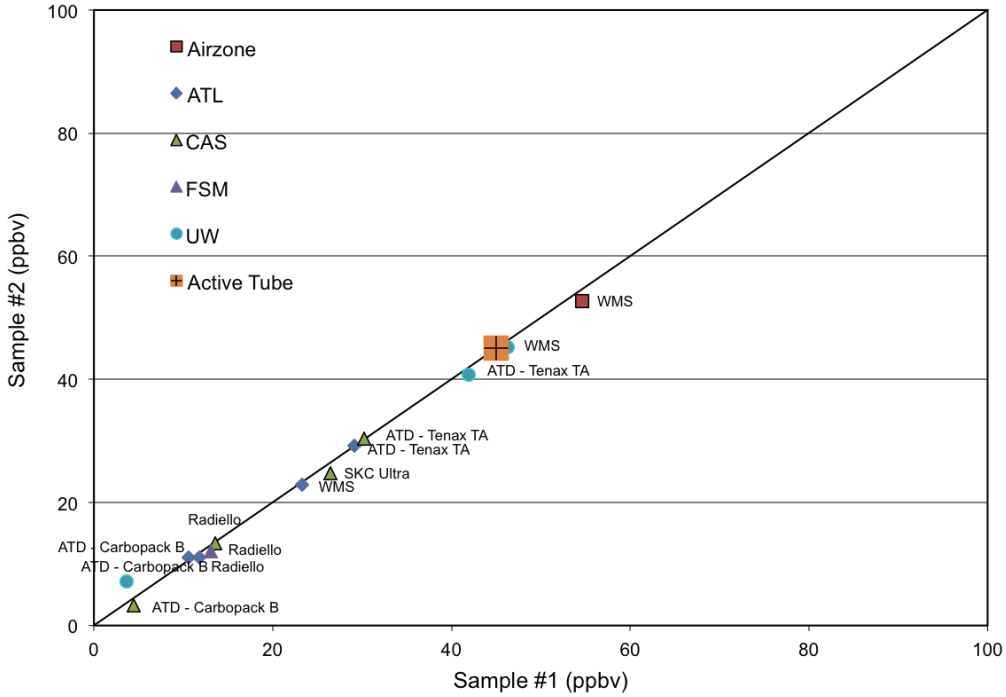
Youden Plot - Carbon Tetrachloride



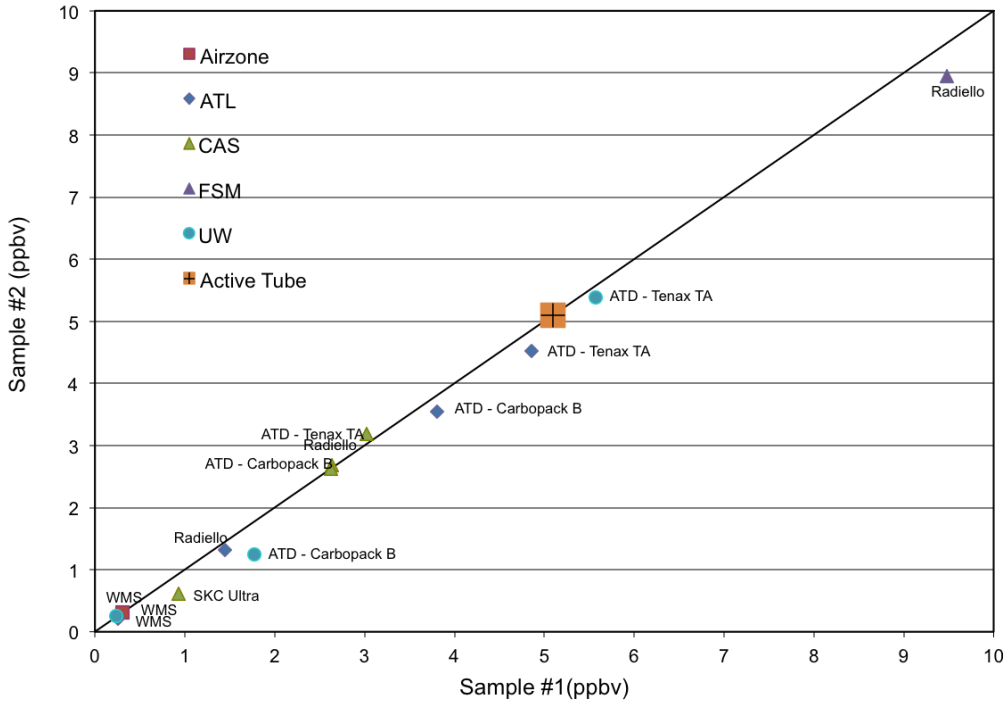
Youden Plot - Hexane

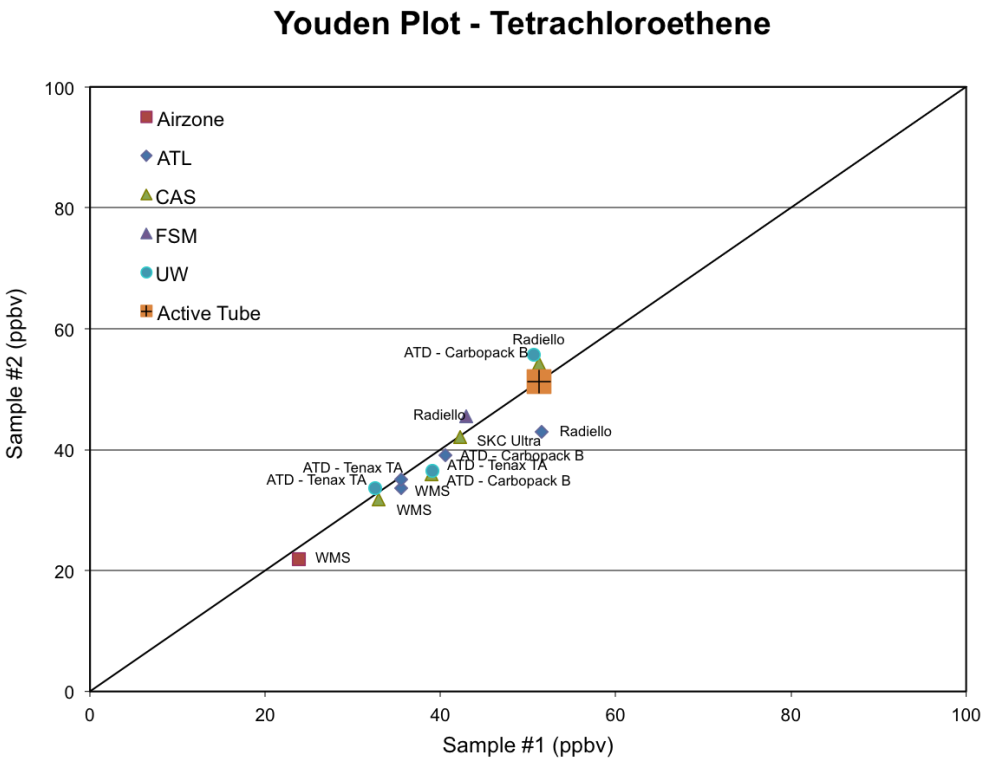


Youden Plot - Methylethyl Ketone



Youden Plot - Naphthalene





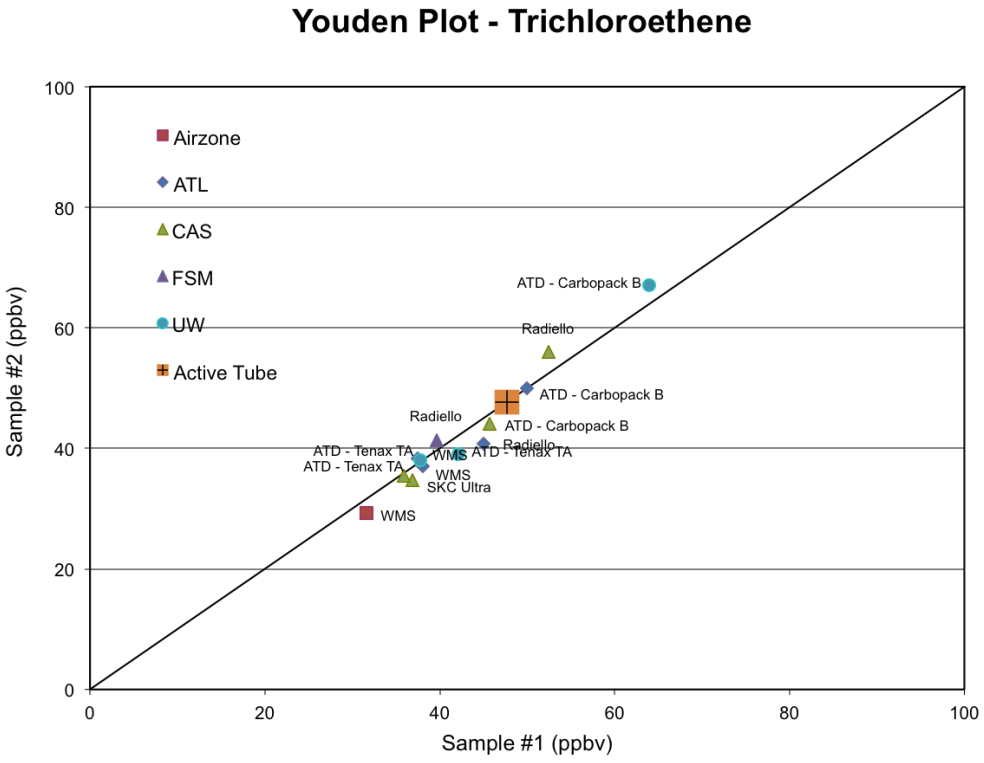


Figure 31: Youden plots for each VOC in the inter-laboratory tests

Figure 32 shows the inter-laboratory data plotted as the results from one laboratory versus the second laboratory, where each pair is for the same compound using the same sampler. Note that since three laboratories analyzed each type of sampler the comparison between one laboratory and another occurs three times for each sampler/compound combination (Lab A:Lab B, Lab B:Lab C, and Lab A:Lab C). For the purpose of Figure 32, these were plotted simply as one lab against another, and generically named Lab 1 vs Lab 2. Comparing Figure 32 to Figure 31 indicates that the inter-laboratory variability was higher than the intra-laboratory variability, which is common because the different laboratories use slightly different equipment and methods. The RPD between one laboratory and another is shown on Table 12. The average RPD for all inter-laboratory pairs of concentration measurements was 26%. This was taken into consideration in the performance objectives and success criteria in Section 3. This degree of variability is consistent with previous studies of inter-laboratory variability for Summa canisters (Pearson, 2005).

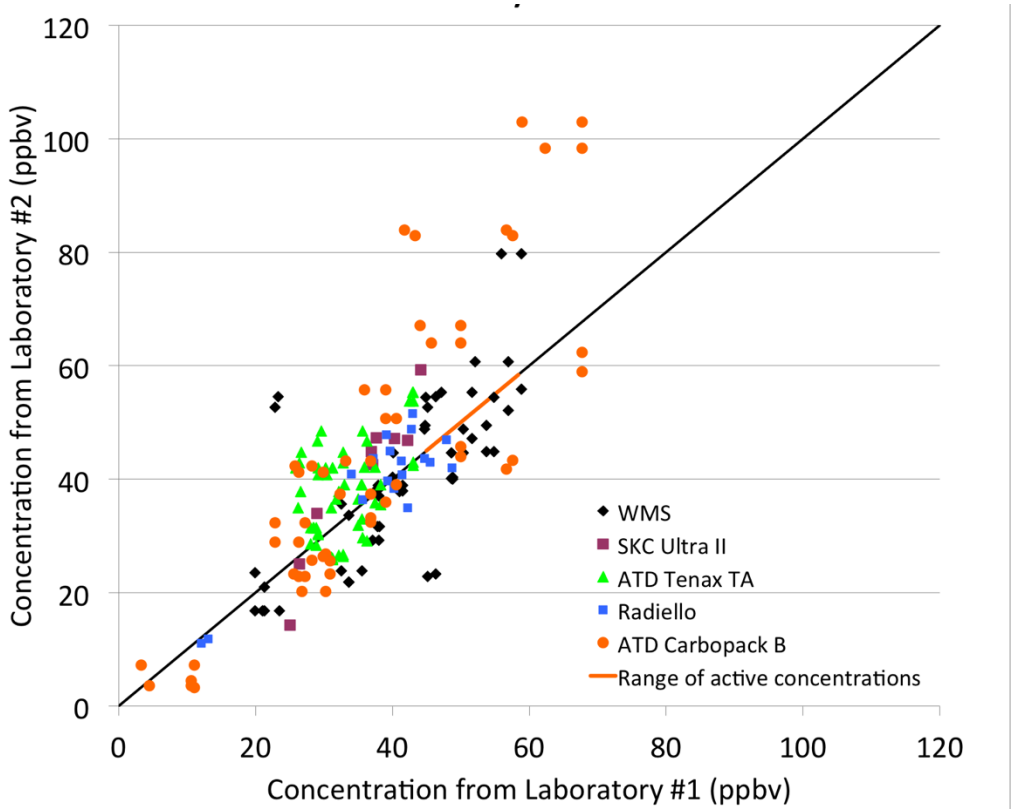


Figure 32: Scatter plot of laboratory 1 versus laboratory 2 for all VOCs and samplers

Table 12: Summary of Accuracy and Precision in the inter-laboratory test

Sampler type		A		B		C		D		B/A	C/A	D/A	RPD (B:C)	RPD (C:D)	RPD (B:D)
		(ppbv)		(ppbv)		(ppbv)		(ppbv)							
		TO-17		U of W		Air Toxics		AirZOne		%	%	%	%	%	%
WMS	MEK	45.2	44.8	46.3	45.2	23.3	22.8	54.6	52.7	102%	51%	119%	66%	80%	16%
	HEX	59	57.6	58.9	57.0	55.9	52.1	79.7	60.7	99%	93%	120%	7%	26%	19%
	12DCA	50.3	49.2	41.5	41.0	37.9	37.9	38.9	38.4	83%	76%	78%	9%	2%	7%
	111TCA	51.0	50.2	51.6	50.4	47.2	44.6	55.4	48.9	101%	91%	103%	10%	13%	2%
	BENZ	47.8	46.8	48.6	48.8	40.1	40.0	44.6	40.3	103%	85%	90%	19%	6%	14%
	CT	54.3	54.0	54.8	53.8	44.8	44.8	54.4	49.5	100%	83%	96%	19%	15%	4%
	TCE	48.0	47.2	37.8	38.0	38.1	37.1	31.6	29.3	80%	79%	64%	1%	21%	22%
	PCE	51.8	50.6	32.5	33.6	35.6	33.6	23.8	21.9	65%	68%	45%	5%	41%	36%
	124TMB	48.5	47.8	19.9	21.3	23.5	21.0	16.8	16.8	43%	46%	35%	8%	28%	20%
	NAPH	5.12	5.06	0.24	0.25	0.26	0.2	0.3	0.3	5%	5%	6%	4%	26%	22%
									Mean	78%	68%	76%	15%	26%	16%
		TO-17		CAS		Air Toxics		AirZOne							
SKC	MEK	45.2	44.8	26.4	24.8	25.0	R	R	R	57%	R	R	2%	R	R
Ultra	HEX	59	57.6	44.2	42.9	59.3	R	R	R	75%	R	R	31%	R	R
	12DCA	50.3	49.2	37.1	35.3	42.5	R	R	R	73%	R	R	16%	R	R
	111TCA	51.0	50.2	29.0	27.6	34.0	R	R	R	56%	R	R	18%	R	R
	BENZ	47.8	46.8	40.3	38.2	47.1	R	R	R	83%	R	R	18%	R	R
	CT	54.3	54.0	37.6	35.7	47.2	R	R	R	68%	R	R	25%	R	R
	TCE	48.0	47.2	36.9	34.7	44.8	R	R	R	75%	R	R	22%	R	R
	PCE	51.8	50.6	42.2	42.1	46.8	R	R	R	82%	R	R	11%	R	R
	124TMB	48.5	47.8	25.0	26.0	14.3	R	R	R	53%	R	R	57%	R	R
	NAPH	5.12	5.06	0.9	0.6	0.00	R	R	R	15%	R	R		R	R
									Mean	64%			22%		
		TO-17		Air Toxics		CAS		U of W							
ATD Tube	MEK	45.2	44.8	10.6	11.1	4.5	3.3	3.6	7.2	24%	9%	12%	95%	33%	67%
Carbopack B	HEX	59	57.6	57.6	56.6	43.3	41.7	82.9	83.9	98%	73%	143%	29%	65%	37%
	12DCA	50.3	49.2	26.4	27.2	22.9	22.8	28.9	32.3	54%	46%	61%	16%	29%	13%
	111TCA	51.0	50.2	30.3	30.9	26.8	25.5	20.2	23.3	60%	52%	43%	16%	18%	34%
	BENZ	47.8	46.8	67.7	67.7	62.4	58.9	98.4	103.0	143%	128%	213%	11%	50%	39%
	CT	54.3	54.0	36.8	36.8	33.2	32.4	43.2	37.4	68%	61%	74%	12%	21%	9%
	TCE	48.0	47.2	50.0	50.0	45.7	44.0	64.0	67.1	105%	94%	138%	11%	37%	27%
	PCE	51.8	50.6	40.6	39.1	39.0	35.9	50.7	55.8	78%	73%	104%	6%	35%	29%
	124TMB	48.5	47.8	29.9	28.2	26.3	25.7	41.2	42.3	60%	54%	87%	11%	46%	36%
	NAPH	5.12	5.06	3.81	3.54	2.63	2.7	1.8	1.2	72%	52%	30%	32%	55%	84%
									Mean	76%	64%	90%	24%	39%	37%
		TO-17		Air Toxics		CAS		U of W							
ATD Tube	MEK	45.2	44.8	29.2	29.2	30.2	30.4	42.0	40.8	65%	67%	92%	4%	31%	35%
Tenax TA	HEX	59	57.6	31.2	31.2	26.0	25.8	41.9	41.9	54%	44%	72%	19%	47%	29%
	12DCA	50.3	49.2	28.1	28.9	28.5	28.4	31.4	31.4	57%	57%	63%	0%	10%	10%
	111TCA	51.0	50.2	32.8	32.8	26.7	26.4	44.7	42.8	65%	52%	87%	21%	49%	29%
	BENZ	47.8	46.8	43.1	43.1	43.0	42.5	55.3	53.8	91%	90%	115%	1%	24%	24%
	CT	54.3	54.0	35.7	36.3	29.6	29.1	48.5	46.8	66%	54%	88%	20%	48%	28%
	TCE	48.0	47.2	37.5	38.3	35.9	35.5	42.1	39.0	80%	75%	85%	6%	13%	7%
	PCE	51.8	50.6	35.5	35.0	33.0	31.8	39.0	36.5	69%	63%	74%	8%	15%	7%
	124TMB	48.5	47.8	32.2	31.0	26.6	26.2	37.8	35.0	66%	55%	76%	18%	32%	14%
	NAPH	5.12	5.06	4.86	4.53	3.03	3.2	5.6	5.4	92%	61%	108%	41%	55%	15%
									Mean	70%	62%	86%	14%	32%	20%
		TO-17		FSM		Air Toxics		CAS							
Radiello	MEK	45.2	44.8	13.1	12.0	11.8	11.1	13.6	13.3	28%	25%	30%	9%	16%	7%
	HEX	59	57.6	42.8	44.7	48.8	43.6	65.5	62.0	75%	79%	109%	5%	32%	37%
	12DCA	50.3	49.2	34.0	35.6	40.8	36.4	47.3	49.6	70%	78%	97%	10%	23%	33%
	111TCA	51.0	50.2	39.1	41.3	47.8	43.2	67.2	71.8	79%	90%	137%	12%	42%	53%
	BENZ	47.8	46.8	40.2	42.2	38.4	35.0	48.8	50.6	87%	77%	105%	12%	30%	19%
	CT	54.3	54.0	37.1	39.3	43.6	39.7	57.5	59.3	71%	77%	108%	9%	33%	42%
	TCE	48.0	47.2	39.6	41.4	45.0	40.8	52.4	56.0	85%	90%	114%	6%	23%	29%
	PCE	51.8	50.6	43.0	45.5	51.6	43.0	51.3	54.3	86%	92%	103%	7%	11%	18%
	124TMB	48.5	47.8	47.9	48.7	46.9	42.0	55.2	56.2	100%	92%	116%	8%	23%	14%
	NAPH	5.12	5.06	9.5	9.0	1.4	1.3	2.6	2.6	181%	27%	52%	148%	62%	111%
									Mean	86%	73%	97%	23%	30%	36%

6.3 Center-point (ANOVA) Test Results

The results of the initial center-point testing are tabulated in Appendix E. The average temperature was within 1°C of the set-point of 22°C, and the standard deviation of the temperature was less than 0.5°C for all six chambers (Table E1). The average relative humidity was within 2% RH of the set-point of 60% RH, and the standard deviation of the relative humidity was less than 6.5% RH. This indicates the chamber conditions were well controlled. The face velocity was controlled at 0.23 m/s by the rotation of the carousel, and the sample duration (4 days) was controlled by the experimental procedure.

The chamber concentrations measured with the pumped ATD tubes (Table E2) were generally lower than the concentrations calculated by mass balance and the flow rates of the supply gas and purified air (set point was 50 ppb_v for all compounds except naphthalene at 5 ppb_v and was achieved by adding 50 mL/min supply gas to 10 L/min purified air). The only compound with an active sample concentration matching the expected concentration calculated from the mass flow controllers was HEX (99% of expected value). The average active ATD tube/TO-17 sample concentrations for the other compounds were generally slightly lower than the set-point, mostly in the range of 33 to 45 ppb_v and 2.9 to 3.2 ppb_v for naphthalene. This appears likely to have been attributable to imperfect calibration of the mass flow controllers. Nevertheless, the passive sampler data were all normalized to active sample concentrations and the active sample results showed minimal variability (COV of 2 to 7%), so the chamber concentrations were reasonably steady and well-characterized for the four-day duration of the center-point tests.

The concentrations measured with passive samplers in the initial center-point tests are presented in Table E3 and summarized on the box and whiskers plots in Figure 33. The box spans the 25^{th} to 75^{th} percentiles and the whiskers span the maximum and minimum measured concentrations. Also shown on Figure 33 are horizontal lines corresponding to C/Co values (passive sampler concentration divided by active sampler concentration) of +/-25% and +/-45%. The passive sampler data showed precision similar to the active ATD tube samples for most of the combinations of sampler/compound, except: 1) hexane with the WMS sampler (subsequently attributable to laboratory contamination) and 2) naphthalene with the Radiello sampler. The accuracy was within a C/Co of +/- 25% for 24 of the 50 combinations of sampler/compound (roughly half). The accuracy was outside of +/-45% for only 9 of the 50 combinations of sampler/compound:

- ATD tube/Tenax showed low bias for 111TCA, 12DCA and CT;
- ATD/Carbopack B showed low bias for 12DCA and MEK and high bias for BENZ;
- WMS and SKC showed low bias for NAPH;
- Radiello showed a high bias for NAPH.

The high bias for BENZ on the ATD/Carbopack B sampler is likely attributable to the uptake rate being too low, as described for the familiarity testing. The low bias for ATD/Tenax may be attributable to poor retention because Tenax is a weaker sorbent than Carbopack B. The recommended maximum sample volumes (RMSVs) for 111TCA, 12DCA and CT on Tenax are 0.2, 1 and 0.2 L, respectively (Supelco 2013). The uptake rate for these compounds for the

passive ATD tube sampler was estimated to be 0.5 mL/min (see Table 3). The product of the sample duration (4 days) and the uptake rate is therefore 2.9 L, which is larger than the RMSV for these compounds on Tenax.

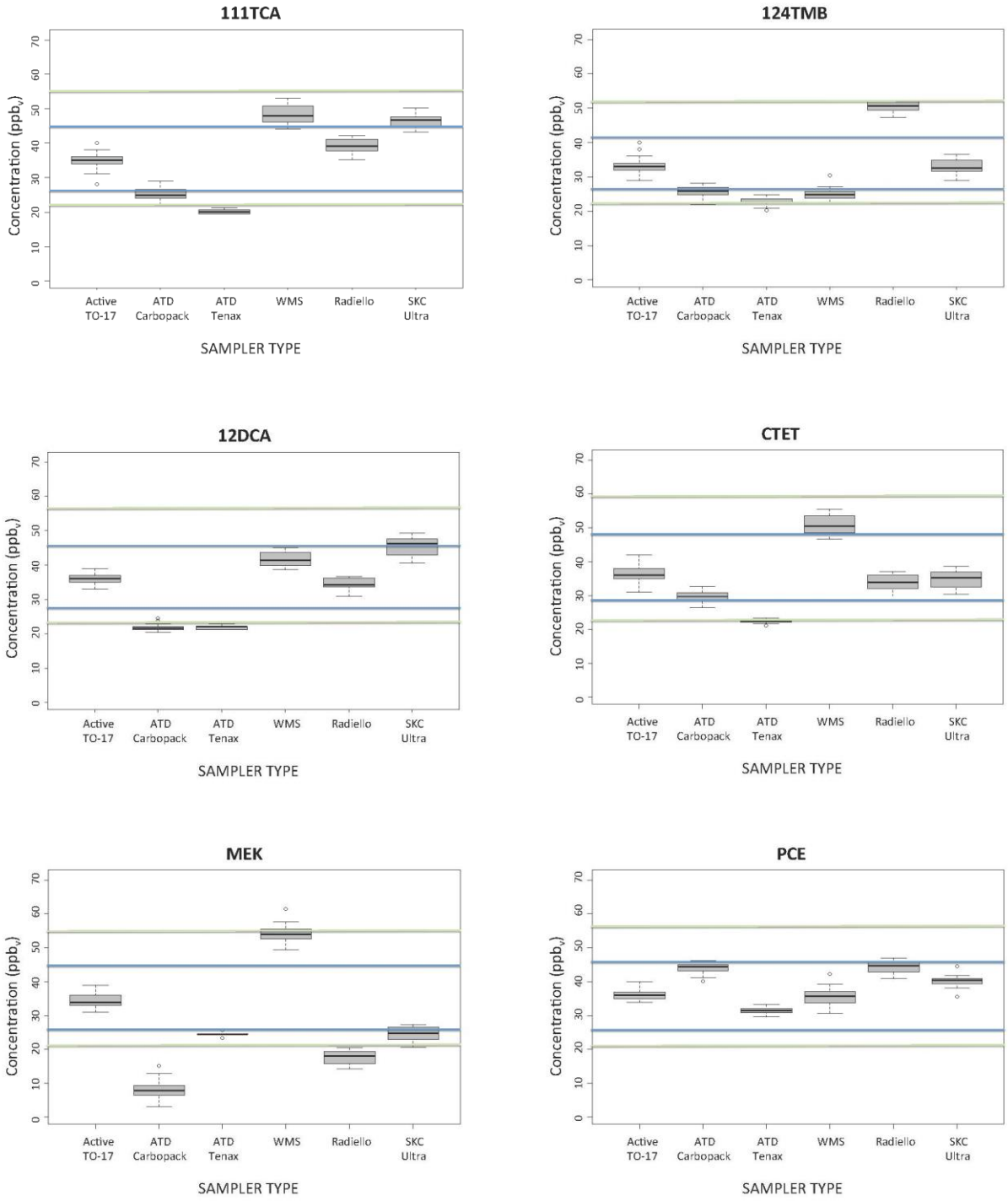


Figure 33: Box and whiskers plots of center-point test results (with control lines corresponding to +/-25% (inside control lines in blue) and +/-45% (outside control lines in beige))

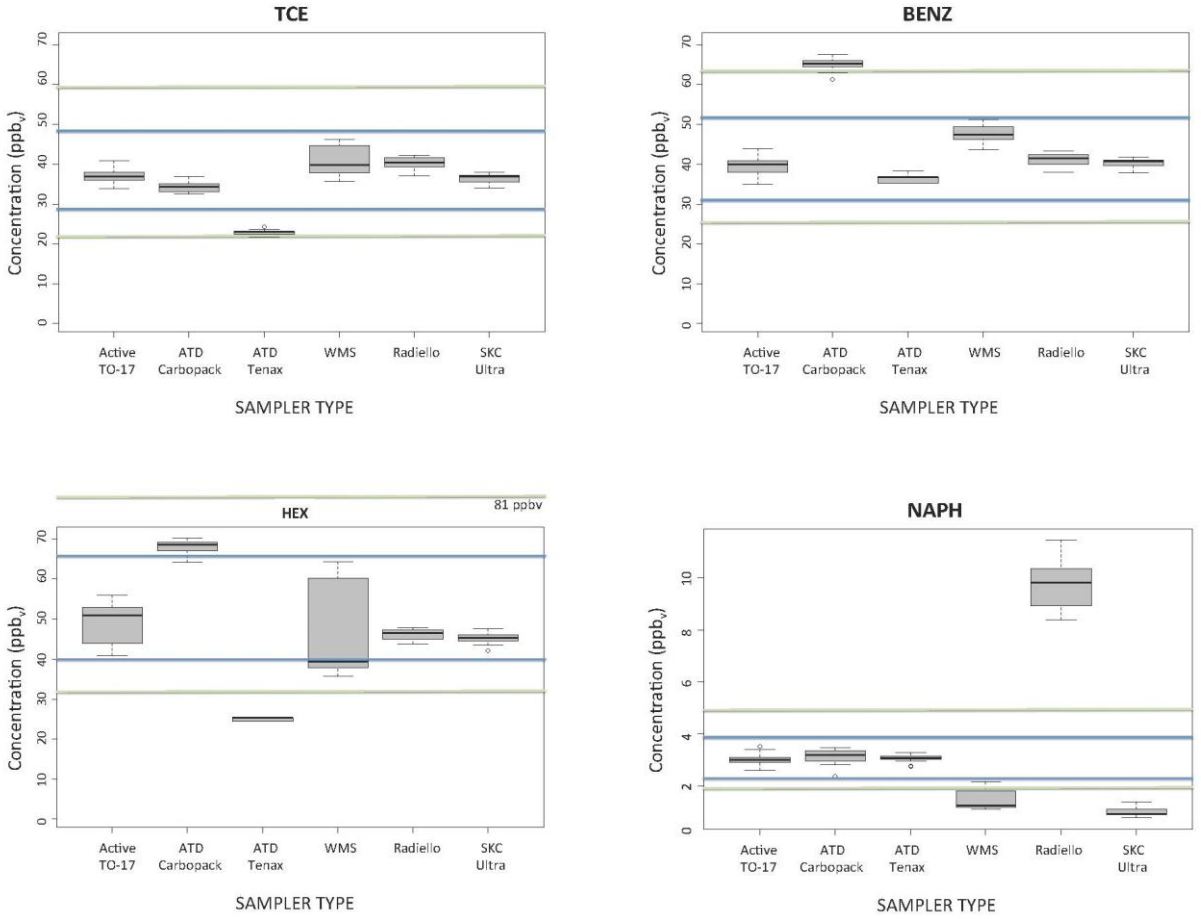


Figure 33(cont'd): Box and whiskers plots of center-point test results (with control lines corresponding to +/-25% (inside control lines) and +/-45% (outside control lines))

Carbopack B has a much higher RMSV for 111TCA and CT (20 L for both according to Supelco, 2013), and did not show as much low bias for these compounds compared to ATD/Tenax. The high bias for the Radiello/NAPH may be attributable to uncertainty in the published uptake rate (25 mL/min). Using the free-air diffusion coefficient for NAPH (0.059 cm^2/s), and the equation in the Radiello manual (FSM, 2013), an uptake rate of 50 mL/min could be calculated, which would have resulted in concentrations 2 times lower, which would have been predominantly within the +/-25% tolerance of the active samples. Napthalene often shows low recovery, and the published uptake rate of 25 mL/min may be set as such to partially account for low recovery. The high bias for NAPH on the Radiello analysed by FSM is consistent with the inter-laboratory test data (Table 11). The WMS and SKC samplers used estimated uptake rates for NAPH, both of which apparently overestimated the true uptake rate for the conditions of the center-point tests by a factor of 2 to 3, which may also be attributable to low recovery of naphthalene from the (strong) sorbents used (Anasorb 747 and charcoal, respectively).

The precision for each passive sampler/compound combination in the center-point tests is shown as a plot of the coefficient of variation (standard deviation divided by the mean) in Figure 34. The precision goal of <10% COV was met for 13 of the 50 sampler/compound combinations and 12 of these were by the ATD tube using either Carbopack B or Tenax. The other samplers had COV values of about 30% or less for 47 of the 50 sampler/compound combinations (exceptions included MEK and NAPH, which are challenging compounds and hexane for the WMS, which appeared to be related to laboratory contamination). The COV for the active samples collected from the exposure chamber as controls was in the range of 2 - 7 %.

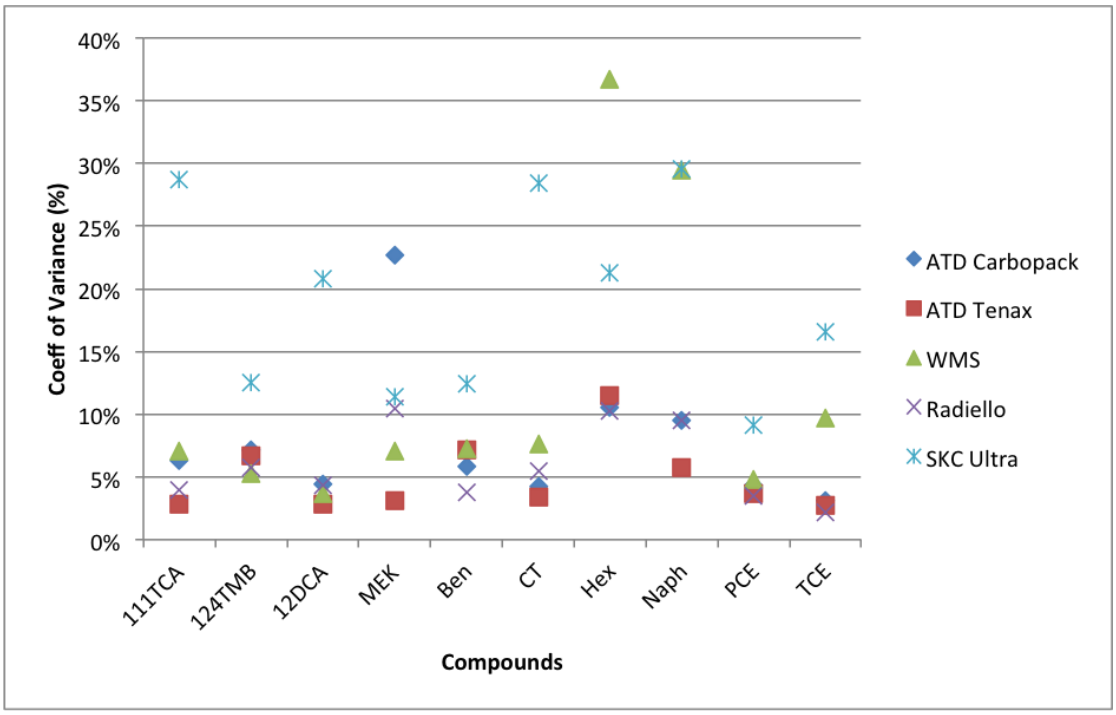


Figure 34: - Coefficient of variation (COV) for the initial center-point (ANOVA) testing

6.4 Fractional Factorial Test Results

The chamber conditions measured during the fractional factorial testing, the results of analysis of active and passive samples and the relative concentrations (passive/active) are presented in Appendix F. These data were combined with the center-point data and are summarized in two sets of figures: Figures 35a to e and Figures 36a to e. The former has the individual VOCs along the x-axis and the chamber runs in the legend. The latter shows the values of each of the five factors on the x-axis and the compounds in the legend. Considering that there were 24 chamber tests, with 10 VOCs, and five sampler types, each in triplicate, there were 3,600 passive concentration measurements, which makes it challenging to convey all of the results on fewer graphs. Figures 35a to e show the results of the laboratory chamber tests (center-point and fractional factorial tests) as normalized concentrations (C/Co, the passive sampler concentration divided by the chamber concentrations measured using pumped ATD tubes and EPA Method TO-17 analysis) for each compound. The success criteria lines (RPD = -45% and +45%) are shown for comparison purposes.

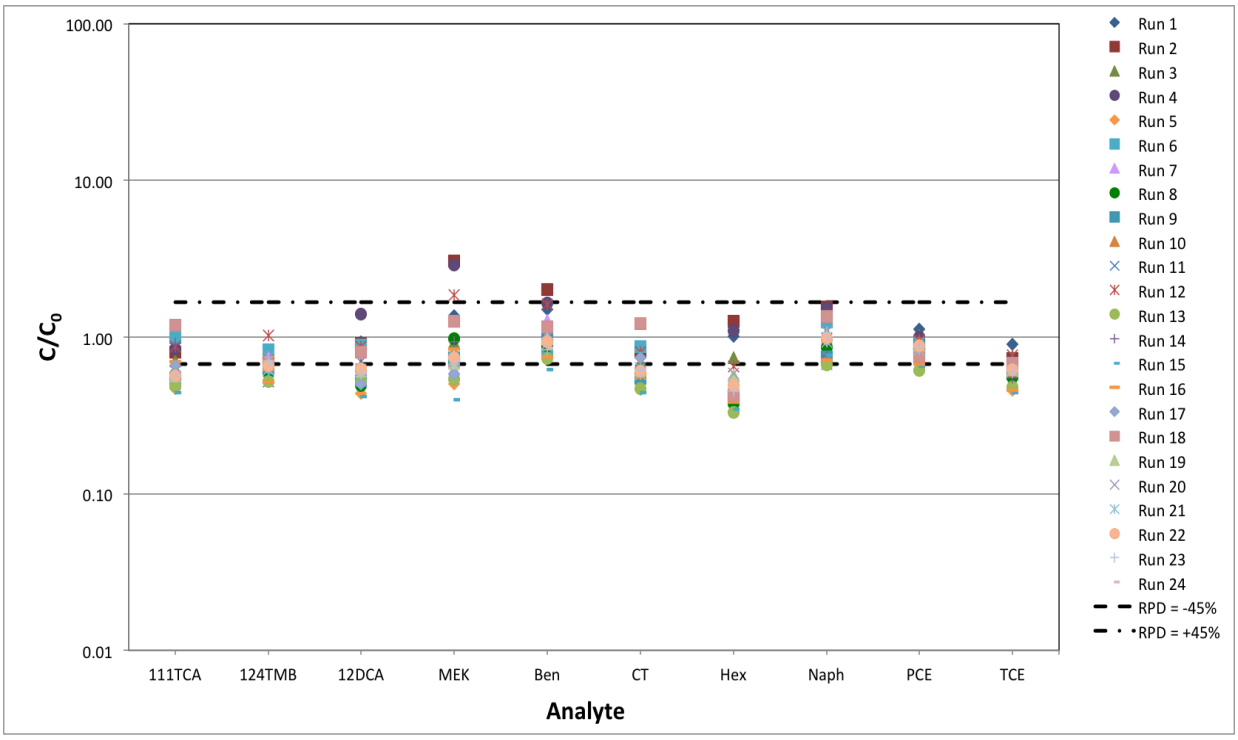


Figure 35a: ATD tube/Tenax TA results for center-point and fractional factorial lab tests

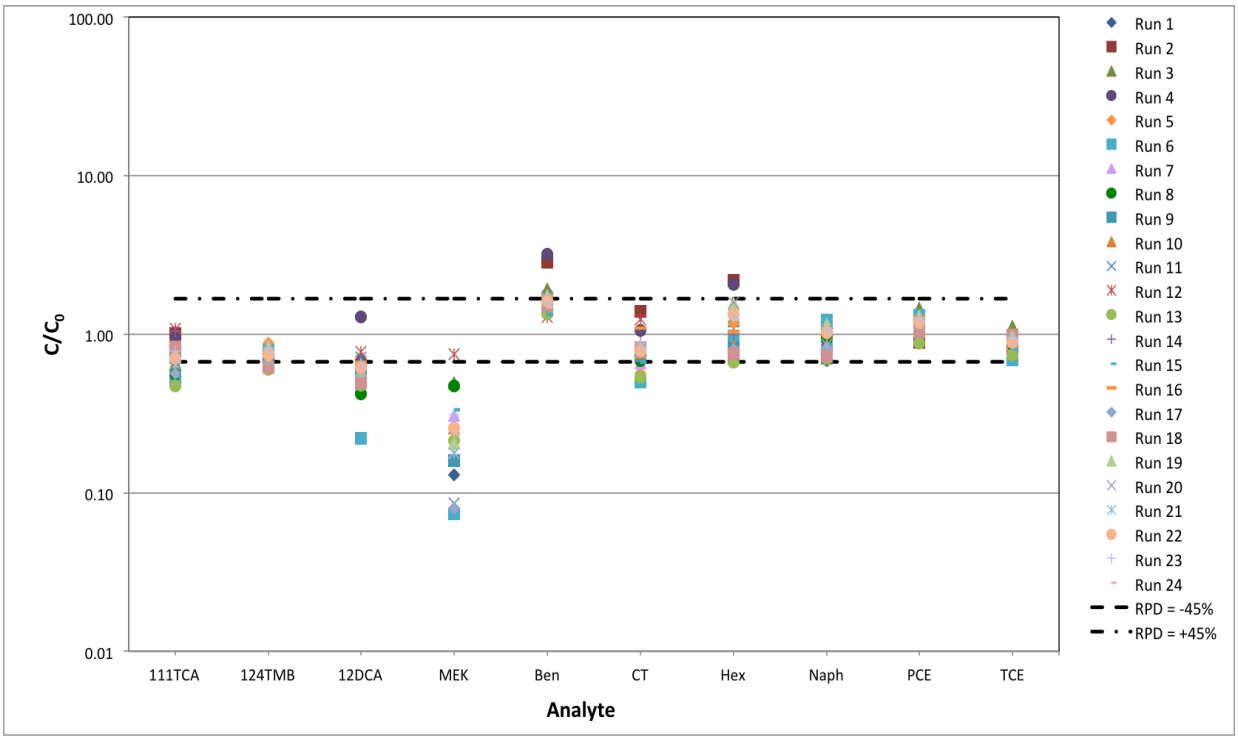


Figure 35b: ATD tube/Carbopack B results for center-point and fractional factorial lab tests

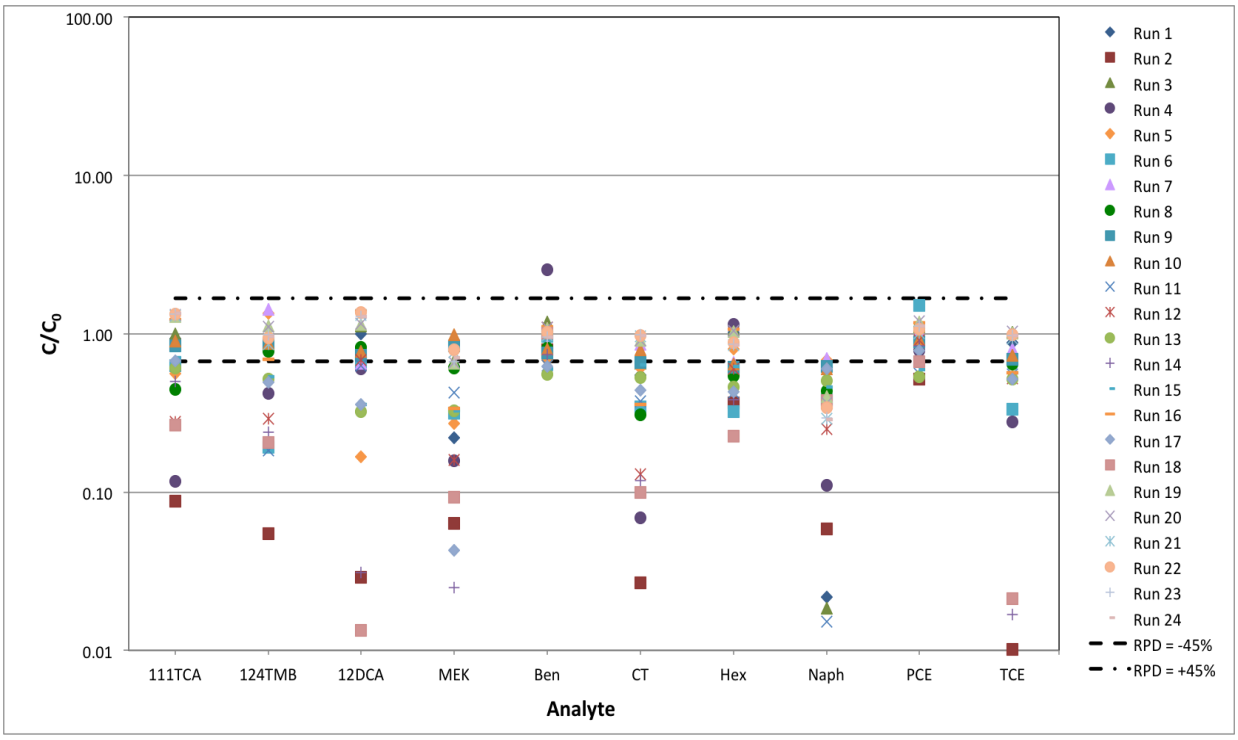


Figure 35c: SKC Ultra II results for center-point and fractional factorial lab tests

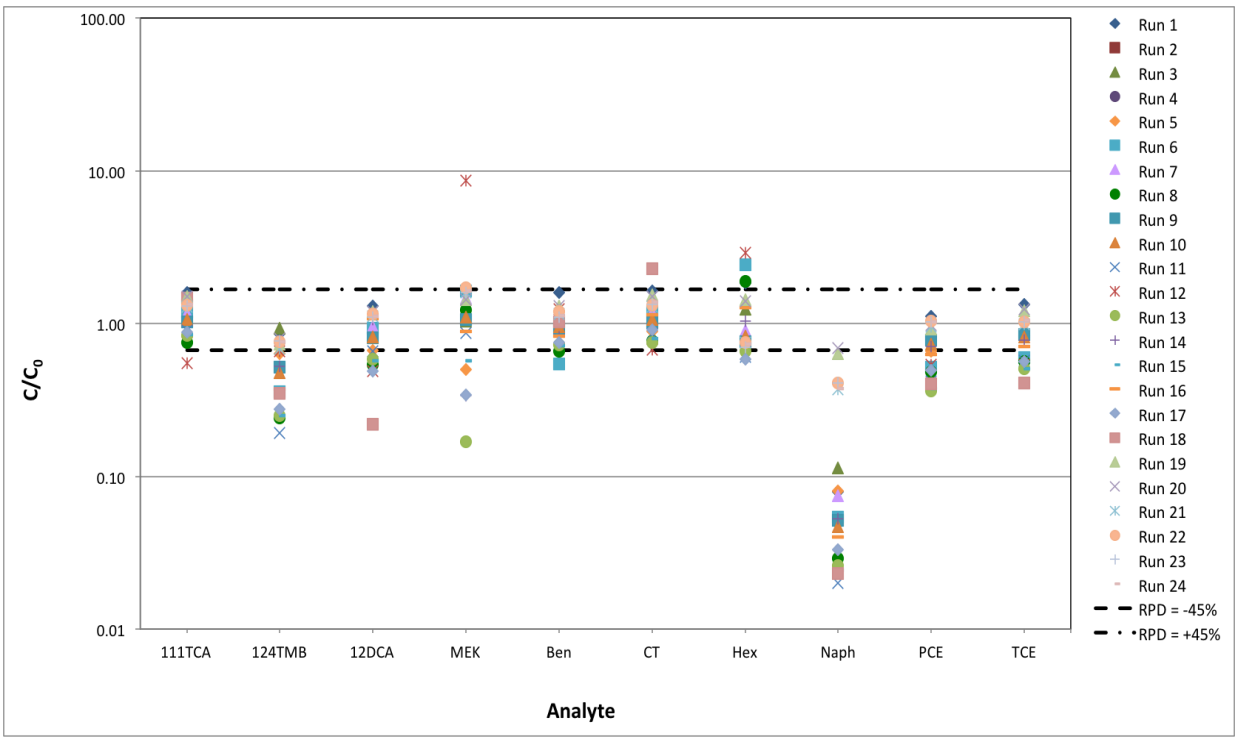


Figure 35d: WMS results for center-point and fractional factorial lab tests

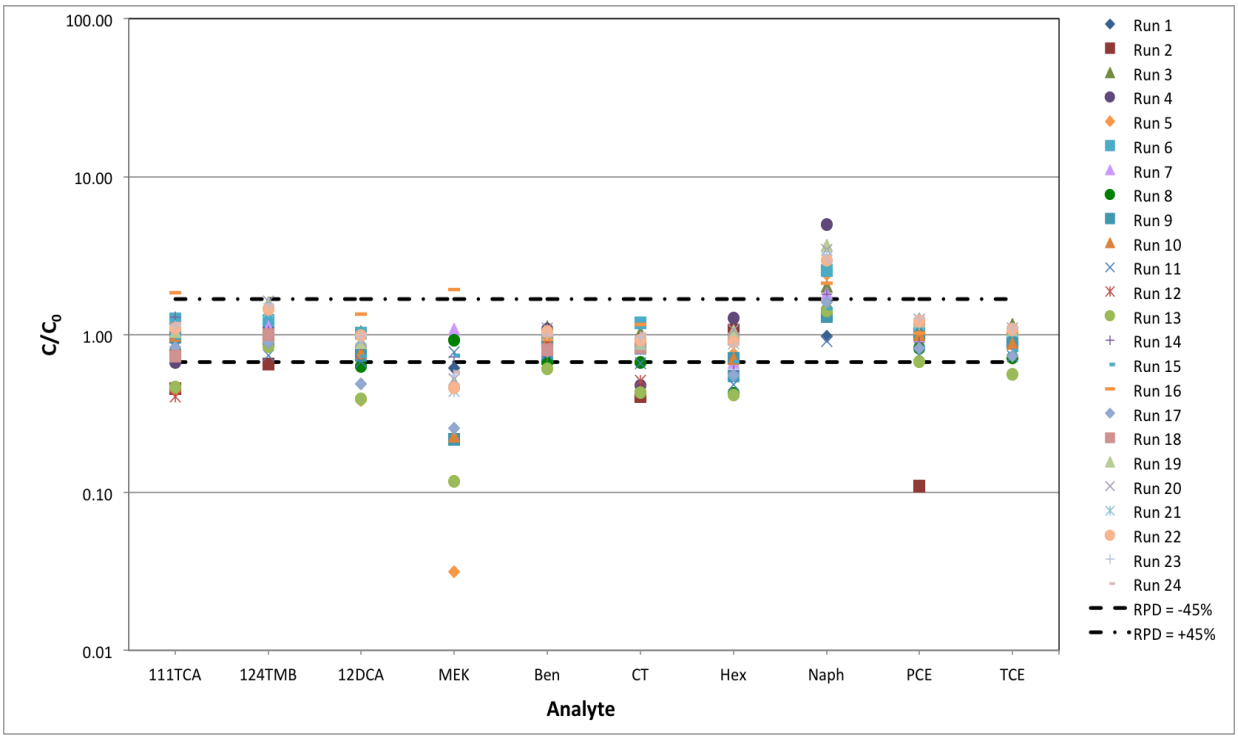


Figure 35e: Radiello results for center-point and fractional factorial lab tests

Some trends are evident in Figure 35:

- The ATD Tube Sampler with Tenax TA showed a low bias for hexane, which was not observed with the ATD tube with Carbopack B. The ATD Tube Sampler with Carbopack B showed a low bias for MEK and a high bias for benzene; whereas, the ATD tube sampler with Tenax TA showed no bias for MEK and benzene. These results demonstrate the importance of sorbent selection.
- Both ATD tube samplers showed a low bias for 12DCA, which likely means the calculated uptake rate of 0.5 mL/min (Table 3) is too high (0.3 mL/min would have provided the most accurate results);
- The SKC Ultra II results were biased low (up to 2 orders of magnitude) for some analyses of all compounds excluding benzene and PCE, most commonly for the low concentration and low velocity conditions. The low bias is partly attributable to sample preparation challenges associated with transferring the sorbent from the sampler to the ATD tube prior to analysis by Method TO-17, as described in Section 2.1.4 and a letter from CAS (Appendix F);
- The WMS showed a low bias for NAPH and 124TMB. These two compounds have the highest partitioning coefficients in the PDMS membrane, which causes much higher uptake rates, so the low bias may be attributable to the starvation effect. Recovery is also a potential issue with naphthalene, but the recovery from Anasorb 747 by CS_2 extraction has been shows to be reasonably good (63-68%) by Seepthapathy, 2009. Also, these compounds both had calculated uptake rates (see Table 3), and the

calculated values may simply have been higher than the actual uptake rates for the chamber conditions (by an average factor of 2 for 124TMB and 6 for NAPH); and

- The Radiello results were biased low by a factor of about 1.6 for MEK and high by a factor of about 2.3 for NAPH.

Figures 36a to f show the influence of the exposure chamber conditions on the relative concentrations (C/Co = passive sampler concentration divided by corresponding active sampler concentration) measured for each of the compounds with each of the samplers (including the Active ATD tube samples). Some observations are apparent by inspection of these charts:

- The high temperature tests were conducted at average temperatures ranging from about 27 to about 30°C;
- The ATD Tube with Tenax showed very low variability and minimal bias compared to the other methods and the Active ATD tubes, and the only apparent trend was slightly low bias in the 4 and 7 day samples compared to the 1-day sample;
- The ATD Tube with Carbopack B showed similar results to the ATD with Tenax, except for the low bias with MEK and high bias with benzene. This is consistent with the familiarity tests, inter-laboratory tests and center-point tests, and could be corrected in all these tests using a more specific uptake rate for these compounds and sorbent;
- The SKC Ultra sampler showed notably less variability and bias at the center-points compared to the high and low levels of each factor where the results were biased low and highly variable;
- The WMS sampler also showed notably less variability and bias at the center-points compared to the high and low levels of each factor. The WMS also showed more variability in the low concentration chamber tests compared to the center-point and high concentrations. The WMS sampler had some results below the reporting limit in the first two chamber tests conducted at the low concentration and short sample duration combination of conditions. To avoid non-detect results, the WMS sampler configuration was then changed to use a thermally-desorbable sorbent (Carbopack B) and a thermal desorption analysis (Modified TO-17) to increase sensitivity in runs 12 and 18. Consequently, some of the variability for the WMS sampler may be attributable to variability between the thermal desorption and solvent extraction methods. Also, the high bias from hexane laboratory contamination was much larger compared to the adsorbed mass from the chamber in the two low concentration/short duration chambers, resulting in a C/Co value >10. Seethapathy and Górecki (2010b) studied the effect of humidity and temperature on the WMS sampler and found humidity had no significant effect and the uptake rates decreased with increasing temperature, but only by a margin of about 20% or so over the range studied here, so the variability is not likely attributable to humidity or temperature; and
- The Radiello showed minimal bias and variability and no clear trends attributable to the five factors except for the high bias with naphthalene and the low bias with MEK. The biases for these two compounds were similar in the inter-laboratory and center-point tests, so the accuracy would improve is a more specific uptake rate was used for the compounds and sorbent.

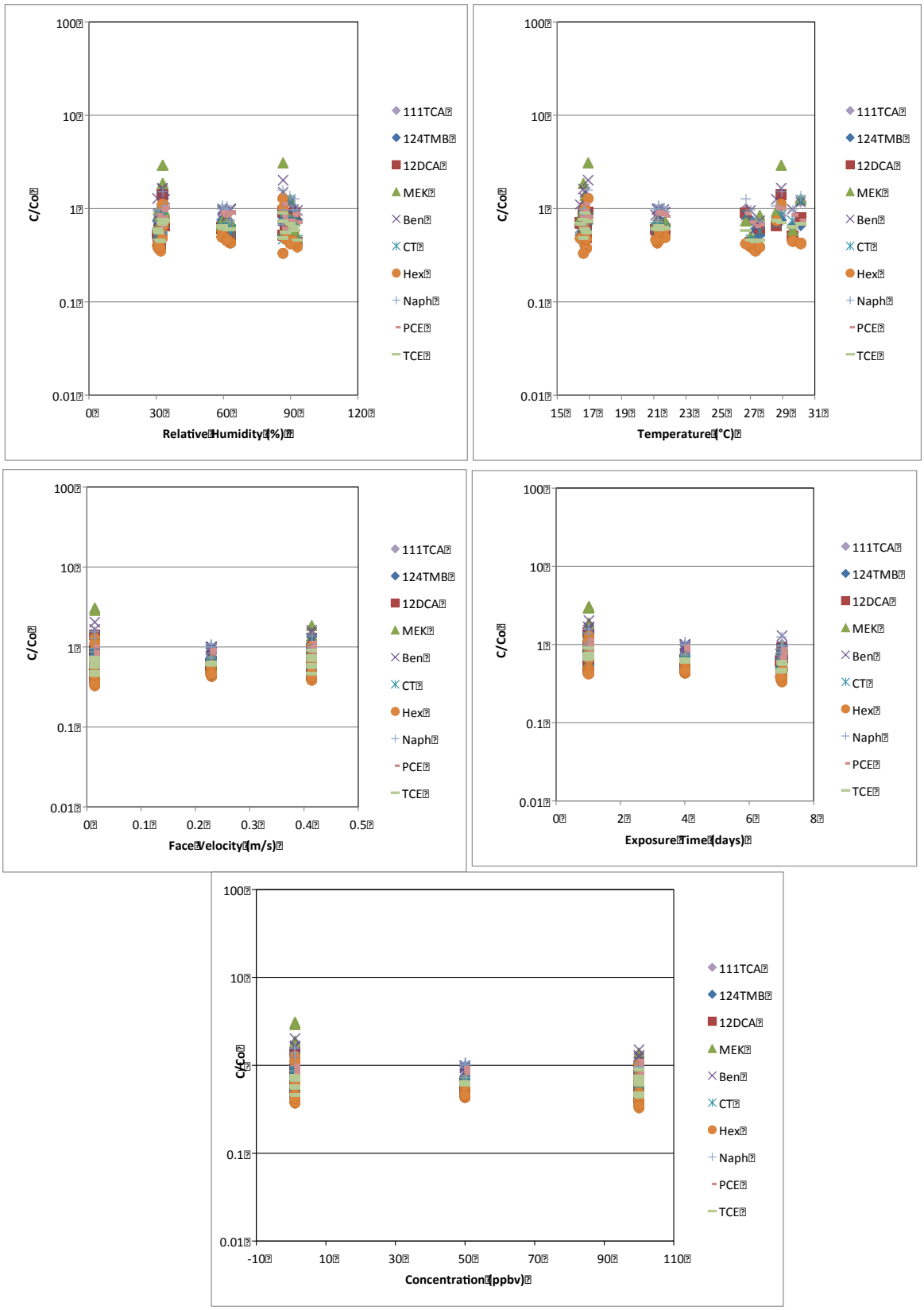


Figure 36a: ATD Tenax low concentration laboratory test data

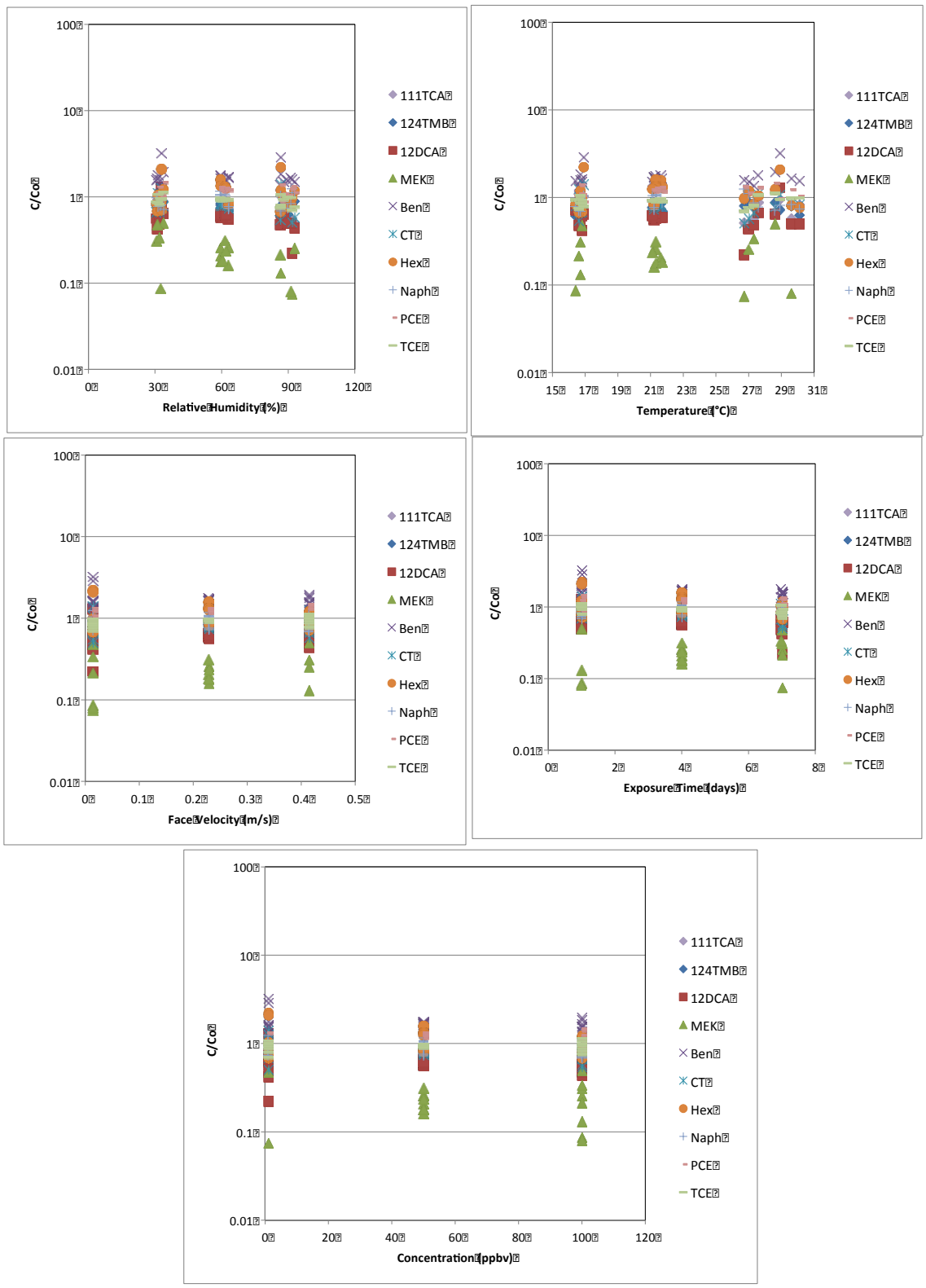


Figure 36b: ATD Carbopack B low concentration laboratory test data

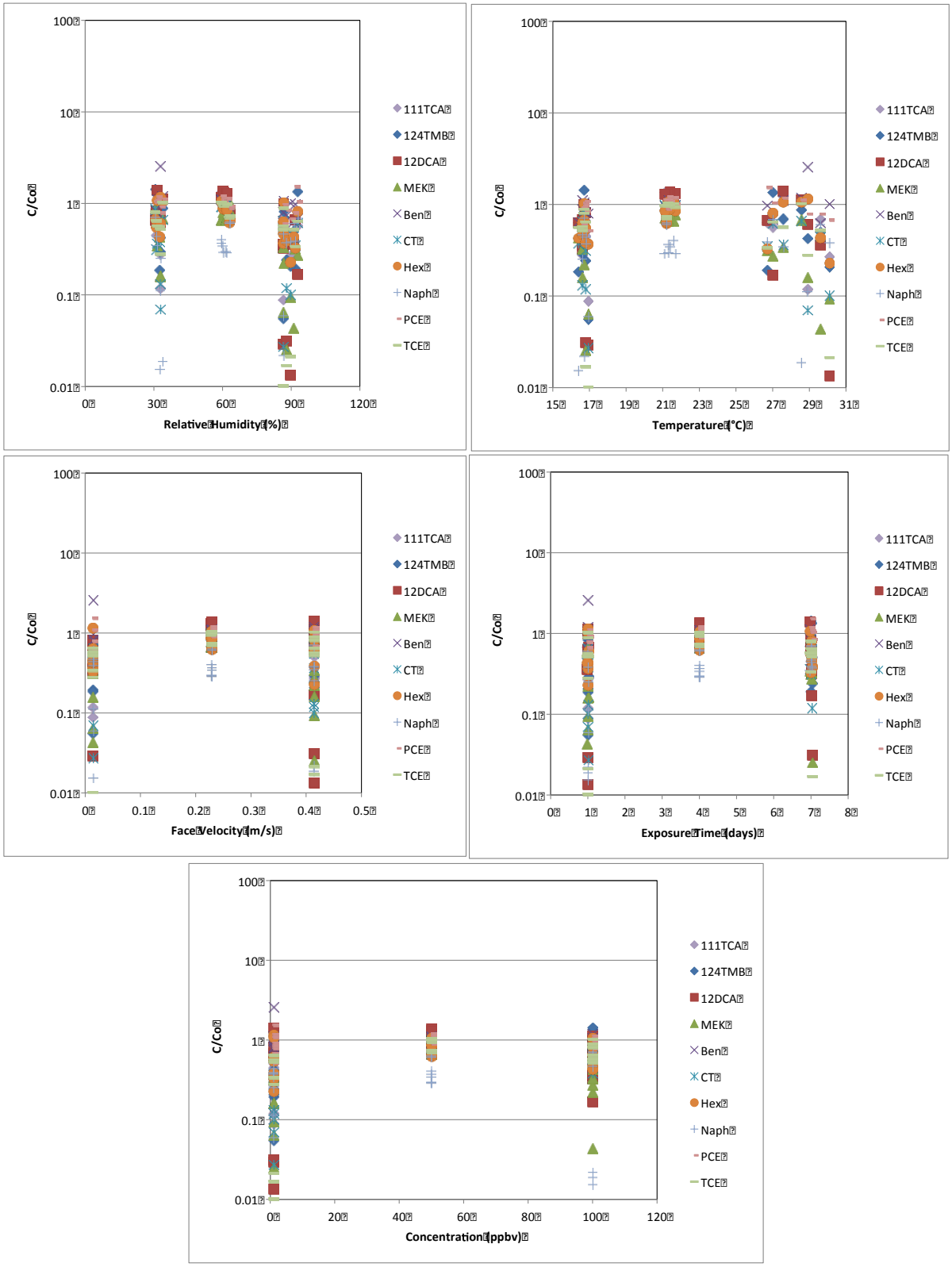


Figure 36c: SKC Ultra II low concentration laboratory test data

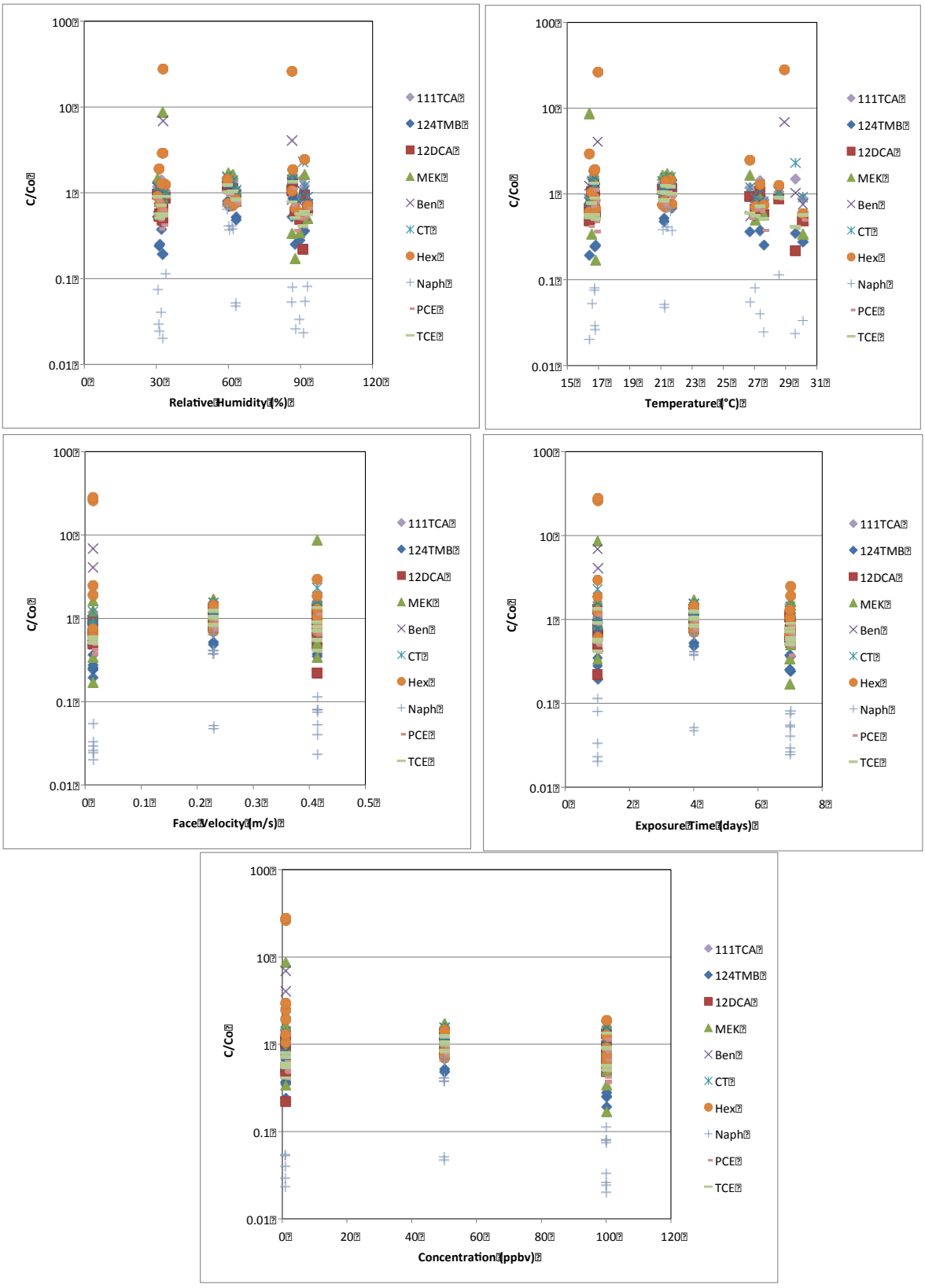


Figure 36d: WMS low concentration laboratory test data

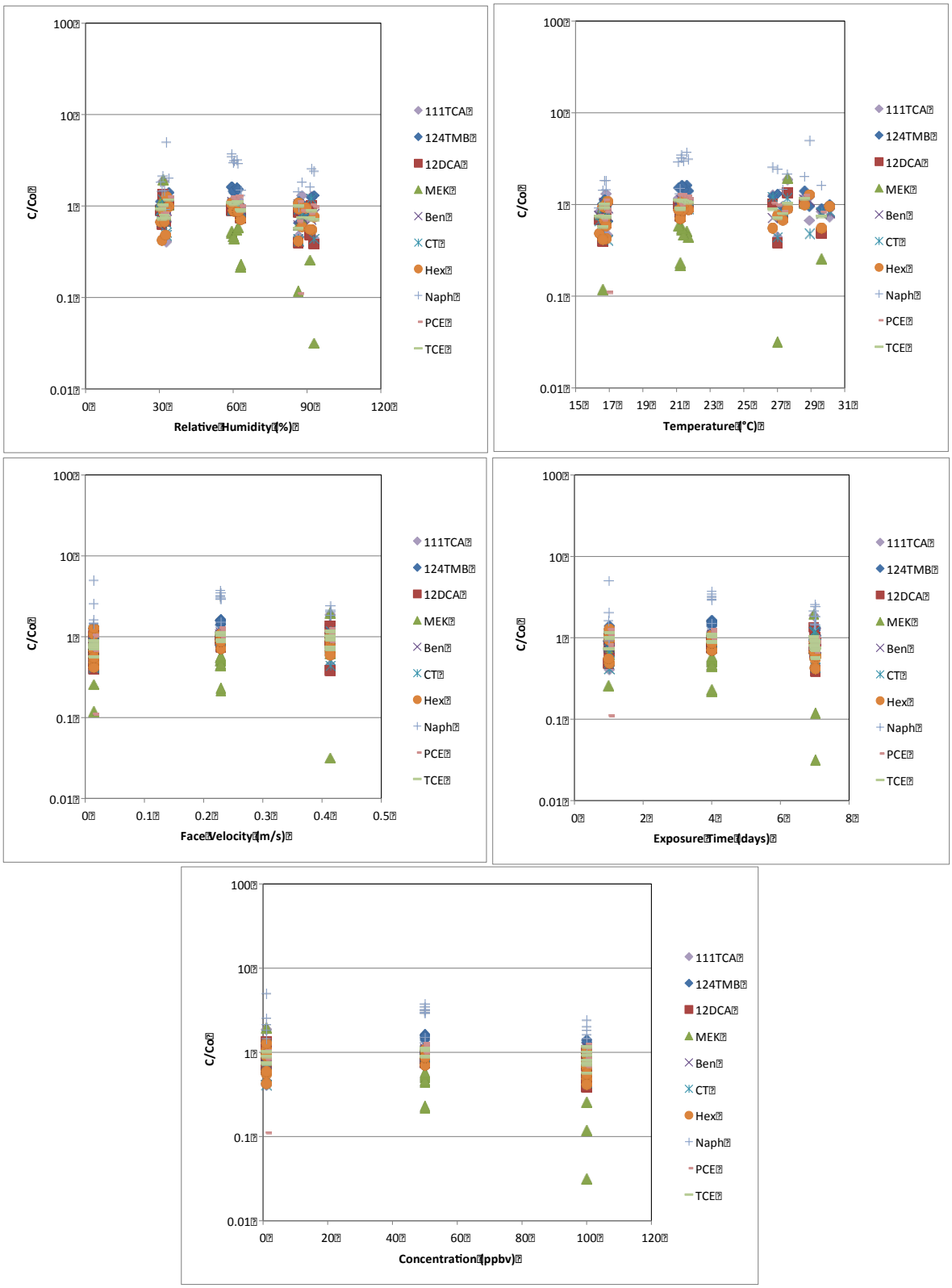


Figure 36e: Radiello low concentration laboratory test data

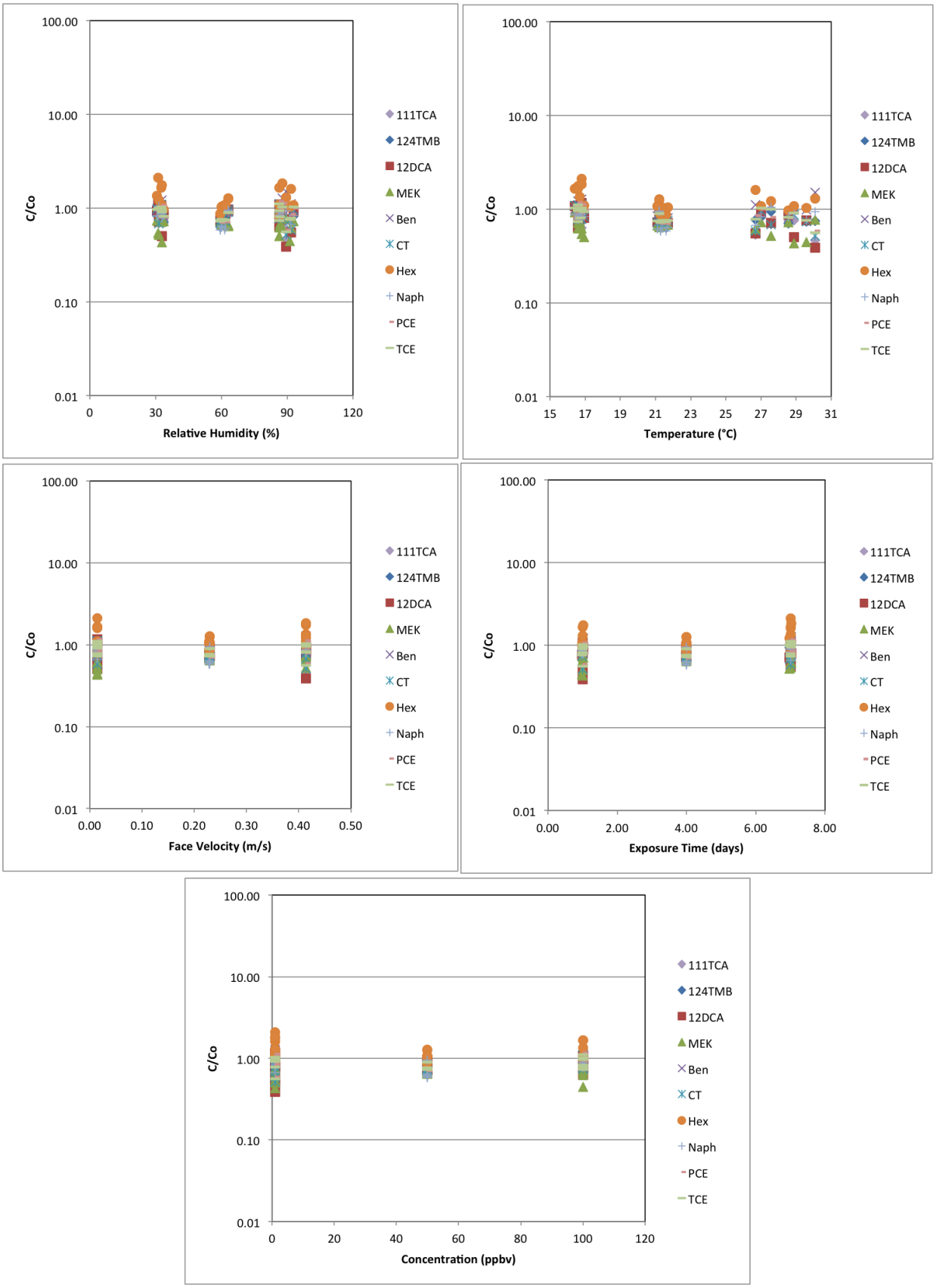


Figure 36f: Active ATD Tube low concentration laboratory test data

6.5 High Concentration Test Results

The temperature, relative humidity and pressure data recorded during the high concentration laboratory tests are presented in Table 13. The temperature showed a standard deviation of less than 1°C and the humidity showed a standard deviation of less than 2% RH, which shows the chamber conditions were very steady throughout the testing program.

Table 13: Chamber conditions during high concentration laboratory testing

Parameter	Temperature (°C)	Humidity (% RH)	Absolute Pressure (PSIA)
1ppmv (Dec 3 to 7, 2010)			
Range	23.5 to 24.2	78 to 83	14.02 to 14.10
Mean	24.0	80	14.06
Standard Deviation	0.121	0.685	0.020
Coefficient of Variation	0.005	0.009	0.001
10 & 100ppmv (Dec 9 to 12, 2010)			
Range	22.2 to 24.3	76 to 84	14.06 to 14.19
Mean	23.3	80	14.12
Standard Deviation	0.813	1.66	0.038
Coefficient of Variation	0.035	0.021	0.003

The concentrations measured using 30-minute sample durations with each of the passive samplers and the Summa canisters are presented in Tables 14a, b and c, for the 1, 10 and 100 ppm_v tests, respectively. The mean, standard deviation and COV for the three replicates for each sampler at each concentration level are also included in Tables 14a, b and c. Most of the samplers provided concentrations that met the success criteria (RPD < 50% compared to results of the Summa canister samples), with the following exceptions:

Naphthalene - Radiello: not detected
3M OVM 3500: not detected in 0.1 ppm_v samples
SKC Ultra: not detected in the 1 ppm_v samples
WMS: low bias of about 8X in the 0.1 ppm_v and 3X in 1 ppm_v samples

MEK - Radiello: low bias by a factor of about 2 to 3
ATD Tube: not detected in the 1 and 10 ppm_v samples
3M OVM 3500: low bias by a factor of about 3 to 5
SKC Ultra: high bias with thermal desorption @ 1ppm_v and low bias via solvent extraction at 10 and 100 ppm_v
WMS: not detected in the 1 ppm_v samples

1,2,4-TMB - Radiello: low bias by about 3X

Naphthalene and 1,2,4-trimethylbenzene were the two compounds with the highest and second highest K_{oc} values (Table 1), and MEK was the compound with the highest solubility. Less sorptive and less soluble compounds yielded better agreement between the passive samplers and Summa canisters. The results of the high concentration laboratory tests are summarized graphically in Figure 37, along with control lines for RPD (+/- 50%).

Table 14a: Concentrations measured in exposure chamber at 1 ppm_v (NAPH=0.1 ppm_v)

1ppm		Analyte	MEK	NHEX	12DCA	111TCA	BENZ	CTET	TCE	PCE	124TMB	NAPH
WMS Anasorb 747	Uptake Rate	(mL/min)	1.3	1.3	2.6	1.3	2.2	1.5	3.3	5.4	13	26
1-WMS-a		($\mu g/m^3$)	ND	1,650	1,020	1,260	574	1,420	1,320	1,620	960	17
1-WMS-b		($\mu g/m^3$)	ND	1,650	1,010	1,260	574	1,420	1,320	1,500	853	16
1-WMS-c		($\mu g/m^3$)	ND	2,800	1,060	1,390	636	1,560	1,320	1,620	880	12
		Mean		2,040	1,030	1,300	594	1,470	1,320	1,580	898	15
		std.dev.		661	27	76	36	77	0	72	56	3
		COV		0.32	0.03	0.06	0.06	0.05	0.00	0.05	0.06	0.18
ATD Tenax TA	Uptake Rate	(mL/min)	0.50	0.50	0.50	0.50	0.35	0.50	0.41	0.50	0.62	0.50
1-ATD-a		($\mu g/m^3$)	ND	1,600	1,000	1,000	2,190	1,530	2,280	2,070	1,020	133
1-ATD-b		($\mu g/m^3$)	ND	1,470	933	867	1,910	1,330	2,110	1,870	753	ND
1-ATD-c		($\mu g/m^3$)	ND	1,530	1,070	1,070	1,910	1,730	2,200	1,930	914	ND
		Mean		1,530	1,000	978	2,000	1,530	2,200	1,960	896	133
		std.dev.		67	67	102	165	200	81	102	135	
		COV		0.04	0.07	0.10	0.08	0.13	0.04	0.05	0.15	
Radiello Charcoal	Uptake Rate	(mL/min)	79	66	77	62	80	67	69	59	50	25
1-RAD-a		($\mu g/m^3$)	611	1,020	1,150	1,730	850	1,610	1,430	1,530	362	ND
1-RAD-b		($\mu g/m^3$)	637	1,340	1,380	2,170	1,070	1,900	1,790	2,060	530	ND
1-RAD-c		($\mu g/m^3$)	645	1,190	1,240	1,940	960	1,840	1,600	1,830	476	ND
		Mean	631	1,180	1,260	1,950	961	1,790	1,610	1,810	456	
		std.dev.	18	163	115	222	111	153	177	265	86	
		COV	0.03	0.14	0.09	0.11	0.12	0.09	0.11	0.15	0.19	
3M OVM 3500	Uptake Rate	(mL/min)	36	32	33	31	36	30	31	28	26	25
1-3M-a		($\mu g/m^3$)	322	979	964	1,400	1,220	1,550	1,390	2,000	1,030	ND
1-3M-b		($\mu g/m^3$)	313	865	873	1,290	826	1,330	1,290	1,760	947	ND
1-3M-c		($\mu g/m^3$)	331	1,040	1,100	1,510	939	1,660	1,500	2,110	1,120	ND
		Mean	322	962	981	1,400	995	1,510	1,390	1,960	1,030	
		std.dev.	9	90	116	108	203	169	107	179	84	
		COV	0.03	0.09	0.12	0.08	0.20	0.11	0.08	0.09	0.08	
SKC Carbograph 5	Uptake Rate	(mL/min)	17	14	13	13	16	13	15	13	13	13
1-SKC-a		($\mu g/m^3$)	3,020	1,100	1,010	1,260	1,090	1,050	1,040	1,290	900	125
1-SKC-b		($\mu g/m^3$)	2,850	1,270	1,284	1,660	1,200	1,470	1,310	1,670	1,180	156
1-SKC-c		($\mu g/m^3$)	2,770	980	957	1,190	1,150	1,050	938	1,210	842	120
		Mean	2,880	1,120	1,080	1,371	1,150	1,190	1,100	1,390	974	134
		std.dev.	130	145	175	252	56	245	192	249	181	19
		COV	0.05	0.13	0.16	0.18	0.05	0.21	0.18	0.18	0.19	0.14
1-SUMMA-a		($\mu g/m^3$)	1,710	1,620	1,810	2,450	1,340	2,580	2,140	2,760	1,950	144
1-SUMMA-b		($\mu g/m^3$)	1,680	1,580	1,770	2,340	1,300	2,700	2,030	2,560	1,800	139
1-SUMMA-c		($\mu g/m^3$)	1,230	1,220	1,320	1,780	944	2,040	1,530	1,870	1,150	80
		Mean	1,540	1,470	1,640	2,190	1,190	2,440	1,900	2,400	1,640	121
		std.dev.	269	218	275	357	217	351	321	470	426	36
		COV	0.17	0.15	0.17	0.16	0.18	0.14	0.17	0.20	0.26	0.29

Table 14b: Concentrations measured in exposure chamber at 10 ppm_v (NAPH=1ppm_v)

10ppm		Analyte	MEK	NHEX	12DCA	111TCA	BENZ	CTET	TCE	PCE	124TMB	NAPH
WMS Anasorb 747	Uptake Rate	(mL/min)	1.3	1.3	2.6	1.3	2.2	1.5	3.3	5.4	13	26
10-WMS-a		($\mu g/m^3$)	8,270	20,100	20,700	28,900	17,100	33,300	26,400	29,900	17,300	365
10-WMS-b		($\mu g/m^3$)	7,730	18,600	19,400	26,000	15,500	31,100	25,400	30,500	18,400	286
10-WMS-c		($\mu g/m^3$)	9,600	18,600	20,700	26,200	17,100	31,100	25,400	29,900	18,700	339
		Mean	8,530	19,100	20,200	27,000	16,500	31,900	25,700	30,100	18,100	330
		std.dev.	961	881	746	1,597	895	1,283	587	360	706	40
		COV	0.11	0.05	0.04	0.06	0.05	0.04	0.02	0.01	0.04	0.12
ATD Tenax TA	Uptake Rate	(mL/min)	0.50	0.50	0.50	0.50	0.35	0.50	0.41	0.50	0.62	0.50
10-ATD-a		($\mu g/m^3$)	ND	26,700	26,700	24,700	34,300	38,700	42,300	40,700	19,400	1,200
10-ATD-b		($\mu g/m^3$)	ND	28,000	26,700	23,300	35,200	36,700	42,300	40,700	18,800	1,400
10-ATD-c		($\mu g/m^3$)	ND	27,300	26,700	26,700	35,200	33,300	42,300	41,300	19,400	1,200
		Mean		27,300	26,700	24,889	34,900	36,200	42,300	40,900	19,200	1,270
		std.dev.		667	0	1,678	550	2,694	0	385	310	115
		COV		0.02	0.00	0.07	0.02	0.07	0.00	0.01	0.02	0.09
Radiello Charcoal	Uptake Rate	(mL/min)	79	66	77	62	80	67	69	59	50	25
10-RAD-a		($\mu g/m^3$)	8,000	22,700	23,500	36,800	18,100	34,600	31,000	35,000	8,650	ND
10-RAD-b		($\mu g/m^3$)	5,930	17,700	18,200	28,600	14,000	27,000	24,000	26,800	6,000	ND
10-RAD-c		($\mu g/m^3$)	8,300	23,100	23,800	37,500	18,400	35,200	31,600	35,700	8,030	ND
		Mean	7,400	21,200	21,800	34,300	16,800	32,200	28,900	32,500	7,560	
		std.dev.	1,280	3,000	3,130	4,920	2,420	4,590	4,230	4,970	1,390	
		COV	0.17	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.18	
3M OVM 3500	Uptake Rate	(mL/min)	36	32	33	31	36	30	31	28	26	25
10-3M-a		($\mu g/m^3$)	3,500	17,700	19,100	27,000	14,100	32,000	27,900	38,700	19,500	420
10-3M-b		($\mu g/m^3$)	3,320	18,800	20,100	28,000	15,000	33,100	28,900	39,900	20,800	420
10-3M-c		($\mu g/m^3$)	3,590	20,800	22,100	30,200	16,000	36,400	32,200	43,400	22,000	474
		Mean	3,470	19,100	20,420	28,400	15,000	33,800	29,700	40,700	20,800	438
		std.dev.	141	1,590	1,530	1,650	939	2,300	2,230	2,440	1,300	31
		COV	0.04	0.08	0.08	0.06	0.06	0.07	0.08	0.06	0.06	0.07
SKC Charcoal	Uptake Rate	(mL/min)	17	14	13	13	16	13	15	13	13	13
10-SKC-a		($\mu g/m^3$)	6,660	33,700	33,500	44,100	22,200	46,800	37,100	51,000	26,000	ND
10-SKC-b		($\mu g/m^3$)	5,080	25,700	32,100	40,700	20,500	44,100	34,600	47,300	23,500	ND
10-SKC-c		($\mu g/m^3$)	7,240	31,300	32,700	41,700	21,600	45,600	36,200	49,300	25,500	ND
		Mean	6,320	30,300	32,800	42,200	21,400	45,500	36,000	49,200	25,000	
		std.dev.	1,120	4,130	719	1,730	868	1,340	1,280	1,850	1,300	
		COV	0.18	0.14	0.02	0.04	0.04	0.03	0.04	0.04	0.05	
10-SUMMA-a		($\mu g/m^3$)	14,100	27,300	30,100	41,700	22,100	41,300	35,600	44,200	23,500	1,068
10-SUMMA-b		($\mu g/m^3$)	15,300	27,300	30,700	41,700	22,100	47,300	35,600	43,500	23,000	961
10-SUMMA-c		($\mu g/m^3$)	16,500	28,400	31,300	43,400	23,100	49,700	37,200	47,000	26,500	1,230
10-SUMMA-d		($\mu g/m^3$)	16,200	26,900	28,900	41,800	21,500	46,100	33,400	38,700	17,500	748
10-SUMMA-e		($\mu g/m^3$)	16,200	26,200	28,500	39,500	21,000	44,900	32,300	38,700	18,500	748
		Mean	15,700	27,200	29,900	41,600	21,900	45,900	34,800	42,400	21,800	951
		std.dev.	983	778	1,220	1,390	849	3,100	1,960	3,640	3,740	208
		COV	0.06	0.03	0.04	0.03	0.04	0.07	0.06	0.09	0.17	0.22

Notes: ND – Not Detected

Table 14c: Concentrations (µg/m^3) measured in the exposure chamber at 100 ppm$_v$

100ppm			MEK	NHEX	12DCA	111TCA	BENZ	CTET	TCE	PCE
WMS Anasorb 747	Uptake Rate	(mL/min)	1.3	1.3	2.6	1.3	2.2	1.5	3.3	5.4
100-WMS-a		(µg/m^3)	98,700	181,000	207,000	252,000	171,000	311,000	264,000	324,000
100-WMS-b		(µg/m^3)	120,000	201,000	220,000	262,000	186,000	333,000	274,000	324,000
100-WMS-c		(µg/m^3)	107,000	168,000	194,000	236,000	155,000	289,000	244,000	293,000
		Mean	108,000	183,000	207,000	250,000	171,000	311,000	261,000	314,000
		std.dev.	11,000	16,700	12,900	13,200	15,500	22,200	15,500	18,000
		COV	0.10	0.09	0.06	0.05	0.09	0.07	0.06	0.06
ATD Tenax TA	Uptake Rate	(mL/min)	0.50	0.50	0.50	0.50	0.35	0.50	0.41	0.50
100-ATD-a		(µg/m^3)	140,000	307,000	320,000	380,000	467,000	440,000	561,000	533,000
100-ATD-b		(µg/m^3)	133,000	280,000	293,000	353,000	429,000	407,000	512,000	487,000
100-ATD-c		(µg/m^3)	147,000	300,000	307,000	367,000	457,000	427,000	537,000	513,000
		Mean	140,000	296,000	307,000	367,000	451,000	424,000	537,000	511,000
		std.dev.	6,670	13,900	13,300	13,300	19,800	16,800	24,400	23,400
		COV	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.05
Radiello Charcoal	Uptake Rate	(mL/min)	79	66	77	62	80	67	69	59
100-RAD-a		(µg/m^3)	67,200	247,000	260,000	396,000	202,000	386,000	357,000	414,000
100-RAD-b		(µg/m^3)	78,400	231,000	252,000	382,000	192,000	372,000	338,000	343,000
100-RAD-c		(µg/m^3)	88,400	236,000	245,000	377,000	190,000	369,000	340,000	410,000
		Mean	78,000	238,000	253,000	385,000	195,000	376,000	345,000	389,000
		std.dev.	10,600	8,140	7,440	9,800	6,260	8,890	10,300	39,600
		COV	0.14	0.03	0.03	0.03	0.03	0.02	0.03	0.10
3M OVM 3500	Uptake Rate	(mL/min)	36	32	33	31	36	30	31	28
100-3M-a		(µg/m^3)	40,500	188,000	201,000	280,000	141,000	331,000	300,000	376,000
100-3M-b		(µg/m^3)	39,600	188,000	201,000	291,000	141,000	342,000	311,000	399,000
100-3M-c		(µg/m^3)	40,500	177,000	191,000	280,000	141,000	320,000	279,000	364,000
		Mean	40,200	184,000	197,000	284,000	141,000	331,000	297,000	379,000
		std.dev.	532	6,010	5,800	6,230	0	11,040	16,400	18,000
		COV	0.01	0.03	0.03	0.02	0.00	0.03	0.06	0.05
SKC Charcoal	Uptake Rate	(mL/min)	17	14	13	13	16	13	15	13
1-SKC-a		(µg/m^3)	43,100	234,000	295,000	382,000	172,000	425,000	334,000	439,000
1-SKC-b		(µg/m^3)	51,200	258,000	297,000	376,000	165,000	421,000	331,000	443,000
1-SKC-c		(µg/m^3)	54,200	295,000	346,000	451,000	189,000	489,000	402,000	535,000
		Mean	49,500	262,000	313,000	403,000	175,000	445,000	355,000	473,000
		std.dev.	5,720	31,100	29,300	41,900	12,500	38,100	40,100	54,400
		COV	0.12	0.12	0.09	0.10	0.07	0.09	0.11	0.12
10-SUMMA-a		(µg/m^3)	123,000	215,000	231,000	311,000	166,000	354,000	252,000	235,000
10-SUMMA-b		(µg/m^3)	117,000	205,000	202,000	296,000	153,000	330,000	241,000	276,000
10-SUMMA-c		(µg/m^3)	138,000	208,000	223,000	295,000	163,000	336,000	252,000	283,000
10-SUMMA-d		(µg/m^3)	147,000	215,000	231,000	300,000	166,000	342,000	252,000	235,000
10-SUMMA-e		(µg/m^3)	150,000	223,000	239,000	317,000	176,000	366,000	279,000	325,000
		Mean	135,000	213,000	225,000	304,000	165,000	345,000	255,000	271,000
		std.dev.	14,600	7,000	14,200	9,860	8,170	14,400	14,300	37,700
		COV	0.11	0.03	0.06	0.03	0.05	0.04	0.06	0.14

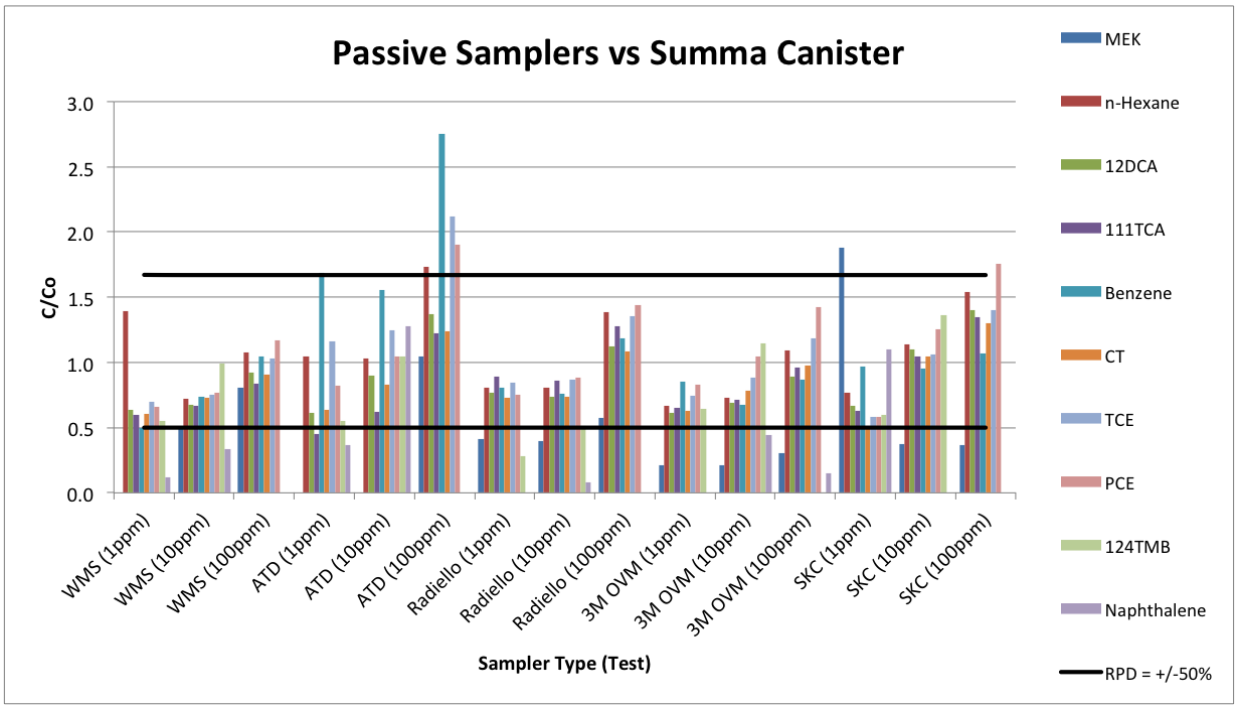


Figure 37: Average (of three replicates) relative concentrations (passive/Summa) for 1, 10 and 100 ppmv laboratory tests

The results for the low-uptake rate samplers are provided in Table 15. The Radiello sampler (yellow body), WMS-LU (0.8 mL vial) and the ATD tube sampler with the low-uptake rate cap showed average results within a factor of 0.72, 1.08 and 0.72, respectively of the Summa canister results in the 10 ppmv test at a flow rate of 100 mL/min, which shows the low uptake rate samplers have a comparable accuracy to the regular uptake rate samplers.

Under no-flow conditions, the Radiello, WMS and ATD passive samplers showed lower concentrations compared to the samples collected with 100 mL/min flow in the chamber. The negative bias under no-flow conditions was similar for all three samplers no-flow/100 mL/min ratios were 0.65, 0.68, and 0.71 for the Radiello, WMS and ATD, respectively). This does not appear to be attributable to the starvation effect because they have considerably different uptake rates (about 25 mL/min for the Radiello, about 0.5 mL/min for the WMS-LU and about 0.05 mL/min for the ATD tube). The low-uptake rate Radiello also showed a marked low bias for 124TMB, and to a lesser degree PCE, which are the compounds with the highest organic carbon partitioning coefficient (Koc) values and lowest free air diffusion coefficients (excepting NAPH which was not detected by the Radiello), so the low bias may be attributable to sorptive losses. The ATD tube sampler showed a high bias for BENZ and NAPH and a marked low bias for 111TCA, CTET and 124TMB. The SKC/Charcoal sampler with the low-uptake rate cap showed detectable concentrations for only 3 compounds in the 100 ppmv stagnant test. The low uptake WMS-LU sampler showed much more consistent results for all compounds under both flowing and stagnant conditions.

Table 15: Low-uptake rate sampler results (in µg/m^3) for three tests: 10 ppmv with 100 mL/min flow; 10 ppmv stagnant, and 100 ppmv stagnant

10 ppmv & 100 mL/min	**MEK**	**NHEX**	**12DCA**	**111TCA**	**BENZ**	**CTET**	**TCE**	**PCE**	**124TMB**	**NAPH**	**Mean**
Active Tube Sample #1	14,400	41,900	41,400	55,800	34,400	65,100	51,200	60,500	41,400	1,020	
Active Tube Sample #2	11,600	34,400	38,600	51,200	30,200	60,500	46,500	55,800	36,700	884	
Average Active Tube Concentration	13,000	38,100	40,000	53,500	32,300	62,800	48,800	58,100	39,100	953	
Radiello Yellow Body	12,200	30,800	35,900	61,340	27,800	44,900	36,800	18,800	230	ND	
Radiello/Active (C/Co)	0.94	0.81	0.90	1.15	0.86	0.72	0.75	0.32	0.01		0.72
SKC 12 hole cap	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
WMS 0.8 mL vial #1	17,500	30,100	42,800	57,100	29,900	66,700	50,000	65,500	33,700	1,470	
WMS 0.8 mL vial #2	17,300	30,100	42,800	59,000	29,900	68,200	48,500	59,500	34,100	1,530	
Average WMS/Active (C/Co)	1.34	0.79	1.07	1.09	0.92	1.07	1.01	1.08	0.87	1.57	1.08
ATD Low Uptake #1	10,700	18,700	29,300	1,870	81,900	16,700	28,700	30,100	2,260	5,600	
ATD Low Uptake #2	16,000	20,000	30,000	14,000	82,900	20,000	28,700	39,000	2,800	6,400	
Average ATD/Active (C/Co)	1.02	0.51	0.74	0.15	2.55	0.29	0.59	0.59	0.06	**6.29#**	0.72
10 ppmv no flow											
Active Tube Sample	17,500	37,500	37,500	54,200	29,200	61,700	49,200	60,800	38,300	833	
Radiello Yellow	12,800	19,300	21,100	37,300	16,400	27,500	22,700	12,200	1,100	ND	
Radiello/Active (C/Co)	0.73	0.52	0.56	0.69	0.56	0.45	0.46	0.20	0.03		0.47
SKC 12 hole cap	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
WMS 0.8 mL vial #1	13,000	24,800	28,900	40,000	21,900	48,100	34,100	39,300	18,300	733	
WMS 0.8 mL vial #2	14,100	20,900	30,800	43,800	22,900	51,200	35,600	42,300	19,800	800	
Average WMS/Active (C/Co)	0.77	0.61	0.80	0.77	0.77	0.80	0.71	0.67	0.50	0.92	0.73
ATD Low Uptake #1	13,300	16,000	17,300	9,330	81,900	12,000	17,300	20,300	2,150	9,330	
ATD Low Uptake #2	10,700	6,200	16,700	2,470	53,300	3,130	10,700	8,940	2,690	5,130	
Average ATD/Active (C/Co)	0.69	0.30	0.45	0.11	2.32	0.12	0.28	0.24	0.06	**8.68#**	0.51
100 ppmv no flow											
Summa	140,000	240,000	250,000	340,000	180,000	440,000	300,000	380,000			
SKC 12 Hole Cap #1	ND	313,000	440,000	520,000	ND	ND	ND	ND			
SKC 12 Hole Cap #2	ND	321,000	442,000	526,000	ND	ND	ND	ND			
SKC 12 Hole Cap #3	ND	290,000	403,000	487,000	ND	ND	ND	ND			
Average SKC/Summa (C/Co)		1.28	1.71	1.50							1.50
ATD Low Uptake	260,000	260,000	327,000	480,000	429,000	593,000	327,000	610,000			
ATD/Summa (C/Co)	1.86	1.08	1.31	1.41	2.38	1.35	1.09	1.60			1.51

Notes:
- Notably different than other results, so these values were not included in the row averages
ND – Not Detected

6.6 Indoor and Outdoor Air Test Results

6.6.1 OTC3

Indoor air samples at OTC3 (Table 16) showed detectable concentrations of TCE in all samples and cDCE in only those samplers with sufficiently low reporting limits (Radiello, SKC and Summa canister). Outdoor air samples showed no detectable concentrations of VOCs except PCE in the SKC samplers. PCE was detected in all indoor and outdoor samples collected by the SKC samplers at similar concentrations, which were below the reporting limits for all the other samplers, including the Summa canisters.

Table 16: Indoor and outdoor VOC concentrations with passive and active samples at OTC3

Sample Media	VOC (ug/m3)	IA-1			IA-2			IA-3			OA-1		
Summa	cDCE	0.28	0.28	0.30	0.31	0.33	0.31	0.28	0.30	0.30	0.12 U	0.12 U	0.11 U
	PCE	0.18 U	0.19 U	0.18 U	0.19 U	0.19 U	0.42 U	0.22 U	0.18 U	0.18 U	0.21 U	0.21 U	0.18 U
	TCE	4.9	3.7	4.6	3.7	3.8	3.7	3.4	3.8	3.9	0.16 U	0.17 U	0.14 U
WMS	cDCE	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U
	PCE	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U
	TCE	3.2	3.9	3.9	3.2	4.3	3.9	3.9	4.3	2.8	0.71 U	0.71 U	0.71 U
3M OVM3500	cDCE	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U
	PCE	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U
	TCE	4.5	4.1	4.1	4.1	4.1	3.8	4.1	4.1	3.8	0.28 U	0.28 U	0.28 U
ATD Carbopack	cDCE	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.2 U	1.2 U	1.2 U
	PCE	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U
	TCE	3.7	4.2	4.4	4.2	4.4	3.7	4	3.7	3.7	1.2 U	1.2 U	1.2 U
Radiello	cDCE	0.36	0.36	0.36 U	0.4	0.38	0.36 U	0.36 U	0.36 U	0.36	0.36 U	0.36 U	0.36 U
	PCE	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U
	TCE	4.7	4.7	4.9	4.6	4.1	3.7	3.7	4.4	4.4	0.17 U	0.17 U	0.17 U
SKC Ultra	cDCE	0.056	0.064	0.07	0.042	0.042	0.042	0.053	0.055	0.051	0.04 U	0.04 U	0.04 U
	PCE	0.052	0.06	0.065	0.059	0.061	0.066	0.059	0.06	0.06	0.05	0.062	0.057
	TCE	1.1	1.4	1.4	1.1	0.93	1.2	1.1	1.2	1.1	0.04 U	0.04 U	0.04 U

U = concentration not detected (associated value is the reporting limit)

Figure 38 shows stacked bar charts of TCE in indoor air, with the triplicate samples averaged to comprise the individual location bars to the left and all samples combined to comprise the "average" bars to the right. This chart indicates a strong agreement between all the passive samplers and the Summa canister samples, except for the SKC sampler, which showed a low bias. The SKC Sampler was used with Chromosorb 106 as the adsorbent medium. The RMSV for TCE and cis-1,2-DCE on Chromosorb 106 is less than 5 liters (Supelco, 2013). The uptake rate for the SKC sampler for these compounds is about 15 mL/min and the samplers were deployed for about 7 days. The product of the uptake rate and sample duration, which can be thought of as an equivalent sample volume, would have been about 150 liters in this instance. The equivalent sampled volume is much larger than the recommended maximum sample volume, which indicates the low bias for the SKC samples is most likely attributable to poor retention. This is an example of a lesson learned from this research because the importance of considering the recommended maximum sample volume was not obvious to any of the members of the study team prior to the OTC3 sampling event.

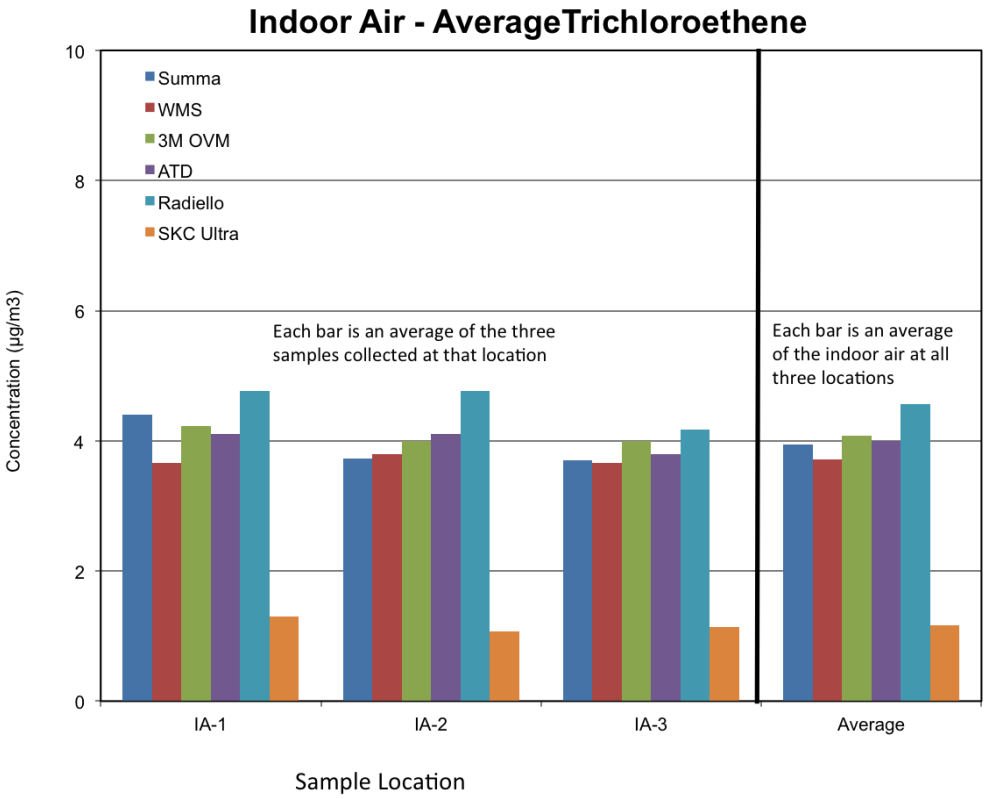


Figure 38: Stacked bar representation of individual measured concentrations at each location to the left, and average bars to the right for TCE in indoor air at OTC3.

6.6.2 CRREL

The indoor air sampling data from CRREL generally showed good agreement between the passive samplers and Summa canisters. The measured concentrations are shown in Table 17. The average of three replicates for each passive sampler and compound are plotted vs. the average of three Summa canister concentrations in Figure 39. Results from the outdoor air samples were generally non-detect or very low, so a comparison to the Summa canister results is not supported.

The indoor air data at CRREL do not show indications of poor retention as observed for the SKC at OTC3. The SKC Ultra was used with charcoal or Carbograph 5 at CRREL, both of which are much stronger sorbents than Chromosorb 106, and the SKC sampler had no results with an unacceptable low bias. The ATD tube used Carbopack B, which has a recommended maximum sample volume of 20 L for TCE and >100 L for all the other detected analytes. The equivalent sample volumes (uptake rates multiplied by sample duration) for the ATD tube sampler were about 5 L, which is less than the recommended maximum sample volumes by a comfortable margin. The ATD tube sampler also had no results with a low bias.

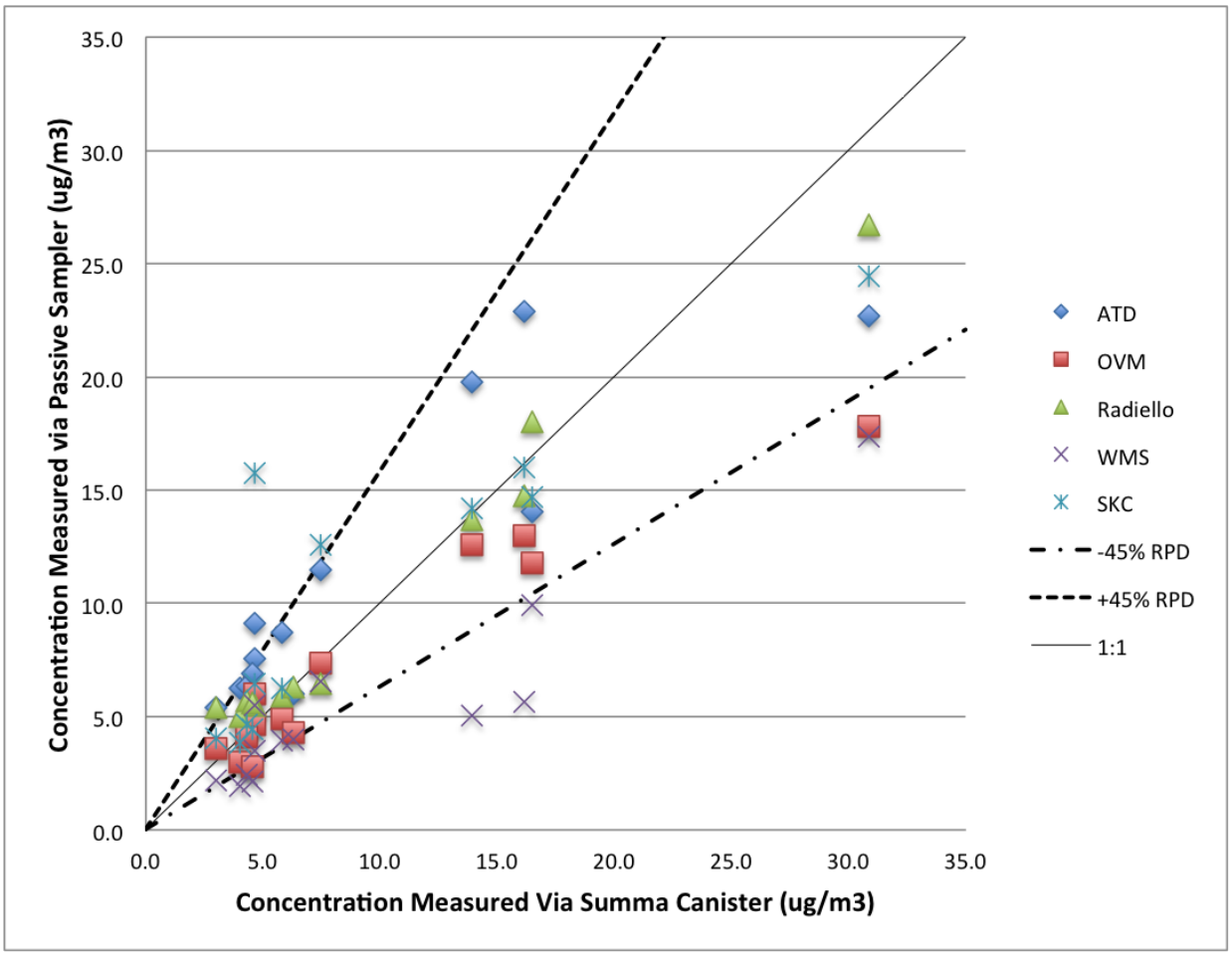


Figure 39: Passive sampler indoor air concentrations vs. Summa canisters at CRREL

The WMS sampler showed a low bias for xylenes, by a factor of about three (and very consistently for both locations 1 and 2). The SKC sampler showed a positive bias for toluene, also by a factor up to about 3. Further discussion of the accuracy and precision are in Section 7.3.

Table 17: Indoor air VOCs by Summa canisters and passive samplers at CRREL

Location	Sampler Type (Subtype/ Sorbent)	TCE ($\mu g/m^3$)	Toluene ($\mu g/m^3$)	Ethyl-benzene ($\mu g/m^3$)	m,p-Xylene ($\mu g/m^3$)	o-Xylene ($\mu g/m^3$)	1,2,4-TMB ($\mu g/m^3$)
IA-1	Summa/TO-15	13.4	3.7	4.3	12.4	0.8	4.0
		18.0	5.1	4.7	14.4	4.1	3.9
		18.0	5.2	5.0	15.0	4.1	4.1
	ATD	14.4	8.6	7.6	20.0	5.3	6.3
	(Regular/	14.4	10.8	7.7	20.0	5.6	6.6
	Carbopack B)	13.4	7.9	7.4	19.3	5.3	5.7
	OVM	11.8	7.3	4.5	12.6	3.7	2.8 J
	(Regular/	11.1	5.5	4.5	11.8	3.7	2.6 J
	Charcoal)	12.5	5.2	4.9	13.4	3.4	3.6 J
	Radiello	18.1	5.7	5.6	13.8	5.4	4.7
	(White body/	18.2	5.4	5.5	13.7	5.5	5.8
	thermal)	17.7	5.5	5.3	13.6	5.3	4.4
	WMS	9.9	6.5	3.8	5.8	2.4	2.2
	(Regular/	9.8	4.5	3.2	4.6	2.0	1.8
	Anasorb 747)	10.1	5.5	3.4	4.8	2.1	1.8
	SKC	16.4	9.5	6.0	16.0	4.5	4.3
	(Regular/mix	16.5	8.8	6.1	16.2	4.5	4.4
	of char & CG5)	11.2	28.9	7.3	10.5	3.1	2.8
IA-2	Summa/TO-15	35.2	7.7	6.7	17.7	4.8	5.1
		28.6	6.7	5.7	15.3	4.2	4.6
		28.8	8.0	5.1	15.4	4.0	4.0
	ATD	21.8	10.8	8.5	23.1	6.9	7.2
	(Regular/	24.5	12.9	9.3	23.9	6.6	7.2
	Carbopack B)	21.8	10.8	8.5	21.6	5.7	6.2
	OVM	17.8	11.0	4.7	12.7	4.1	2.7 J
	(Regular/	17.1	4.9	4.8	12.7	4.0	2.7 J
	Charcoal)	18.6	6.1	5.1	13.5	4.2	3.0 J
	Radiello	25.6	6.1	6.0	14.6	5.7	5.4
	(White body/	26.5	6.4	5.7	14.4	5.5	6.0
	thermal)	28.0	6.8	6.0	15.2	5.9	5.3
	WMS	16.9	4.9	3.8	5.7	2.5	2.2
	(Regular/	17.6	7.6	4.2	6.0	2.6	2.4
	Anasorb 747)	17.6	7.1	3.8	5.2	2.3	1.8
	SKC	23.7	10.3	6.3	16.1	4.8	4.6
	(Regular/mix	23.1	9.3	6.2	15.9	4.5	4.4
	of char & CG5)	26.5	18.2	17 U	34 U	17 U	18 U
IA-3	Summa/TO-15	7.2	0.75U	0.87U	2.2U	0.87U	0.98U
		6.5	0.75U	0.87U	2.2U	0.87U	0.98U
		5.2	0.75U	0.87U	2.2U	0.87U	0.98U
	ATD	6.9	7.9	1.7 U	1.7 U	1.7 U	2.0 U
	(Regular/	4.5	2.0	1.7 U	1.7 U	1.7 U	2.0 U
	Carbopack B)	6.5	5.9	1.7 U	1.7 U	1.7 U	2.0 U
	OVM	4.2	1.2	0.6 U	0.6 U	0.6 U	0.68 J
	(Regular/	3.6	1.3	0.6 U	0.6 U	0.6 U	0.68 J
	Charcoal)	5.1	6.5	0.6 U	0.6 U	0.6 U	0.68 J
	Radiello	7.7	0.7	0.2 U	0.4	0.2 U	0.23 U
	(White body/	5.5	0.7	0.2 U	0.3	0.2 U	0.23 U
	thermal)	5.7	0.7	0.2 U	0.3	0.2 U	0.23 U
	WMS	3.6	2.8 U	1.8 U	1.9 U	1.7 U	0.93 U
	(Regular/	4.3	2.8 U	1.8 U	1.9 U	1.7 U	0.93 U
	Anasorb 747)	4.0	8.3	1.8 U	1.9 U	1.7 U	0.93 U
	SKC	16 U	16 U	17 U	34 U	17 U	18 U
	(Regular/mix	16 U	19.5	17 U	34 U	17 U	18 U
	of char & CG5)	16 U	16 U	17 U	34 U	17 U	18 U

U = non-detect (associate value is the reporting limit)

6.6.3 MCAS Cherry Point

The results of the MCAS Cherry Point sampling event are presented in Appendix G. Indoor air samples had detectable concentrations of chlorinated VOCs, benzene, toluene, ethyl benzene, and xylenes (BTEX) at the three sample locations. Outdoor air samples had detectable concentrations of VOCs, but generally at concentration less than 1 $\mu g/m^3$.

The concentrations measured at MCAS Building 137 with the passive samplers were plotted against the concentrations measured with the Summa canisters to show the correlations graphically (Figures 40a to e) using logarithmic scales to show the data because the numbers span a range of almost two orders of magnitude. Where there were sufficient detections, a linear regression was plotted, with a fixed intercept of zero to focus on the slope and correlation coefficient (which should have only 2 significant figures, but the plotting software automatically displays more). The intercept was fixed to zero because a passive sampler would show a non-zero concentration for any compound that is not actually present only if there was a blank contamination issue. There were some compounds detected in some trip blanks (Appendix H), so selected data sets were re-plotted with the intercept not set to zero, but the correlation coefficient and slope were only marginally different.

The WMS and Radiello samplers had a low bias for cDCE, tDCE, 11DCA (up to one order of magnitude), and 11DCE (up to two orders of magnitude), and a slight low bias (less than one order of magnitude) for 12DCA. The uptake rate for these compounds is about 1 to 2 mL min^{-1} for the WMS sampler and about 20 to 30 mL min^{-1} for the Radiello. When multiplied by the sample time (about 7 days), this equates to an "equivalent" sample volume of 10 to 20 liters for the WMS sampler and 200 to 300 liters for the Radiello. The RMSV for these compounds on Carbograph 4 (used in the Radiello) is less than about 20 liters and the RMSV for these compounds is less than 5 liters with Carbopack B (used in the WMS sampler). The ATD tubes contained the same sorbent (Carbopack B) as the WMS sampler, but the uptakes rates are lower by up to a factor of 5, so the equivalent sample volume for the ATD tube sampler was about 5 L, which is similar to the RMSV. For the ATD tubes, cDCE, tDCE, 11DCE and 11DCA are also biased slightly low (to a lesser degree than the Radiello and WMS samplers). The SKC and 3M OVM samplers showed no significant bias for these compounds, presumably because the adsorbents used in these samplers were activated carbon, which retains VOCs more strongly than the thermally-desorbable adsorbents. The MCAS 137 data show a notable improvement for the SKC Ultra Sampler, relative to the results from San Diego OTC3 where Chromosorb 106 (a weaker adsorbent) was used. This improvement in the performance of the SKC sampler demonstrates the importance of careful selection of the adsorbent media for those samplers where the sorbent is interchangeable.

Several other compounds were detected with one or more of the passive samplers with concentrations either higher or lower than the Summa canister values, but with a consistent trend. This is attributable to the uptake rate used to calculate the concentrations being either higher or lower than the actual uptake rates for the compounds and conditions.

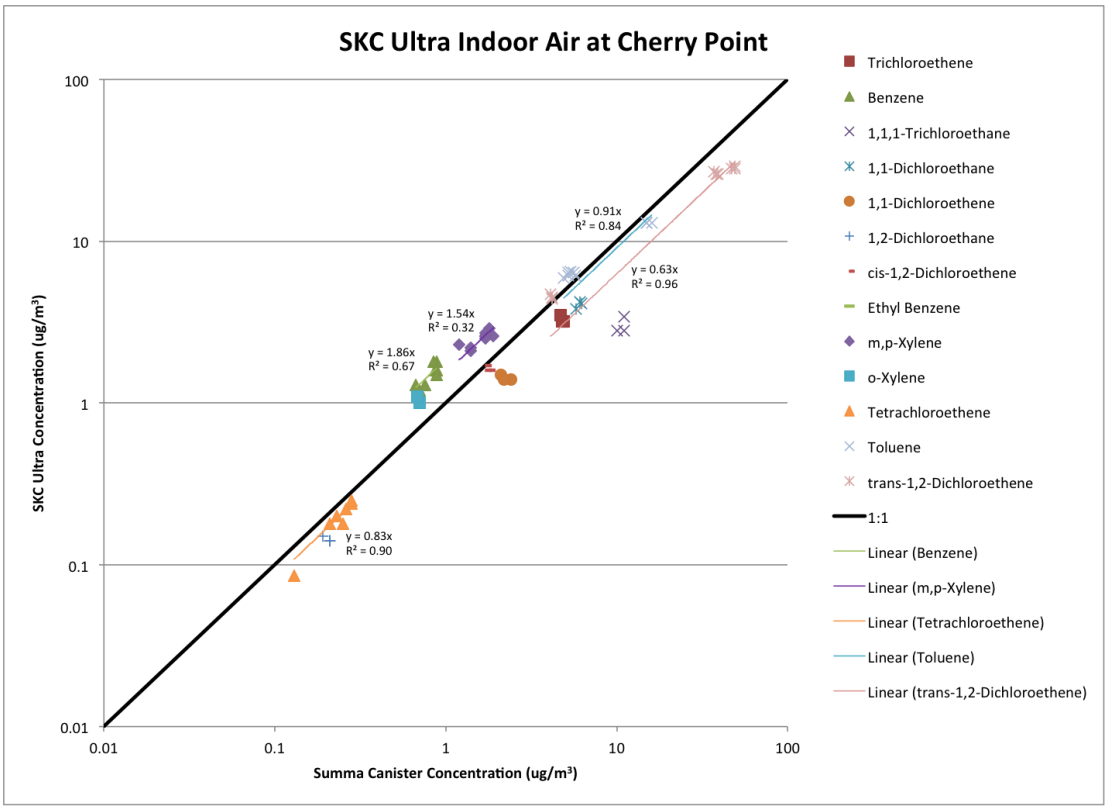


Figure 40a: VOCs in indoor air by SKC Ultra II vs. Summa canister at MCAS 137

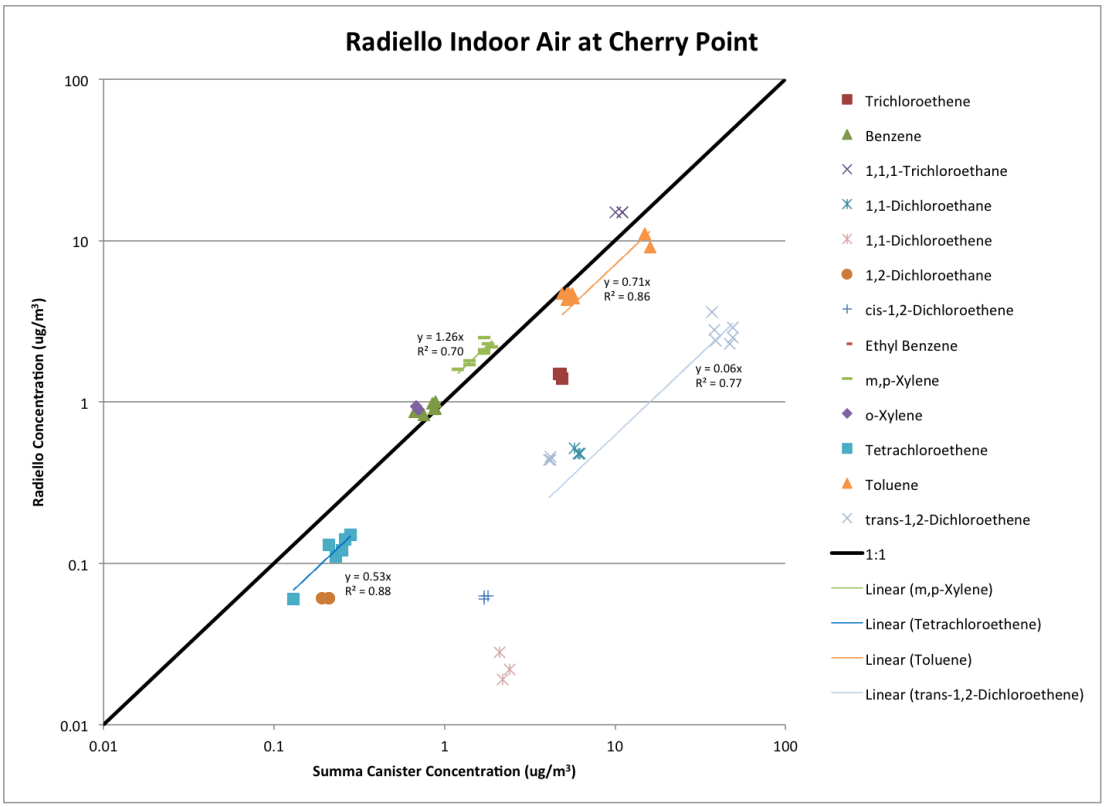


Figure 40b: VOCs in indoor air by Radiello vs. Summa canister at MCAS 137

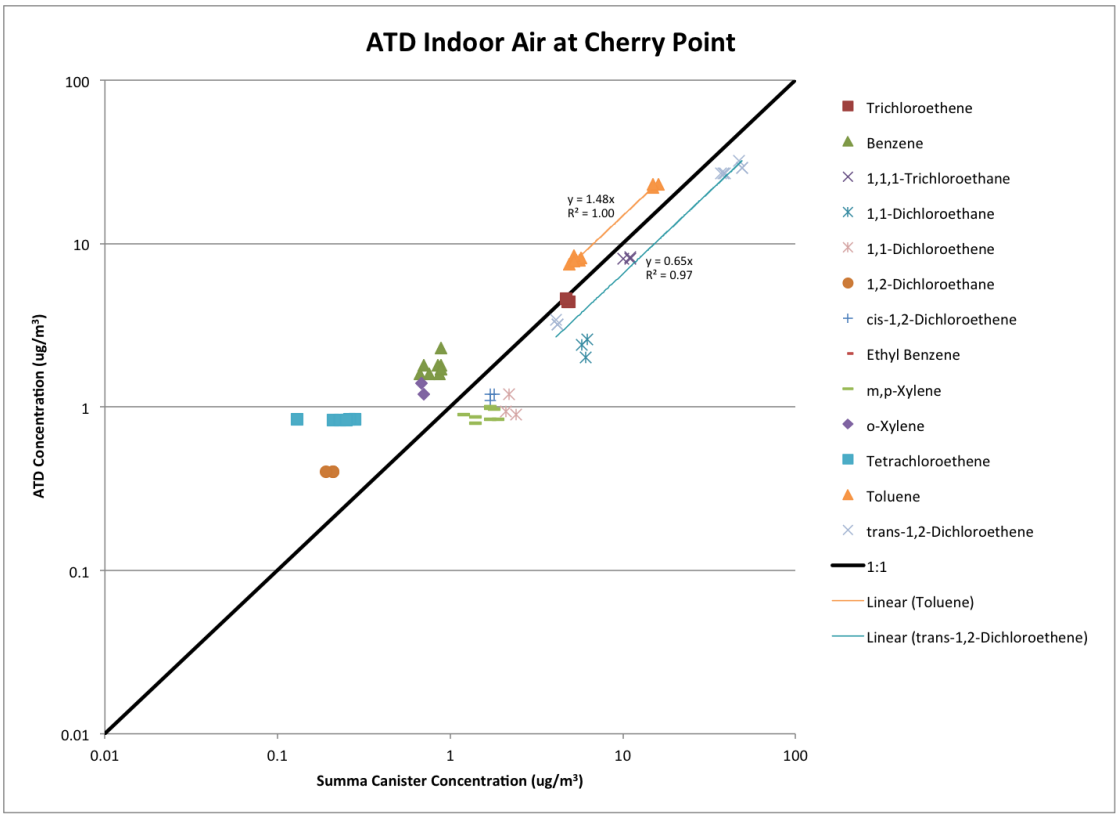


Figure 40c: VOCs in indoor air by ATD/Carbopack B vs. Summa canister at MCAS 137

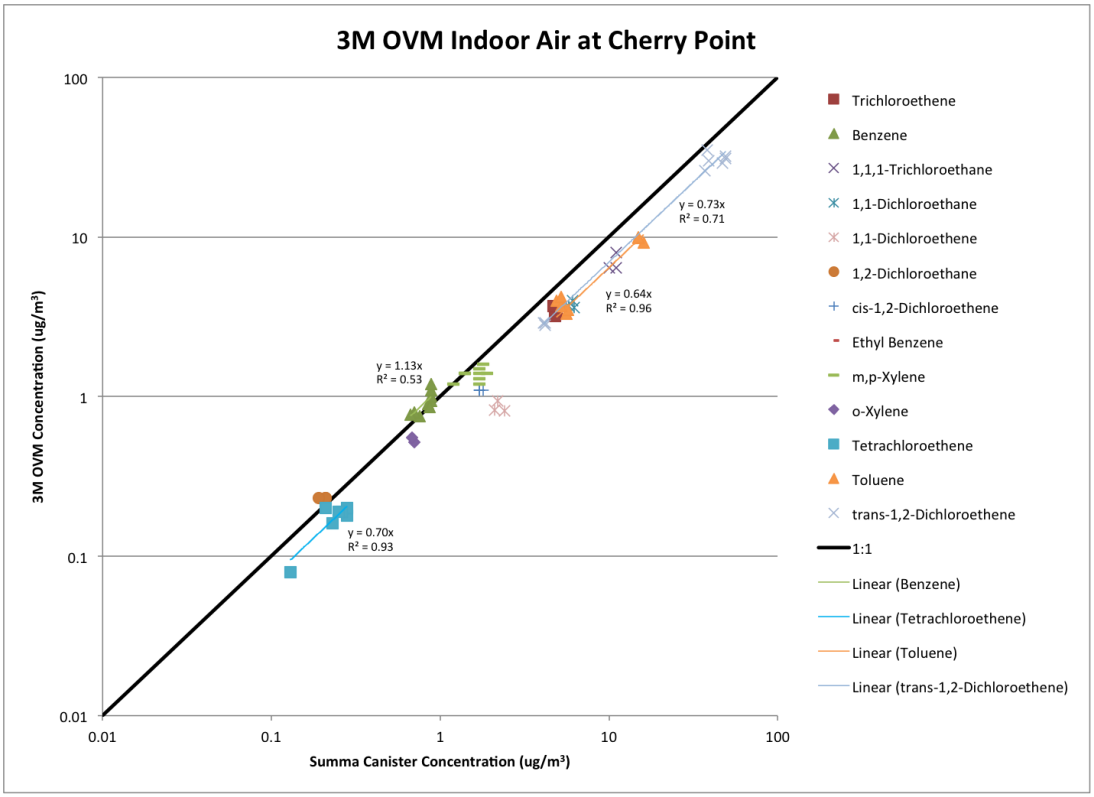


Figure 40d: VOCs in indoor air by 3M OVM vs. Summa canister at MCAS 137

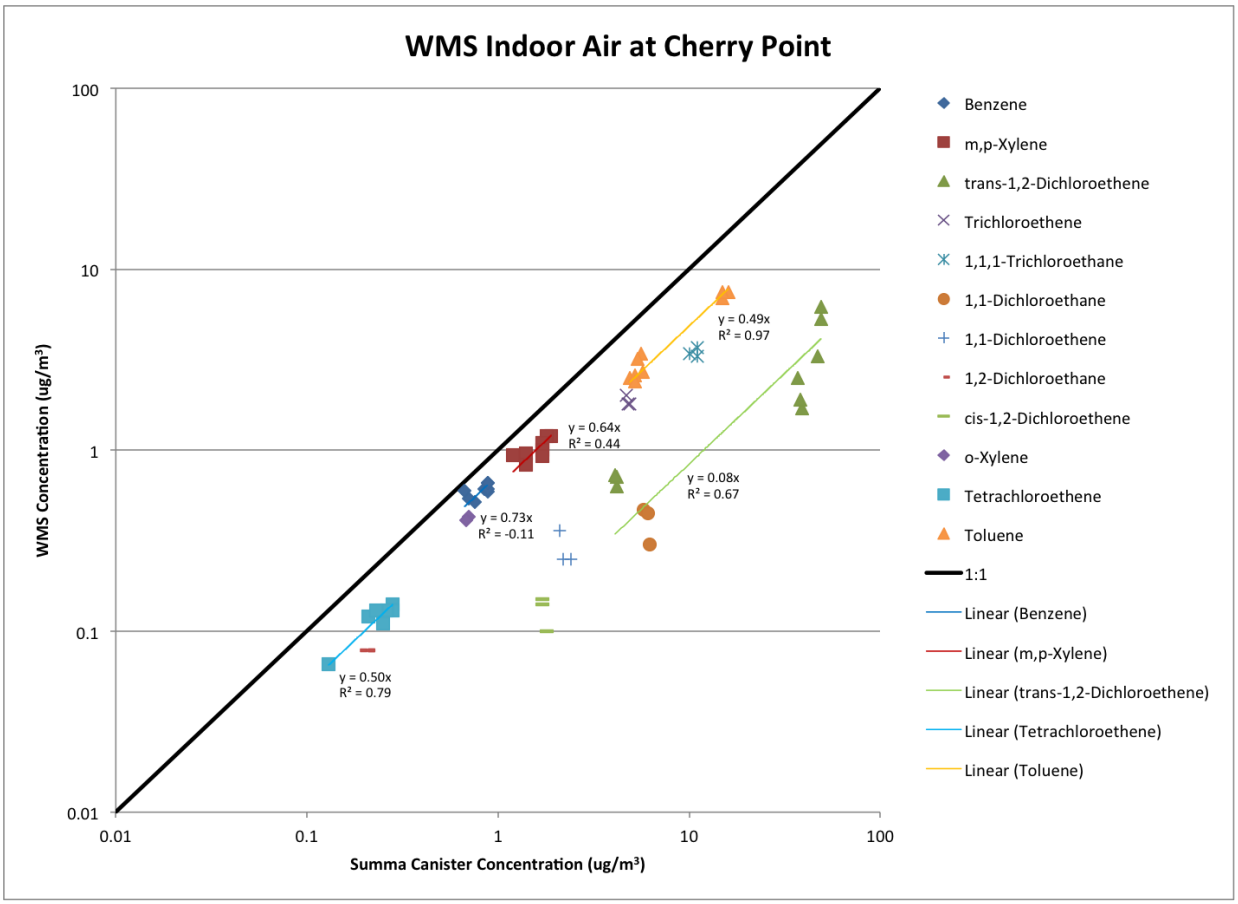


Figure 40e: VOCs in indoor air by WMS vs. Summa canister at MCAS 137

6.7 Passive Soil Vapor Test Results

6.7.1 Mathematical Modeling Results

Transient Model Simulations

A series of simulations were performed using the transient model to show the relationship between the mass entering the void space (which is initially free of VOC vapors) from the surrounding soil and time for a 2.54 cm (1-inch) diameter drillhole, a soil vapor concentration (C_s^0) of 100 µg/m^3 and a vertical interval of 10 cm. Figure 41 shows simulations for a variety of different water-filled porosities (θ_w) and the corresponding effective diffusion coefficients from Equation 2. For all water contents simulated, the concentration of TCE in the void space eventually equilibrates with the surrounding soil. For relatively dry soils (e.g., $\theta_w < 0.1$), the void space concentration would be within 10% of the soil vapor concentration in as little as about 10 minutes. For wet soils (e.g., $\theta_w = 0.30$), a similar level of equilibration may require up to about 1 day.

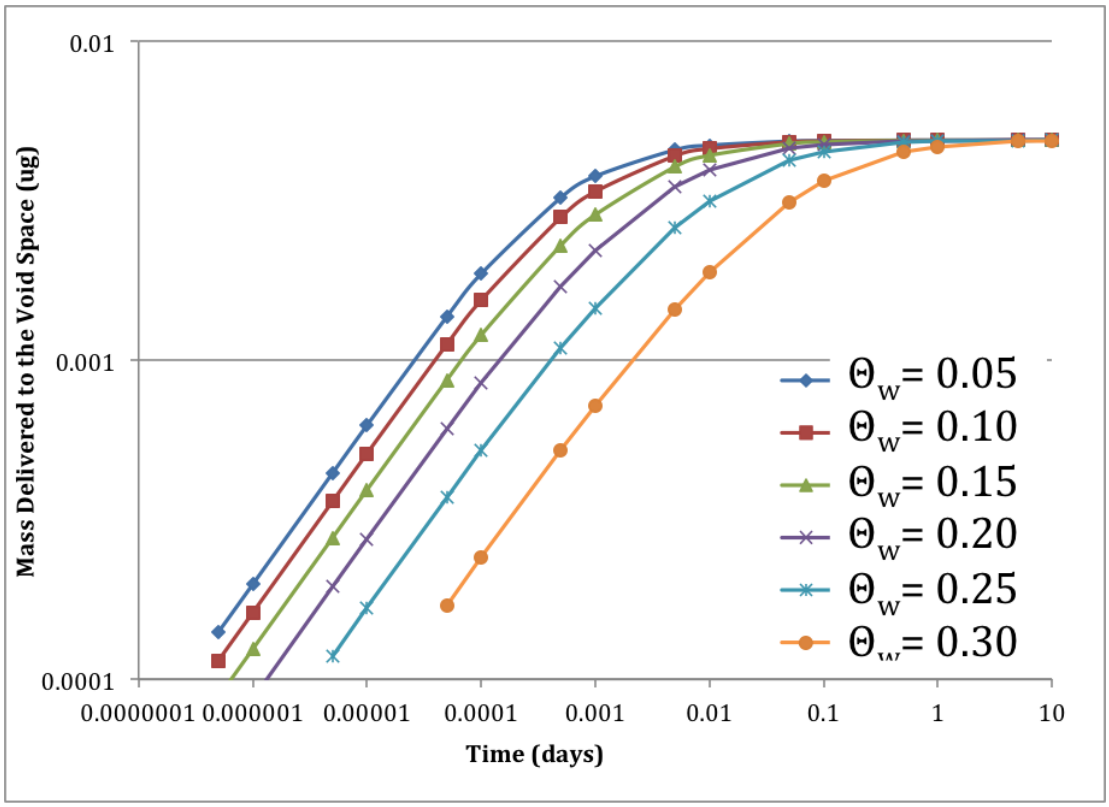


Figure 41: Simulated mass of TCE delivered by diffusion from surrounding soil to the void space versus time (for a 2.5 cm diameter borehole in a sandy soil with 37.5% total porosity and an initial soil vapor concentration of 100 µg/m^3 assuming no removal of mass by a passive sampler).

Equilibration occurs more slowly with larger diameter boreholes. A comparison of the equilibration time for a nominal 1-inch and 4-inch diameter voids of 10 cm height are shown in Table 18, which shows that the difference in equilibration time is proportional to the difference in the volume of the void space (i.e., varies in proportion to the square of the borehole radius). Most passive samplers can fit within a borehole of 2-inch diameter or less, so the vapor concentration in the void-space of the borehole would equilibrate with the surrounding soil in less than about 1 day for most soil types.

Table 18: Comparison of time to reach 95% of steady-state TCE concentration, Cs0 (without the sampler present) in the void space comparing nominal 1-inch and 4-inch diameter boreholes (total porosity 37.5%)

Water-filled porosity (vol/vol)	D_{eff} (m^2/day)	Time to reach 95% of Cs0 (day)		Ratio of (t_4/t_1)
		t_1 (r_2 = 0.5 in)	t_4 (r_2 = 2 in)	
0.01	0.15	0.0048	0.076	16
0.05	0.10	0.0070	0.11	16
0.1	0.058	0.012	0.19	16
0.15	0.030	0.024	0.38	16
0.2	0.013	0.055	0.87	16
0.25	0.0042	0.17	2.7	16
0.3	0.00080	0.87	13	16
0.31	0.00052	1.3	21	16
0.32	0.00033	2.1	34	16
0.33	0.00020	3.5	56	16
0.34	0.00013	5.5	88	16
0.35	0.000093	7.5	120	16
0.36	0.000084	8.3	132	16

The transient model simulations do not account for mass removed by a passive sampler in the borehole, which would draw a small but finite amount of mass from the surrounding soil over time. At steady-state, the uptake rate of the passive sampler (UR) and the diffusive delivery rate from the surrounding soil (DDR) would be equal; therefore, Equation (1) can be re-arranged to:

$$DDR = \frac{M_v}{C_s^0\, t} \qquad (6)$$

In the period of time before steady-state is achieved, the diffusive delivery rate (DDR) gradually slows down as the concentration inside the void space approaches the concentration in the surrounding soil and the concentration gradient diminishes. During the transient stage, Equation 6 would calculate a DDR value that was a time-weighted average over the selected time interval, and this can be used to estimate the passive sampler uptake rate needed to minimize the starvation effect. In other words, the ideal operating condition for a passive soil vapor sampler is where the sample duration is long relative to the time required for the vapor concentration in the void-space to approach a steady value and the steady concentration in the void space is not significantly lower than the concentration in the surrounding soil, and this can be achieved where the sampler uptake rate is similar to the diffusive delivery rate as the concentration in the void space approaches the concentration in the surrounding soil. The transient model is an approximate solution, so this is subject to further assessment using the steady-state model and the field experimental data. The transient model simulation results were used to calculate the average DDR as a function of time and moisture content, as shown in Figure 42. The DDR is less than about 1 mL/minute within about 30 minutes for moisture

contents up to 0.30. Quantitative passive samplers for indoor air quality monitoring typically have uptake rates of 10 to 100 mL/min, so these simulations demonstrate that a customized sampler with a lower uptake rate would be needed to minimize the starvation effect during quantitative soil vapor sampling.

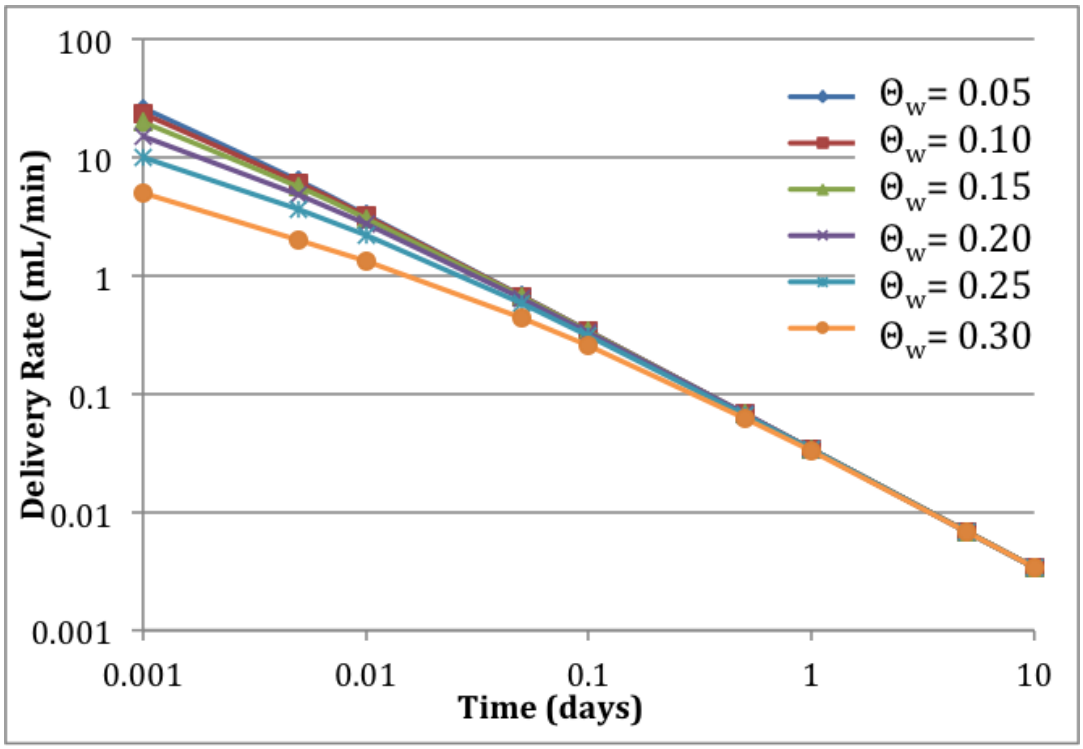


Figure 42: Diffusive delivery rate of TCE versus time (for mass entering void space of a 2.5 cm diameter borehole in a soil with 37.5% total porosity and an initial soil vapor concentration of 100 µg/m^3 assuming no removal of mass by a passive sampler).

The DDR decreases as the concentration in the void space approaches equilibration with the surrounding soil vapor. Figure 43 shows this relationship for the scenario simulated in Figures 41 and 42, where Mass/Mass$_{max}$ is the instantaneous mass of TCE in the void space divided by the mass of TCE in the void space at steady state (which is equal to δ, defined in Equation 5). For very dry soils, the DDR is greater than 10 mL/min until about 90% of the mass has entered the void-space. In this scenario, a passive sampler with an uptake rate as high as 10 mL/min may still provide data with an acceptably small starvation effect, i.e., the sampler uptake rate remains below the diffusive delivery rate from the soil until the mass delivered to the void space is about 90% of the steady-state value, so a low bias of up to about 10% may be expected, but this would still meet the performance objectives in Section 3. For moisture contents typical of most vadose zone soils ($0.10 < \theta_w < 0.25$), an uptake rate of about 1 mL/min would be expected to result in an acceptably small starvation effect. For example, a water-filled porosity of 25% in a soil with 37.5% porosity and a sampler with an uptake rate of 1 mL/min would correspond to a δ value of 80% on Figure 43, i.e., the concentration in the void space would

have a 20% low bias via the starvation effect. For very wet soils (θ_w = 0.30), the average DDR is about 0.1 mL/min by the time the concentration in the void space has nearly equilibrated (δ ~ 90%) with the surrounding soil (which would occur after roughly 1 day, according to Figure 41).

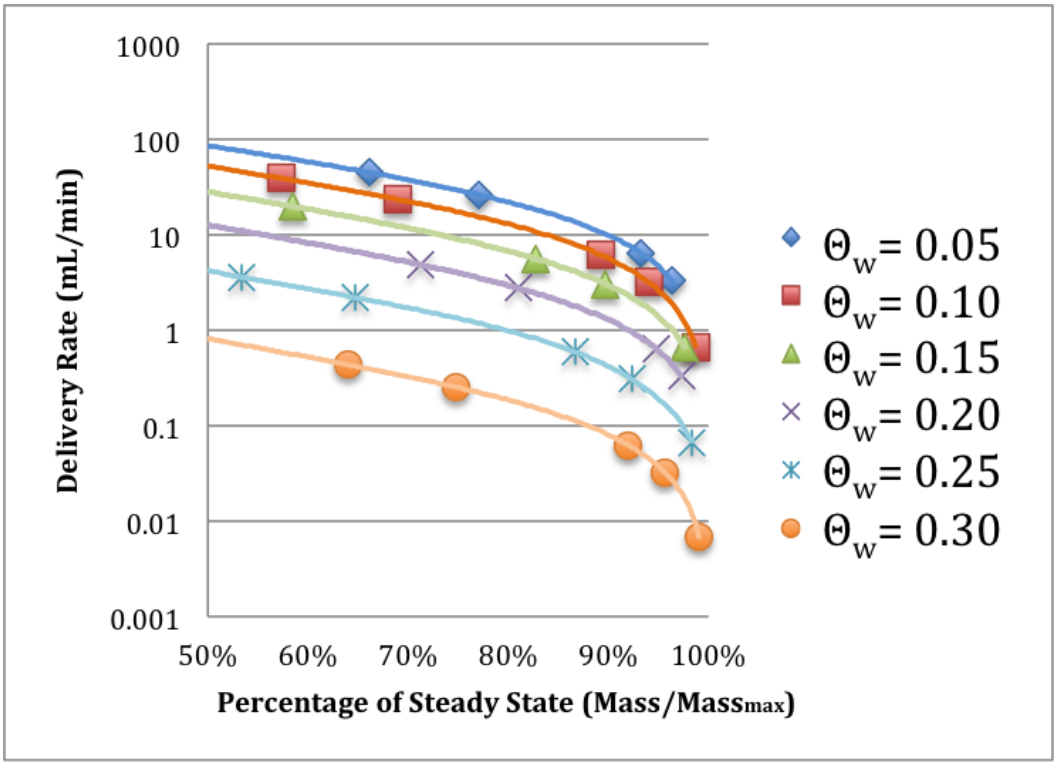


Figure 43: Relationship between the diffusive delivery rate of TCE vapors into the void space versus the percent of mass entering the void space (where $Mass_{max}$ is the maximum TCE vapor mass in the void space at equilibrium, assuming a 2.5 cm (1-inch) diameter borehole in a soil with 37.5% total porosity, initial soil vapor concentration of 100 µg/m^3 and no removal of mass by a passive sampler).

6.7.2 Superposition of Diffusive Delivery Rate and Uptake Rate

The transient mathematical model is a simplification because it assumes that there is no mass sink (which a passive sampler would be) in the void space. This assumption is appropriate early in the process, and becomes less representative as the system approaches equilibrium. An approximate model that includes the influence of the passive sampler can be derived by adding the diffusive delivery rate (Figure 42) and the sampler uptake rate to estimate the effect of both processes occurring at the same time. As long as the uptake rate of the sampler is small, the combined model will differ from the transient analytical model of radial diffusion (Equation 48, Appendix D) only after the diffusion into the void space has very nearly attained steady-state, at which time the diffusive delivery rate of vapors into the void space will stabilize at the same value as the uptake rate of the sampler (assuming the rate of diffusion through the air in the void-space is not a rate-limiting step). Figure 44 shows an example of the diffusive delivery rate as a function of time that would be expected if a passive sampler with an uptake rate of 1

mL/min was placed in the void-space in the same scenario as simulated in Figures 41 to 43. Within about 1 day, the delivery rate for water-filled porosities up to 0.30 approaches the uptake rate of the sampler (Figure 44), so if the sampler was deployed for several days, the majority of the sampling period would occur under a steady-state condition. The combined uptake and diffusive delivery rate is within about a factor of 2 of the steady value within about 0.05 days (about 1 hour), so even if the sampling period was a single day, the uptake rate would be relatively close to the steady value for most of the sample period. If a sample duration of less than an hour was planned, the result would show a low bias attributable to the time required for vapors to diffuse into the void space; however, this could be overcome by purging provided there were appropriate seals to prevent the entry of atmospheric air in the process.

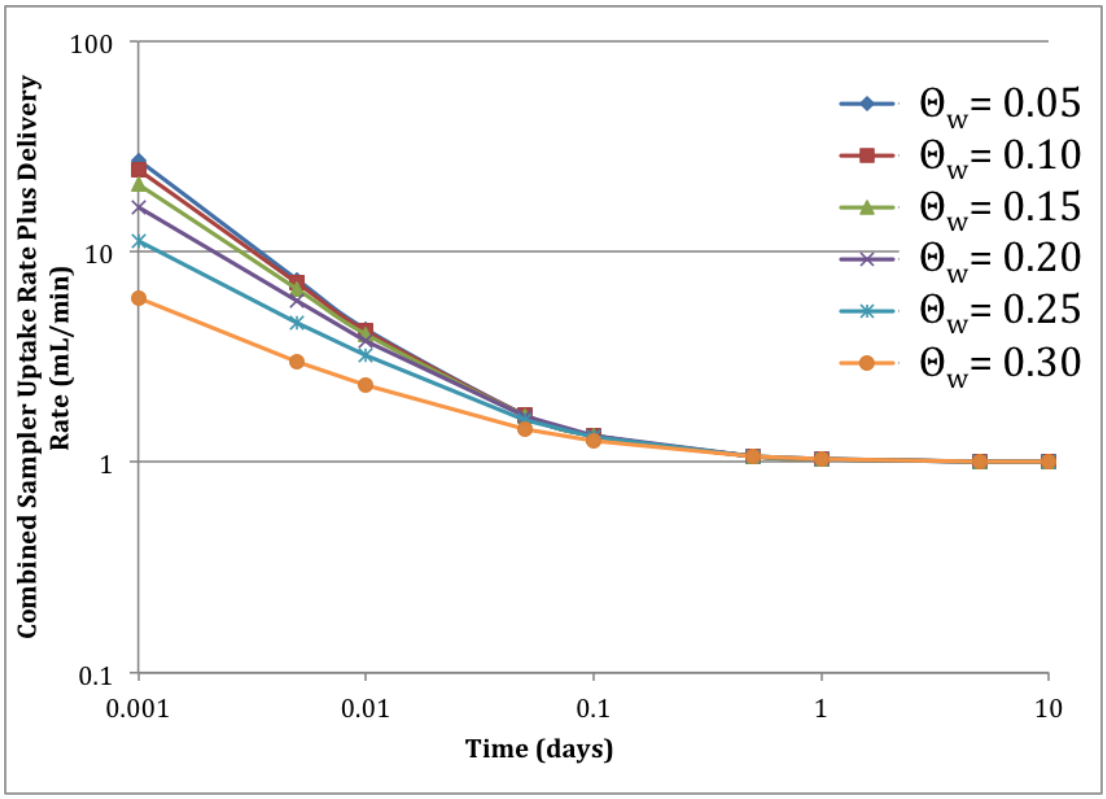


Figure 44: Superimposed diffusive delivery rate plus uptake rate (for a 10 cm tall and 2.5 cm diameter void space containing a passive sampler with an uptake rate of 1 mL/min).

It should be noted that for very wet soils (water-filled porosity greater than 0.25), the steady-state delivery rate may be less than 1 mL/min, in which case there are two possibilities: 1) a lower uptake rate sampler could be used, or 2) a low bias attributable to starvation may still be experienced. Wet soils are a poor pathway for vapor intrusion, so this concern is minor.

Steady-State Model Simulations

If a passive sampler is deployed in a nominal 1-inch diameter borehole (r_2 = 1.25 cm) and sealed within a 10 cm void space (h = 10 cm), the uptake rates calculated using Equation (6) are shown in Figure 45 for δ values of 0.5, 0.75 and 0.95 (recall that $\delta = C_{bh}/C_{sg}$, where C_{bh}

concentration inside the void space of the borehole and C_{sg} is the concentration in the surrounding soil). The r_3 value (radius at which soil vapor concentrations are unaffected by the borehole and passive sampler) for these calculations was assigned to be 1 m. Figure 45 shows that an uptake rate of 10 mL/min might be acceptable for very dry soil if the data quality objective was to quantify concentrations within a factor of 2 (i.e., $\delta = 0.5$), however; an uptake rate of 1 mL/min would be more suitable for soils with a water-filled porosity up to 15% in a soil with total porosity of 37.5%, assuming a more stringent data quality objective of +/-25% (i.e., $\delta = 0.75$). Progressively lower uptake rates would be required to further reduce the low bias or meet typical data quality objectives in very wet soils. Figure 45 shows similar information to Figure 43, except that Figure 43 includes the early time transient response, where the concentration gradient is steepest, so the uptake rates in Figure 45 (steady-state) are lower for any given water filled porosity and δ value. Both models are simplifications of the process, but they provide results within about an order of magnitude of one another, which provides a useful guide for interpretation of the field experimental data.

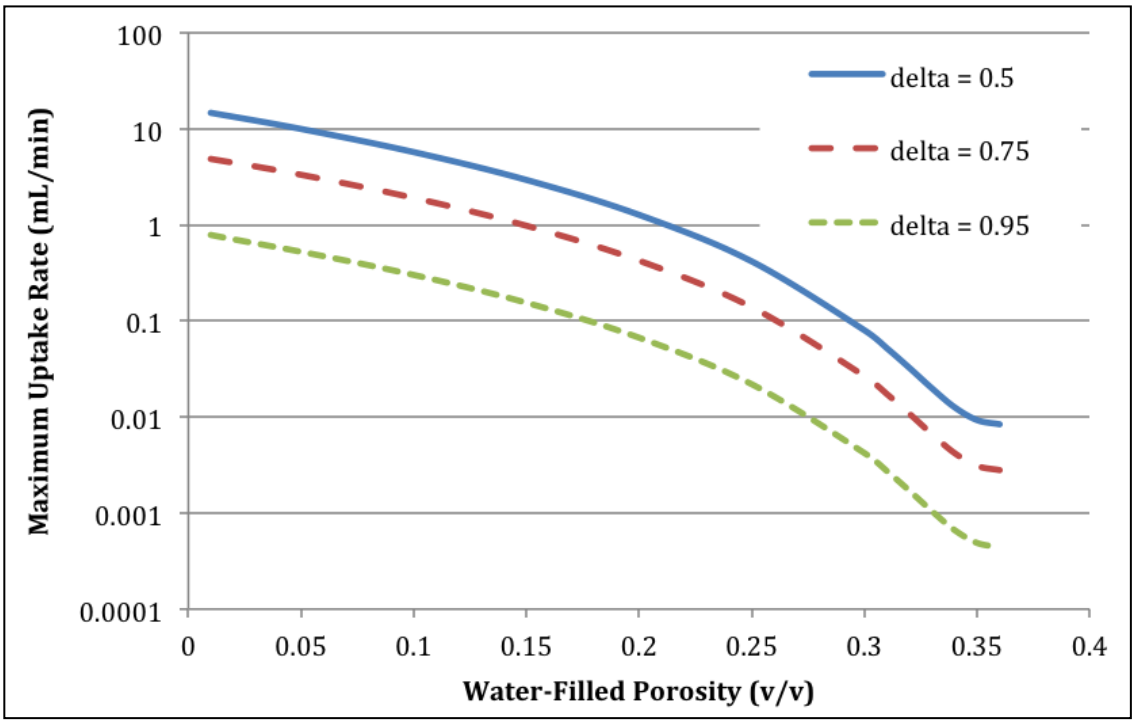


Figure 45: Calculated TCE uptake rate corresponding to various δ values as a function of water-filled porosity for a 1-inch diameter drillhole assuming $r_2 = 1$m

A sensitivity analysis on the r_3 value is shown in Figure 46 for the same conditions as in Figure 45 and a δ value of 0.75 (which would correspond to a concentration in the void space that is within 25% of the concentration in the surrounding soil). This plot shows that the assumed value for r_3 does not change the outcome dramatically. Similar results (not shown) are found for delta values of 0.5 and 0.95.

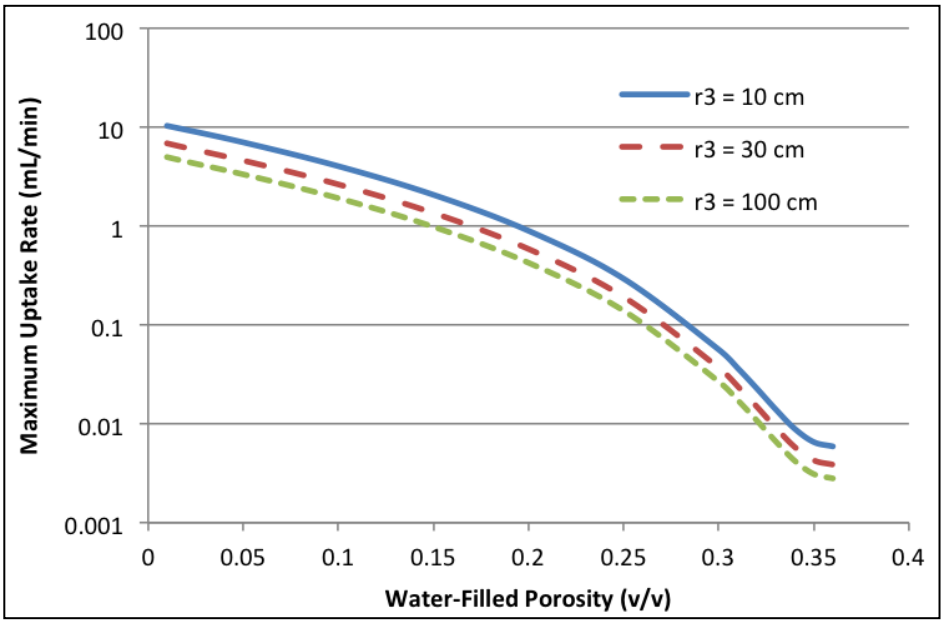


Figure 46: Calculated uptake rate corresponding to various r_2 values as a function of water-filled porosity for a 1-inch diameter drillhole assuming $\delta = 0.75$.

The transient and steady-state mathematical models indicate that conventional passive samplers designed for indoor air quality monitoring (which typically have uptake rates of 10 to 100 mL/min) would be expected to show a significant negative bias attributable to starvation if used without modification for passive soil vpaor sampling. However, passive samplers with uptake rates of about 0.1 to 1 mL/min would likely show no significant bias from starvation except in very wet soils. The relationship between the uptake rate and the passive sampler accuracy is discussed further in the field experiment results and interpretation.

6.7.3 Passive Soil Vapor Field Sampling Results

OTC3

The results of sampling at the Navy OTC site are shown in Table 19. The compounds detected in the Summa canisters included TCE and cDCE, in the range of 450 to 63,000 µg/m^3. The passive sub-slab samplers had a low bias of about 10X to 100X relative to the active samples collected via Summa canister. Figure 47 shows the results of passive samples collected over a 2-hour duration in SS-2. The magnitude of the low bias generally increased as the uptake rate of the sampler increased, which is consistent with expectations from the starvation effect. (Note that for these tests, there was no effort made to use low uptake rate samplers) The C/Co values were very consistent for TCE and cDCE, which were the only two consistently detected compounds. The actual uptake rate can be calculated by dividing the mass adsorbed by the Summa canister concentration and the sample duration (Equation 1, where the Summa canister concentration is used as C_o), which yielded uptake rates from 0.02 to 0.6 mL/min and an average value of 0.2 mL/min. Note that the actual uptake rates are within the range of expectations from the mathematical modeling of diffusive delivery rates. For the subsequent field sampling events, lower uptake rate samplers were used to minimize the starvation effect.

Table 19: Results of sub-slab passive vapor sampling at OTC3

Compound	Sampler	Passive Concentration (ug/m^3)	Active (Summa/TO-15) Concentration (ug/m^3)	C/Co (Passive / Active)	Sampler Uptake Rate (mL/min)	Uptake rate x sample time (mL)
cDCE at probe SS-2 (t = 120 min)	WMS (Anasorb 747)	1,400	13,000	0.11	1.9	228
	3M OVM 3500	130	13,000	0.01	29	3,480
	ATD (Chromosorb 106)	570	13,000	0.04	0.47	56
	Radiello (Charcoal)	<26	13,000	<0.002	64	7,680
	SKC (Chromosorb 106)	57	13,000	<0.01	14	1,680
TCE at Probe SS-2 (t = 120 min)	WMS (Anasorb 747)	3,800	63,000	0.06	3.3	396
	3M OVM 3500	640	63,000	0.01	31	3,720
	ATD (Chromosorb 106)	2,700	63,000	0.04	0.50	60
	Radiello (Charcoal)	75	63,000	0.001	69	8,280
	SKC (Chromosorb 106)	72	63,000	0.001	15	1,800
TCE at Probe SS-5 (t = 15 hr)	WMS (Anasorb 747)	<6.6	450	<0.015	3.3	2,970
	3M OVM 3500	8.8	450	0.020	31	27,900
	ATD (Chromosorb 106)	37	450	0.082	.50	450
	Radiello (Anasorb 747)	1.9	450	0.004	69	62,100
	SKC (Chromosorb 106)	8.1	450	0.018	15	13,500

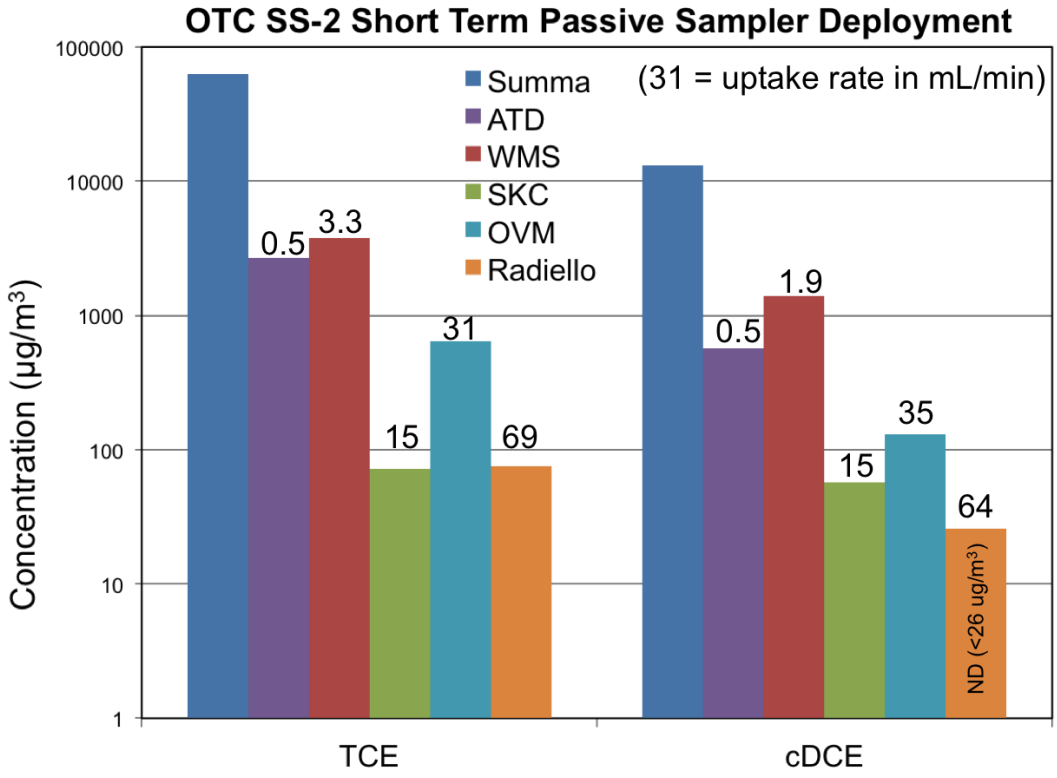


Figure 47: Results of passive sub-slab samples at locations SS-2 in OTC3, measured after 2-hour exposures. The passive samplers show a low bias that increases with the uptake rate of the sampler (listed above each bar), which is expected from the starvation effect.

Layton House

At the Layton house, TCE and 1,1-DCE were the primary compounds detected, typically in the range of 100 to 500 µg/m^3 in the active samples (Tables 20a and 20b). The average active sample concentrations were calculated as the mean of the concentrations measured at the beginning and end of the associated passive sampler exposure interval. The concentrations measured with the passive soil vapor samplers (C) were divided by the average active concentration (C_o) as shown in Figure 48. These data showed several trends that were consistent with expectations based on theory:

- The sampler with the highest uptake rate (Radiello: 79 and 69 mL/min for 11DCE and TCE, respectively) generally showed the lowest concentrations, which appears to be attributable to the starvation effect. The average C/Co values would have been 1.0 (i.e., ideal) if the uptake rates used for the Radiello were 7.3 and 8.7 mL/min for 11DCE and TCE, respectively. These values are similar to expectations from the mathematical modeling of the diffusive delivery rate in Section 6.7.1. The low bias was relatively consistent for sample durations from 1 to 11.7 days, so retention is not indicated to be problematic;
- Three data sets showed low bias in the longer-duration samples (ATD with Tenax TA for both 11DCE and TCE, and ATD Carbopack B for 11DCE). The recommended maximum sample volumes (Supelco, 2013) for these combinations are 0.2, 1.0 and 0.2 L, respectively. The uptake rates were 0.5 and 0.57 mL/min for TCE and 11DCE, respectively and the sample durations were up to 11.7 days, so the equivalent sample volume (UR x t) was up to 9.6 L, which is considerably greater than the RMSV. The ATD sampler with Carbopack B showed good retention for TCE, which has a recommended maximum sample volume of 20 L or more. These data indicate that the low bias is likely attributable to poor retention for the sorbent/analyte combinations with low RMSV values and long sample durations.
- The SKC sampler (low uptake cap and charcoal) and WMS sampler (1.8 mL vial and Anasorb 747) showed data very comparable to the active samplers (concentrations generally within a factor of 2X). This supports the mathematical modeling because the uptake rates (0.58 to 3.3 mL/min were in the range where the starvation effect would be expected to be small or negligible. Furthermore, these samplers showed no apparent lack of retention in the longer-term samples. The SKC and WMS samplers had similar uptake rates to the ATD samplers, so the improved performance in the longer sample intervals is apparently attributable to better retention of 11DCE and TCE by activated carbon-based sorbents, which are stronger sorbents that Carbopack B and less likely to experience saturation and back-diffusion as the sample duration increases.

Table 20a: Soil vapor concentrations for 11DCE at the Layton House, Utah.

Compound	Sample Time (t) (days)	Sampler	Passive Soil Gas Probe	Passive Concentration (ug/m^3)	Average Active Concentration (ug/m^3)	C/Co (Passive / Active)	Uptake Rate (UR) (mL/min)	UR x t (L)
11DCE	1.0	ATD CarbopackB	PSG-1	178	326	0.55	0.57	0.8
		Radiello Charcoal	PSG-3	15	482	0.03	79	118.8
		SKC Charcoal	PSG-6	--	--	--	1.3	1.9
		ATD Tenax TA	PSG-2	106	393	0.27	0.6	0.8
		WMS Anasorb	PSG-4	348	469	0.74	0.82	1.2
	2.0	ATD CarbopackB	PSG-3	277	365	0.76	0.57	1.7
		Radiello Charcoal	PSG-5	1.51U	89	< 0.02	79	235.2
		SKC Charcoal	PSG-2	209	406	0.51	1.3	3.8
		ATD Tenax TA	PSG-4	103	221	0.46	0.6	1.7
		WMS Anasorb	PSG-6	250	264	0.94	0.82	2.4
	2.2	ATD CarbopackB	PSG-2	434	425	1.02	0.57	1.8
		Radiello Charcoal	PSG-4	17	165	0.10	79	249.6
		SKC Charcoal	PSG-1	99	290	0.34	1.3	4.1
		ATD Tenax TA	PSG-3	51	365	0.14	0.6	1.8
		WMS Anasorb	PSG-5	35	87	0.41	0.82	2.6
	7.9	ATD CarbopackB	PSG-6	70	212	0.33	0.57	6.5
		Radiello Charcoal	PSG-2	13	312	0.04	79	910.1
		SKC Charcoal	PSG-5	30	52	0.57	1.3	14.8
		ATD Tenax TA	PSG-1	79	207	0.38	0.6	6.5
		WMS Anasorb	PSG-3	250	272	0.92	0.82	9.3
	8.1	ATD CarbopackB	PSG-5	15	49	0.30	0.57	6.6
		Radiello Charcoal	PSG-1	2	155	0.01	79	928.8
		SKC Charcoal	PSG-4	393	144	2.74	1.3	15.1
		ATD Tenax TA	PSG-6	4	166	0.02	0.6	6.6
		WMS Anasorb	PSG-2	327	370	0.88	0.82	9.5
	9.8	ATD CarbopackB	PSG-4	75	177	0.42	0.57	8.1
		Radiello Charcoal	PSG-6	49	154	0.32	79	1,132.8
		SKC Charcoal	PSG-3	133	243	0.55	1.3	18.4
		ATD Tenax TA	PSG-5	7	77	0.09	0.6	8.1
		WMS Anasorb	PSG-1	130	186	0.70	0.82	11.6
	11.7	ATD CarbopackB	PSG-1	22	346	0.06	0.57	9.6
		Radiello Charcoal	PSG-3	14	109	0.13	79	1,344.0
		SKC Charcoal	PSG-6	too wet	351	---	1.3	21.8
		ATD Tenax TA	PSG-2	3	330	0.01	0.6	9.6
		WMS Anasorb	PSG-4	363	154	2.35	0.82	13.8

Table 20b: Soil vapor concentrations for TCE at the Layton House, Utah.

Compound	Sample Time (t) (days)	Sampler	Passive Soil Gas Probe	Passive Concentration ($\mu g/m^3$)	Average Active Concentration ($\mu g/m^3$)	C/Co (Passive /Active)	Uptake Rate (UR) (mL/min)	UR x t (L)
TCE	1.0	ATD Carbopack B	PSG-1	342	374	0.91	0.5	0.7
		Radiello Charcoal	PSG-3	65	452	0.14	69	102.5
		SKC Charcoal	PSG-6	77	280	0.27	0.58	0.9
		ATD Tenax TA	PSG-2	151	492	0.31	0.5	0.7
		WMS Anasorb	PSG-4	210	380	0.55	3.28	4.9
	2.0	ATD Carbopack B	PSG-3	611	488	1.25	0.5	1.5
		Radiello Charcoal	PSG-5	7	111	0.06	69	202.9
		SKC Charcoal	PSG-2	541	555	0.98	0.58	1.7
		ATD Tenax TA	PSG-4	300	271	1.11	0.5	1.5
		WMS Anasorb	PSG-6	182	282	0.64	3.28	9.6
	2.2	ATD Carbopack B	PSG-2	611	555	1.10	0.5	1.6
		Radiello Charcoal	PSG-4	48	286	0.17	69	215.3
		SKC Charcoal	PSG-1	345	492	0.70	0.58	1.8
		ATD Tenax TA	PSG-3	319	461	0.69	0.5	1.6
		WMS Anasorb	PSG-5	53	118	0.45	3.28	10.2
	7.9	ATD Carbopack B	PSG-6	77	261	0.30	0.5	5.7
		Radiello Charcoal	PSG-2	43	691	0.06	69	784.9
		SKC Charcoal	PSG-5	113	96	1.18	0.58	6.6
		ATD Tenax TA	PSG-1	286	424	0.68	0.5	5.7
		WMS Anasorb	PSG-3	301	631	0.48	3.28	37.3
	8.1	ATD Carbopack B	PSG-5	103	105	0.99	0.5	5.8
		Radiello Charcoal	PSG-1	22	348	0.06	69	801.1
		SKC Charcoal	PSG-4	728	292	2.49	0.58	6.7
		ATD Tenax TA	PSG-6	13	207	0.06	0.5	5.8
		WMS Anasorb	PSG-2	347	710	0.49	3.28	38.1
	9.8	ATD Carbopack B	PSG-4	287	260	1.10	0.5	7.1
		Radiello Charcoal	PSG-6	69	201	0.34	69	977.0
		SKC Charcoal	PSG-3	511	424	1.21	0.58	8.2
		ATD Tenax TA	PSG-5	63	98	0.64	0.5	7.1
		WMS Anasorb	PSG-1	219	345	0.64	3.28	46.4
	11.7	ATD Carbopack B	PSG-1	279	295	0.95	0.5	8.4
		Radiello Charcoal	PSG-3	21	402	0.05	69	1,159.2
		SKC Charcoal	PSG-6	too wet	144	---	0.58	9.7
		ATD Tenax TA	PSG-2	11	476	0.02	0.5	8.4
		WMS Anasorb	PSG-4	238	280	0.85	3.28	55.1

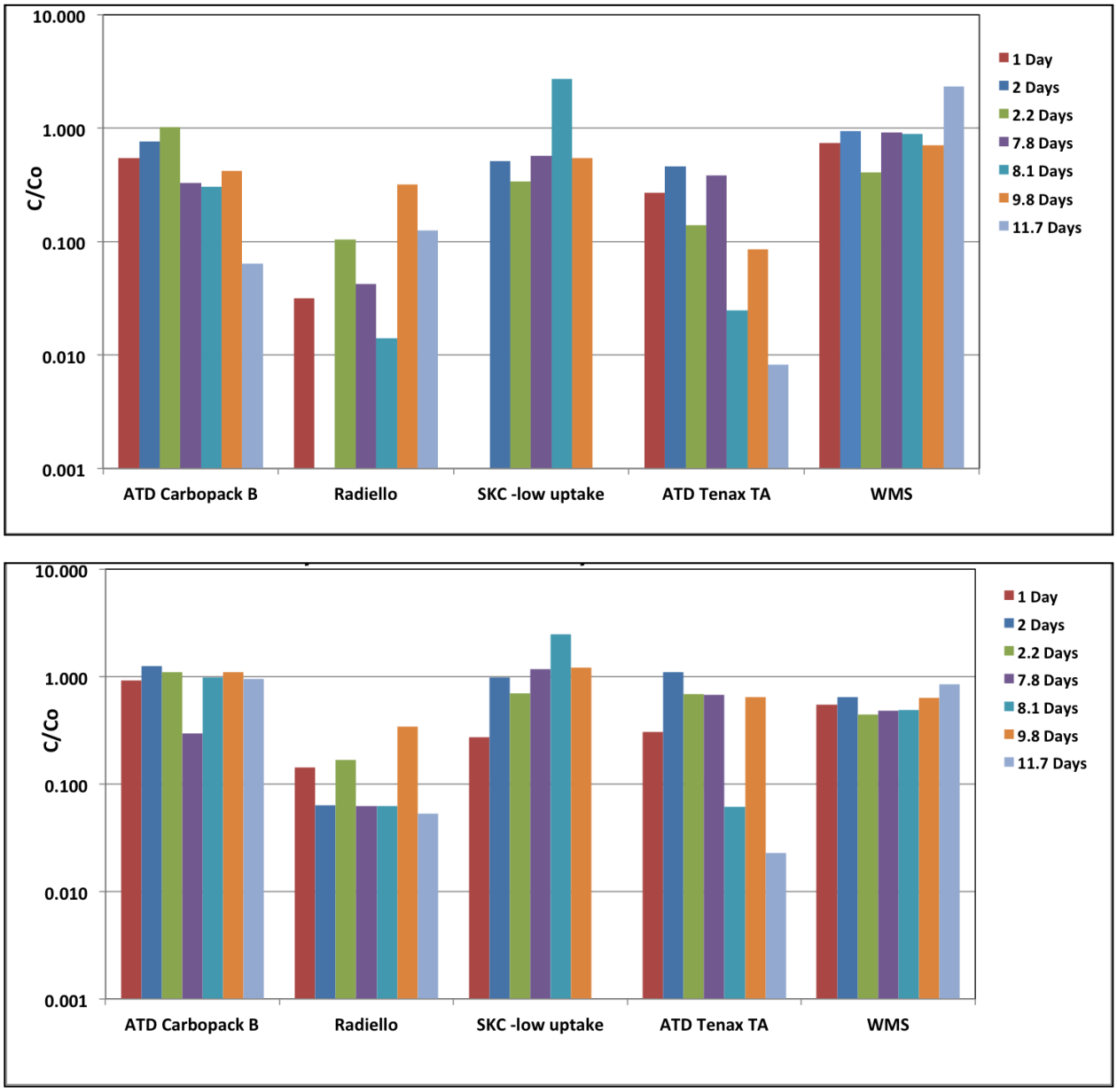


Figure 48a,b: Relative concentration (passive/active, or C/C_o) at the Layton House, Utah, near Hill AFB for 11DCE (top) and TCE (bottom).

The average C/Co values for each sampler and both 11DCE and TCE are summarized below:

Sampler	ATD/CPB	Radiello	SKC-LU	ATD/Tenax	WMS
11DCE	0.58	0.07	1.2	0.42	1.1
TCE	1.0	0.14	1.4	0.57	0.78

All of these combinations meet the success criteria of 0/5 <C/Co <1.67 (Section 3), except the Radiello (attributable to starvation) and 11DCE for ATD/Tenax (attributable to poor retention).

The results of the active (Hapsite and Summa) samples at the Layton house showed the ranges of variability that are typically observed with active soil gas sampling (Table 21). Temporal variability can be assessed by comparing the concentrations measured in each probe over 9 events in 6 weeks, while spatial variability can be assessed by comparing the concentrations from 6 probes within one meter of one another. The coefficient of variation (COV, standard deviation divided by the mean) ranged from 0.23 to 0.57 for temporal variability and 0.31 to 0.84 for spatial variability, which sets a baseline for comparison of the passive sampler data.

Table 21: TCE and 11DCE concentrations measured in active soil gas samples analyzed by the Hapsite transportable GC/MS (H) or Summa canister and TO-15 (S) at the Layton house.

Temporal Variability									Spatial Variability		
11DCE (µg/m^3)	*	SGP-1	SGP-2	SGP-3	SGP-4	SGP-5	SGP-6	average	mean	std.dev.	COV
21-Jul-10	H	361.5	348.4	485.6	461.0	160.8	370.7		364.7	114.7	0.31
22-Jul-10	S	290.5	437.8	477.6	477.6	159.2	242.8		347.6	135.4	0.39
03-Aug-10	H	25.8#	264.7	214.7	183.2	58.5	66.0		135.5	98.0	0.72
04-Aug-10	H	306.5	535.8	432.4	116.0	101.5	301.4		298.9	171.1	0.57
05-Aug-10	H	273.0	475.7	447.5	197.0	101.3	301.2		299.3	143.8	0.48
07-Aug-10	H	259.6	337.0	282.3	245.9	77.4	227.7		238.3	87.4	0.37
17-Aug-10	S	111.4	346.3	203.0	107.5	16.3#	79.6		144.0	116.0	0.81
25-Aug-10	H	199.2	393.6	325.6	179.8	48.6	252.7		233.3	120.6	0.52
02-Sep-10	H	214.9	230.8	218.9	226.9	55.7	171.1		186.4	67.5	0.36
Mean		226.9	374.5	343.1	243.9	86.6	223.7	249.8	249.8	117.2	0.50
std.dev		103.9	97.6	118.8	135.6	49.3	102.0	101.2			
COV		0.46	0.26	0.35	0.56	0.57	0.46	0.44			
TCE (µg/m^3)		SGP-1	SGP-2	SGP-3	SGP-4	SGP-5	SGP-6	average	mean	std.dev.	COV
21-Jul-10	H	452.9	557.5	483.6	437.6	145.4	367.4		407.4	142.5	0.35
22-Jul-10	S	294.3	425.1	419.7	321.6	109.0	190.8		293.4	125.4	0.43
03-Aug-10	H	36.1#	524.9	382.5	238.1	95.3	96.4		228.9	191.8	0.84
04-Aug-10	H	528.7	570.3	471.8	400.1	135.3	304.9		401.8	161.1	0.40
05-Aug-10	H	452.9	568.0	525.8	218.8	122.8	276.3		360.8	180.3	0.50
07-Aug-10	H	448.3	539.4	448.3	322.2	98.1	287.2		357.3	156.9	0.44
17-Aug-10	S	239.8	523.2	397.9	196.2	39.2#	114.5		251.8	180.2	0.72
25-Aug-10	H	454.8	894.7	790.3	387.7	104.4	298.2		488.3	300.4	0.62
02-Sep-10	H	392.4	485.1	468.7	332.5	87.2	223.5		331.5	153.3	0.46
Mean		366.7	565.4	487.6	317.2	104.1	239.9	346.8	346.8	176.9	0.53
std.dev		152.8	131.7	121.9	84.6	30.9	91.1	102.2			
COV		0.42	0.23	0.25	0.27	0.30	0.38	0.29			

(# - indicate samples suspected of low bias because of incomplete purging)

A similar calculation of the mean, standard deviation and COV for the passive samplers (Table 22) showed that the WMS sampler had the lowest COV values (0.46 and 0.55 for TCE and 11DCE, respectively). The SKC sampler had the second lowest COV values (0.52 and 0.80 for TCE and 11DCE, respectively). The Radiello sampler had the next highest COV values (0.64 and 0.93 for TCE and 11DCE, respectively). The ATD had the highest COV values, ranging from 0.72 to 1.14 with Carbopack B for TCE and 11DCE, respectively. These are all comparable to or slightly higher than the active sampler COV values, which is encouraging

considering the passive samples were collected in different probes for each round, so the passive sampler data set included both spatial and temporal variability.

Table 22: Passive sampler variability at the Layton House

Inter-Sampler Variability for 11DCE (µg/m^3)									Spatial and Temporal Variability		
Duration (days)	1	2	2.2	7.9	8.1	9.8	11.7	mean	mean	std.dev.	COV
ATD CPB	77	277	434	70	15	75	22		149	169	1.14
Radiello	15	ND	17	13	2	49	14		19	18	0.93
SKC	ND	209	99	30	393	133	ND		173	139	0.80
ATD Tenax	106	103	51	79	4	7	3		41	43	1.05
WMS	348	250	35#	250	327	130	363		226	123	0.55
Mean	109	168	106	75	125	67	83	104.8	122	98	0.89
std.dev	140	114	164	91	183	56	157	129.3			
COV	1.28	0.68	1.54	1.21	1.47	0.83	1.90	1.27			
Inter-Sampler Variability for TCE (µg/m^3)											
Duration (days)	1	2	2.2	7.9	8.1	9.8	11.7	mean	mean	std.dev.	COV
ATD CPB	342	611.0	611.0	77.0	103.0	287.0	279.0		328	236	0.72
Radiello	65	7.0	48.0	43.0	22.0	69.0	21.0		35	23	0.64
SKC	77	541	345.0	113.0	728.0	511.0	ND		448	231	0.52
ATD Tenax	151	300.0	319.0	286.0	13.0	63.0	11.0		165	151	0.91
WMS	210	182.0	53.0	301.0	347.0	219.0	238.0		223	102	0.46
Mean	123.4	219.7	193.0	115.0	175.7	151.9	102.8	154.5	240	149	0.65
std.dev	114.5	243.8	216.5	116.8	253.1	176.8	119.6	177.3			
COV	0.93	1.11	1.12	1.02	1.44	1.16	1.16	1.13			

(ND – not detected)

NAS JAX

The results of passive sampling at NAS JAX (Table 23) showed a broader range of concentrations (~100 to ~30,000 µg/m^3) than the other soil vapor data sets, so the data are presented on x-y scatter plots using logarithmic scales. The passive soil gas and passive subslab data are shown on Figures 49a and b, respectively.

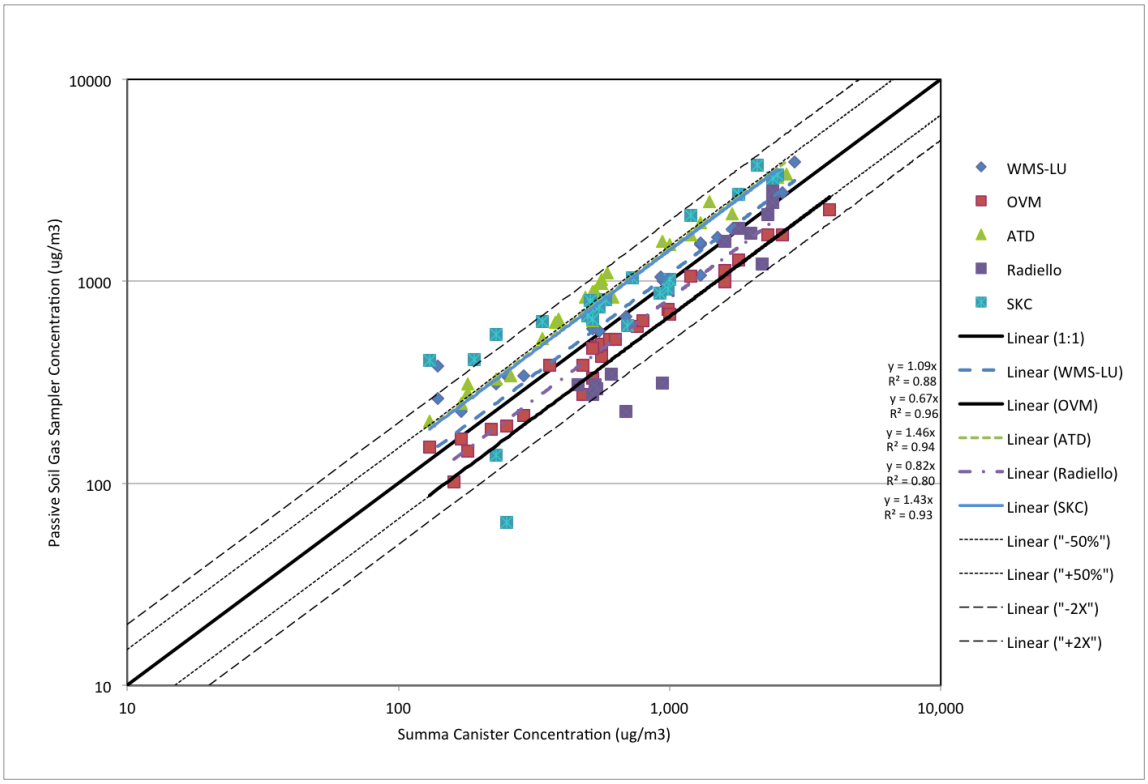
The exterior soil gas passive sampler concentrations all yielded regression lines with slopes ranging from 0.67 to 1.46, which meet the success criteria in Table 3 for accuracy (+/-50% corresponds to a range of 0.5 to 1.67). The correlation coefficient (R^2) values ranged from 0.80 to 0.96. Only 8 of the 117 detectable results for all the samplers fell outside the +/- 2X range (outer dotted lines), of which 4 were for TCE in SKC samplers. TCE was detected at 23.4 ng in the SKC trip blank (Appendix H) and the SKC investigative samples all had TCE mass measured at levels two times or less the value reported for the trip blank; consequently, the investigative samples were corrected for the blank, but this may impose a potential bias. Some results fell below the reporting limits ("U-qualified"), including tDCE for the WMS sampler, TCE for the Radiello and some of the PCE and tDCE values for the Radiello.

Table 23: Passive and active soil vapor concentrations for four VOCs in soil gas (SG) probes and sub-slab probes (SSPs) at NAS Jacksonville.

Sampler Type (Subtype/Sorbent)	Sample ID	Void Space Volume (L)	Exposure Time (min)	Concentration (µg/m3)							
				cis-1,2-DCE		PCE		trans-1,2-DCE		TCE	
				Passive Sampler	Summa Canister	Passive Sampler	Summa Canister	Passive Sampler	Summa Canister	Passive Sampler	Summa Canister
3M OVM (Regular/ charcoal)	SG-FP-20-1	1	20	1,136	1,600	424	560	384	480	145	180
	SG-FP-20-3	3	20	1,065	1,200	477	540	384	360	151	130
	SG-FP-40-2-A	2	40	1,705	2,300	601	760	490	560	185	220
	SG-FP-40-2-B	2	40	2,273	3,900	724	990	639	800	217	290
	SG-FP-40-2-C	2	40	1,705	2,600	689	1,000	518	600	193	250
	SG-FP-60-1	1	60	994	1,600	277	480	331	520	102	160
	SG-FP-60-3	3	60	1,278	1,800	518	630	469	520	166	170
ATD Tube (Regular/ Carbopack B)	SG-FP-20-1	1	20	2,157	1,700	1,024	560	637	520	310	180
	SG-FP-20-3	3	20	1,961	1,300	902	530	627	380	270 U	140
	SG-FP-40-2-A	2	40	3,775	2,100	1,098	590	833	490	280	180
	SG-FP-40-2-B	2	40	3,382	2,700	1,524	1,000	833	620	340	260
	SG-FP-40-2-C	2	40	3,284	2,500	1,585	940	784	540	330	230
	SG-FP-60-1	1	60	2,484	1,400	976	560	654	390	250	170
	SG-FP-60-3	3	60	1,699	1,200	894	520	523	340	203	130
WMS (0.8 mL Amber Vial / Anasorb 747)	SG-FP-20-1	1	20	1,806	1,700	670	690	9,823 U	500	162 U	190
	SG-FP-20-3	3	20	1,521	1,300	580	520	9,823 U	370	380	140
	SG-FP-40-2-A	2	40	3,897	2,900	1,004	950	4,912 U	650	340	250
	SG-FP-40-2-B	2	40	2,757	2,600	1,071	1,300	4,912 U	720	340	290
	SG-FP-40-2-C	2	40	2,757	2,400	1,049	930	4,912 U	540	312	230
	SG-FP-60-1	1	60	1,648	1,500	565	550	3,274 U	410	227	170
	SG-FP-60-3	3	60	1,553	1,300	625	520	3,274 U	380	265	140
Radiello (Yellow body/ Charcoal)	SG-FP-20-1	1	20	1,730	2,000	295 U	480	476 U	580	369 U	170
	SG-FP-20-3	3	20	1,222	2,200	295 U	790	476 U	650	369 U	220
	SG-FP-40-2-A	2	40	2,794	2,400	148 U	720	238 U	580	185 U	210
	SG-FP-40-2-B	2	40	2,143	2,300	226	690	294	540	185 U	200
	SG-FP-40-2-C	2	40	2,452	2,400	315	940	310	530	185 U	220
	SG-FP-60-1	1	60	1,831	1,800	98 U	650	275	520	123 U	190
	SG-FP-60-3	3	60	1,582	1,600	348	610	307	460	123 U	160
SKC* (12-hole cap, Carbograph 5)	SG-FP-20-1	1	20	2,704	1,800	1,040	730	770	520	*	200
	SG-FP-20-3	3	20	2,129	1,200	648	520	634	340	407	130
	SG-FP-40-2-A	2	40	3,758	2,100	875	920	806	510	546	230
	SG-FP-40-2-B	2	40	3,356	2,500	1,023	1,000	811	580	64	250
	SG-FP-40-2-C	2	40	3,236	2,400	920	990	747	550	139	230
	SG-FP-60-1	1	60	2,693	1,800	603	700	675	500	410	190
	SG-FP-60-3	3	60	2,683	1,300	558	550	734	390	572	140
ATD Tube (Pin-hole/ Carbopack B)	SSP-4	--	60	5,998	3,800	13,140	7,400	3,999	2,300	1,549	960
	SSP-5	--	60	7,331	4,400	28,332	17,000	8,331	4,900	3,030	1,900
	SSP-6	--	60	21,328	14,000	49,273	18,000	29,326	19,000	7,071	3,400
WMS (0.8 mL Amber Vial / Anasorb 747)	SSP-4	--	60	4,753	3,800	8,185	7,400	2,679 U	2,300	1,134	960
	SSP-5	--	60	4,753	4,400	17,857	17,000	5,566	4,900	2,079	1,900
	SSP-6	--	60	18,695	14,000	26,786	18,000	29,470	19,000	4,913	3,400
Radiello (Yellow body/ Charcoal)	SSP-4	--	60	2,233	3,800	1,850	7,400	1,344	2,300	326	960
	SSP-5	--	60	2,820	4,400	4,770	17,000	2,952	4,900	1,224	1,900
	SSP-6	--	60	10,444	14,000	6,535	18,000	13,233	19,000	2,620	3,400

Notes

*The SKC trip blank contained a significant level of TCE (23.4 ng); this mass was subtracted from the sample masses. Sample SG-FP-20-1-SKCPH had less than 23.4 ng TCE on it, so this result is excluded from the table



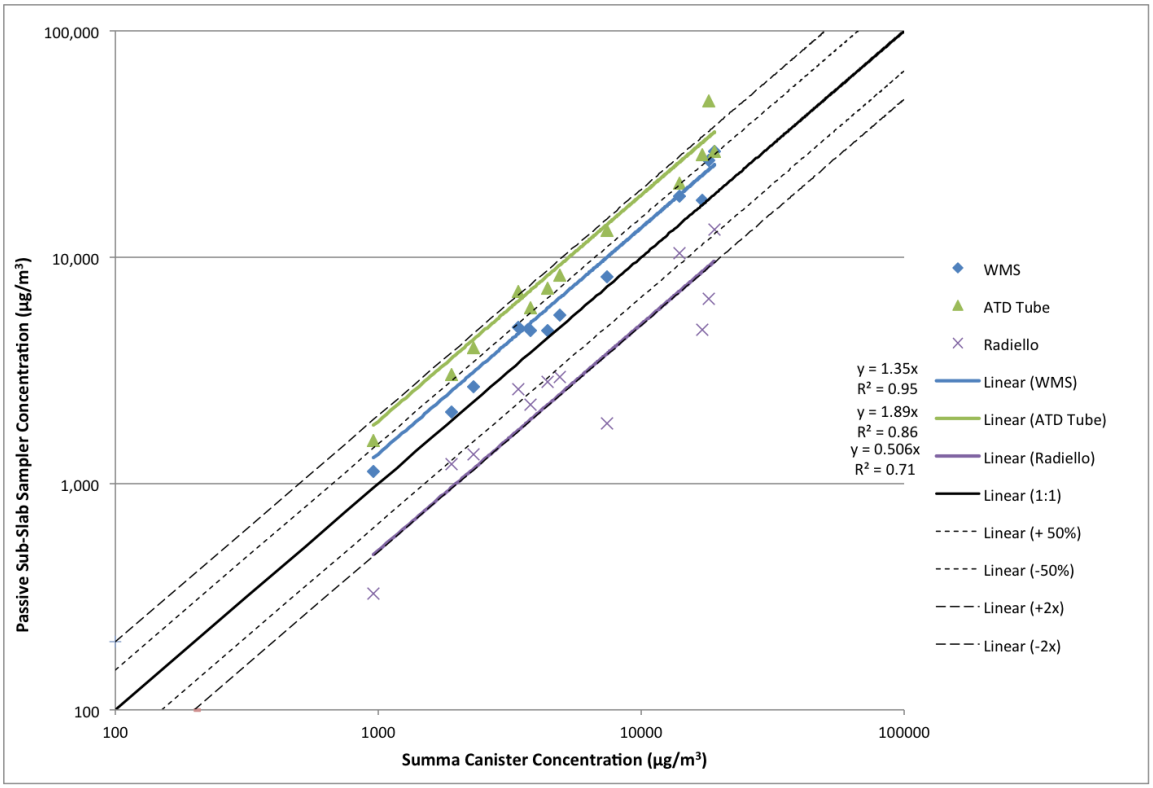


Figure 49a,b: Correlation between passive samples and Summa canister samples at NAS Jacksonville with linear regressions and correlation coefficients (R^2) for (a) soil gas and (b) sub-slab samples

Statistical analysis of the fractional factorial soil gas sampling experimental design via analysis of variance (ANOVA) at the 5% level of significance showed that the sampler type was a significant factor for all four compounds detected (in other words, the variance was small enough to enable the differences between the samplers to be discerned). Sampling duration (20, 40 and 60 minutes) had no statistically significant effect. Void volume was only statistically significant for tDCE and TCE, but not PCE and cDCE, which is somewhat ambiguous because there is no reason to expect difference between compounds for this factor.

The interior passive sub-slab samples at NAS JAX also showed strong positive correlations with active sample results (Figure 49b). The passive samplers all yielded regression lines with slopes ranging from 0.51 to 1.89 and R^2 values of 0.71 to 0.95. The regression line for the WMS samplers fell within the +/- 50% range (average C/Co of 1.35), with a correlation coefficient (R^2) of 0.95. The regression lines for the ATD and Radiello samplers were within the +/-2X range (50% and 200% C/Co) of an ideal (1:1) correlation, with slightly lower R^2 (0.86 and 0.71, respectively) than the WMS sampler. SKC and 3M samplers were not tested because they were too large to fit in the 1-inch drillhole.

The exterior passive soil gas samples from a temporary (uncased) hole also showed good correlation to the active (Summa canister) samples (Figure 50), which indicates that uptake rates of 0.5 to 1.1 mL/min for the four compounds detected are low enough to avoid a low bias via starvation for these compounds in a small diameter (2.5 cm) drillhole in a sandy soil. This is encouraging because this is consistent with expectations based on mathematical modeling (Section 6.7.1) and temporary sampling is a common application of passive soil vapor monitoring because the costs of deployment are much lower compared to the installation of a probe that can be sampled on multiple occasions. The results showed no notable trend with sample duration in the range of 1.7 to 18 hours.

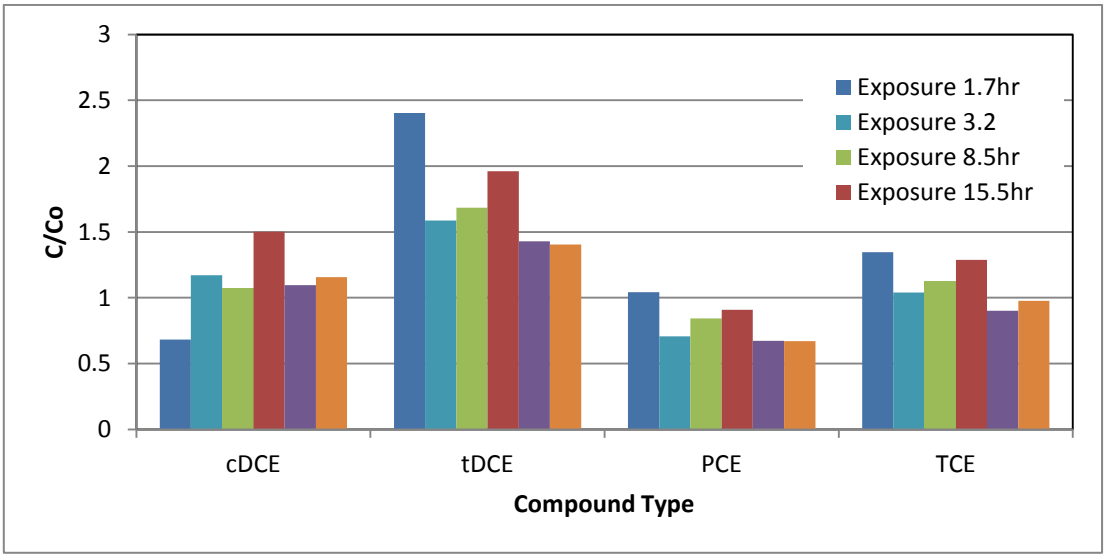


Figure 50: Relative concentration (passive/Summa canister) for WMS/low-uptake sampler in a 1-inch (2.54 cm) diameter open borehole open from 4 to 5 feet below ground at NAS Jacksonville.

6.8 Flow-Through Cell Test Results

The results of active and passive sampling in the flow-through cell are presented in Table 24. The relative concentration (C/Co) met the accuracy criteria (RPD<50%, corresponding to C/Co between 0.5 and 1.67) in 32 of 35 cases.

A total volume of about 320 L was purged during the two days of sampling, which is equivalent to the gas contained within a nominal 6-inch thick gravel layer beneath the floor slab with a 35% air-filled porosity within a radial distance of 1.7 m of the sub-slab probe. PID readings on soil vapor samples drawn from sub-slab probe LB-01 were 25 parts per million by volume (ppm_v) the night before testing began (November 9, 2010) and the final PID screening reading at the end of the second day of sampling was 19 ppm_v. Intermittent readings during the conduct of the test were within this range, which indicated that minimal changes in subsurface conditions occurred during the conduct of the testing. A PID reading of 25 ppmv corresponds to a TCE concentration of about 80,000 $\mu g/m^3$ (PID response factor = 0.62, 1 ppm_v = 5,400 $\mu g/m^3$), which was consistent with expectations from sampling in March and June 2010.

Active (Summa canister) soil gas samples collected upstream of the flow-through cell had TCE concentrations ranging from 12,000 to 55,000 $\mu g/m^3$ (Figure 51), with a mean of 38,650 $\mu g/m^3$ and a COV of 19%. The average Summa canister concentration was 38,200 $\mu g/m^3$ on November 9 and 39,200 $\mu g/m^3$ on November 10, which indicates similar conditions over the two days of testing. Individual Summa canister samples showed differences of up to 20,000 $\mu g/m^3$ from one sample to the next, which was unexpected based on the overall consistency in the TCE concentrations over two days of testing. The Summa canister data appeared to be more variable than expected from experience with similar extended purging studies (McAlary et al., 2010), but the root cause is not known.

The passive sampler data (Figure 52) had TCE concentrations in a similar range to the Summa canister data. The relative percent difference between the passive sampler and the Summa canister results are also shown on Table 24. In 17 of 35 cases, the relative percent difference (RPD) between the passive sampler result and Summa canister result is within +/-25%, which would generally be considered acceptable for laboratory duplicates using the same sample method in the same laboratory. In all but three cases (low flow rate and short duration for ATD, Radiello and WMS samplers), the passive sampler results were within a factor of 2 of the Summa canister results. Considering the Summa canisters showed concentration changes of up to 20,000 $\mu g/m^3$ in successive samples in some instances (an RPD of about 67%), the variability in the C/C_0 values cannot be attributed entirely to the passive samplers.

Table 24: TCE concentrations measured in the flow-through cell

Sampler Type	Flow Rate	Sample duration	Passive Sampler TCE Concentration	Summa Canister TCE Concentration	Relative Concentration	Relative Percent Difference
(Subtype/sorbent)	(mL/min)	(min)	(µg/m^3)	(µg/m^3)	(C/Co)	(%)
ATD Tube	930	20	69,000	37,000	1.9	60
(Regular/	930	10	47,000	37,000	**1.3**	24
Carbopack B)	80	20	46,000	43,000	**1.1**	7
	80	10	7,100	31,000	0.23	125
	670	15	34,000	38,000	**0.90**	11
	670	15	29,000	53,000	**0.55**	59
	670	15	50,000	39,000	**1.3**	25
OVM 3500	930	20	27,000	43,000	**0.63**	46
(Regular/	930	10	51,000	43,000	**1.2**	16
charcoal)	80	20	29,000	43,000	**0.66**	40
	80	10	19,000	35,000	**0.55**	58
	670	15	42,000	39,000	**1.1**	8
	670	15	38,000	36,000	**1.1**	6
	670	15	40,000	30,000	**1.3**	29
	930	20	40,000	34,000	**1.2**	15
Radiello	930	20	49,000	53,000	**0.92**	8
(White body/	930	10	55,000	36,000	**1.5**	42
charcoal)	80	20	32,000	44,000	**0.74**	30
	80	10	11,000	36,000	0.30	107
	670	15	59,000	45,000	**1.3**	27
	670	15	39,000	29,000	**1.3**	28
	670	15	33,000	***35,500#***	**0.93**	7
SKC Ultra	930	20	34,000	40,000	**0.85**	16
(Regular Uptake Rate/	930	10	40,000	44,000	**0.92**	9
Carbograph 5, or	80	20	32,000	33,000	**0.97**	3
charcoal [100-10	80	10	50,000	42,000	**1.2**	18
only])	670	15	42,000	***32,500#***	**1.3**	26
	670	15	30,000	35,000	**0.86**	15
	670	15	44,000	30,000	**1.5**	39
WMS	930	20	44,000	44,000	**0.99**	1
(Regular 1.8 mL vial/	930	10	39,000	38,000	**1.0**	3
Anasorb 747)	80	20	27,000	20,000	**1.4**	30
	80	10	22,000	51,000	0.42	81
	670	15	40,000	29,000	**1.4**	32
	670	15	20,000	34,000	**0.58**	54
	670	15	38,000	50,000	**0.76**	27

Notes # - Summa data are averages of preceding and following samples

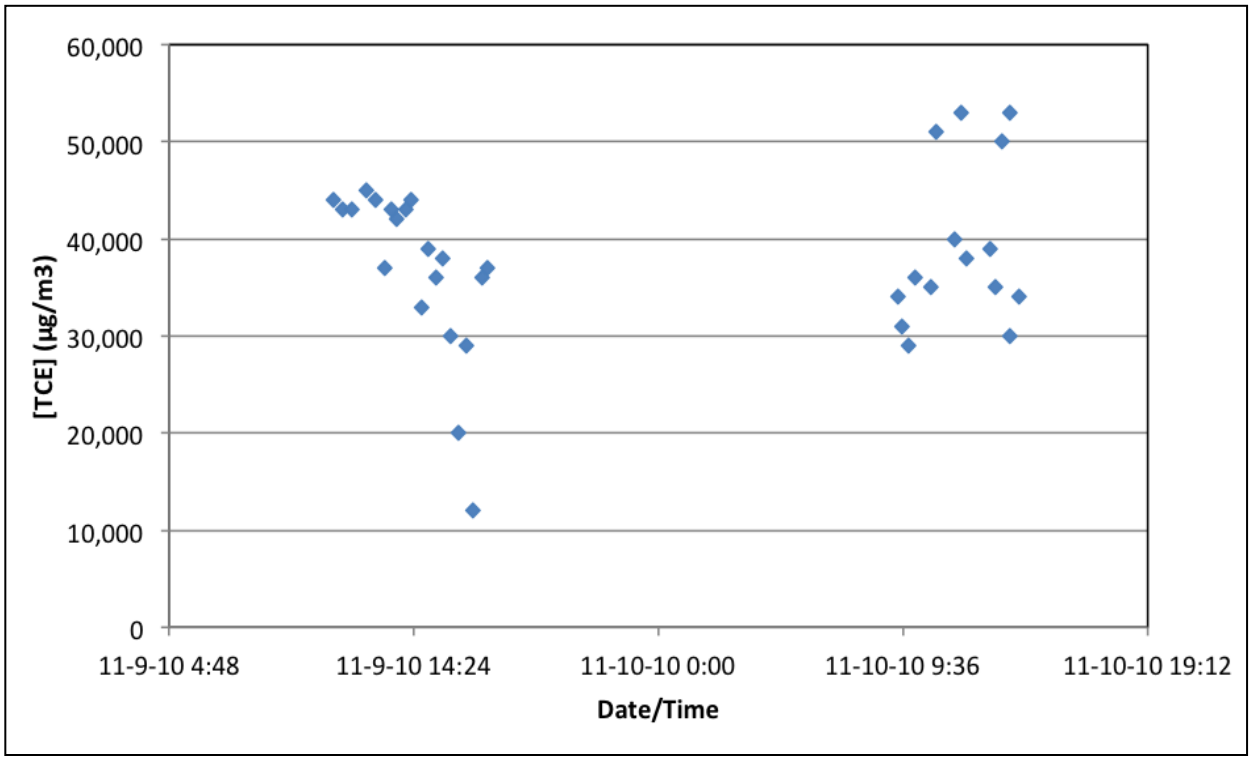


Figure 51: TCE concentrations measured with Summa canisters in the flow-through cell

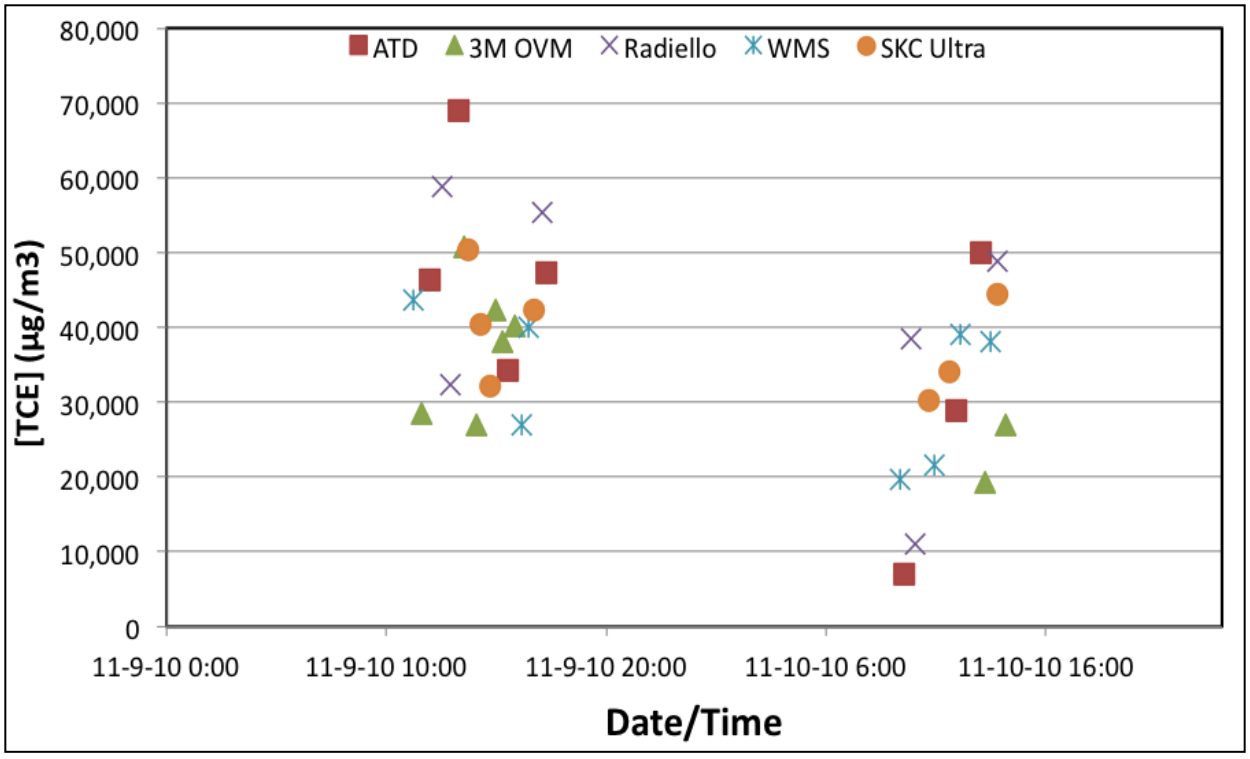


Figure 52: Passive sampler TCE concentrations measured in the flow-through cell

The passive sampler TCE concentrations divided by the coincident Summa canister TCE concentrations are plotted as relative concentrations (C/C_o) in Figure 53. The legend numbers are the flow rate in mL/min (first) and the sample duration in minutes (second). The low flow rate and short sample duration (100 mL/min for 10 min) showed a low bias for all the passive samplers except the SKC, which is likely attributable to insufficient purging of the flow through cell during the sampling interval. Nevertheless 32 of 35 results met the success criteria for soil vapor sampling (C/Co between 0.5 and 1.67), and about half were within +/-25%.

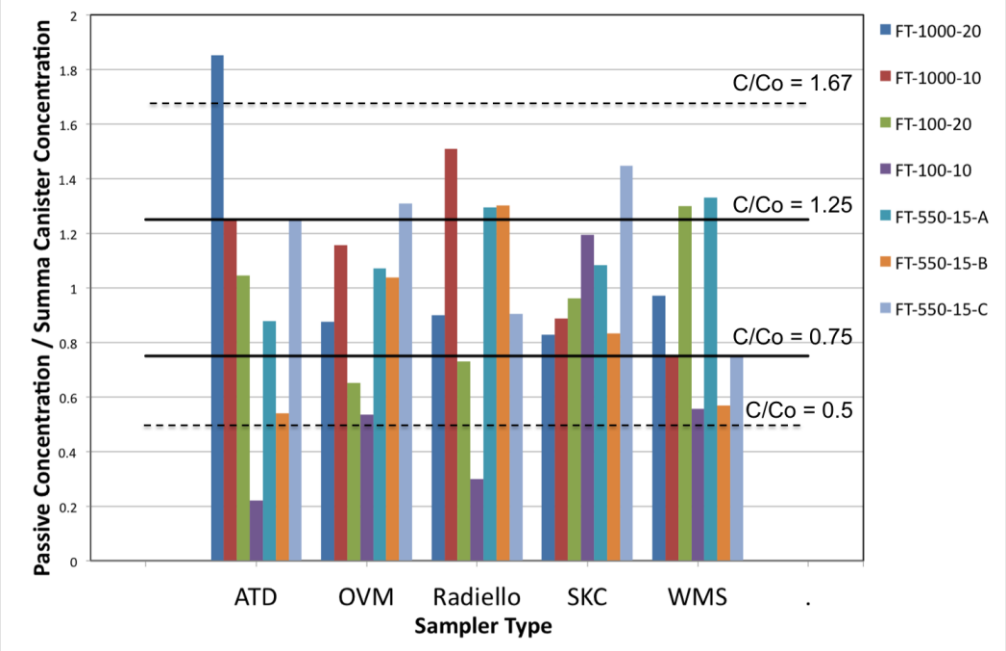


Figure 53: Relative TCE concentration (C/C_o) for passive samplers in the flow-through cell

A three-way analysis of variance (ANOVA) analysis was run on the concentration values using sampler type, flow rate and sample duration as the three factors of interest. No interaction terms were included. The data consisted of 72 observations and were run as an unbalanced design using the PROC GLM function in SAS 9.2. The overall F-test was not significant ($F=1.88$, $p = 0.0789$), indicating that there was no statistically significant difference in the TCE concentrations between the Summa canisters and the passive samplers or between the different types of passive samplers at the 5% significance level (alpha =0.05). The analysis of individual factors showed that the sampler type and sample duration was also not significant at the 5% level; however, the flow rate did show a statistically significant effect for the ATD tube sampler. The ATD tube sampler is the only one without a porous plastic or membrane between the sorbent inside the sampler and the medium being monitored, and therefore, may be more susceptible to a positive bias in the uptake rate via convection or turbulence at higher flow rates.

Summary statistics for the flow-through cell test are provided in Table 25. The mean C/C_o value (average of 7 individual C/Co values for each sampler) was between 0.93 and 1.08 for all five passive samplers, indicating the average accuracy was good. The SKC Ultra and WMS

samplers had COV values similar to their respective Summa canister results and met the precision goal of <30% COV, but the COV for the ATD tube, OVM3500 and Radiello were more than double the Summa canister COVs. If the one sample collected with the low flow rate and low duration is excluded (insufficient flushing of the cell cause a low bias), then the COV for the ATD, OVM and Radiello samplers would have been 31%, 23% and 26%, respectively, which would be comparable to the success criteria of <30%.

Table 25: Summary statistics for all sampler types in the flow-through cell

	Mean Passive TCE Concentration	COV	Mean Summa TCE Concentration	COV	Mean of seven C/C_o values
Sampler	($\mu g/m^3$)	(%)	($\mu g/m^3$)	(%)	(dim)
ATD Tube	40,400	48	39,700	17	1.03
OVM 3500	35,700	28	37,900	13	0.96
Radiello	39,700	41	39,800	20	1.01
SKC Ultra	39,100	19	36,600	15	1.08
WMS	32,700	30	38,000	30	0.93

7 PERFORMANCE ASSESSMENT

This section provides analysis and interpretation of the results presented in Section 6, particularly with respect to the passive sampler performance and the factors that influence the performance.

7.1 Low Concentration Laboratory Tests

The accuracy success criteria (RPD <45%, corresponding to C/Co range of 0.63 to 1.58) was met for at least 7 of the 10 compounds for each of the passive samplers in the overall average results of the low concentration laboratory tests (shown using boldface in Table 26a). The mean C/Co (passive concentration/active control) values were calculated for all 24 chamber tests, which includes 8 tests at the center-points and 16 tests conducted at high and low set points of the sample duration, face velocity, temperature, humidity, and concentration, so they represent the average accuracy over a wide range of indoor air monitoring conditions. In Table 26a, a column has been added comparing the average results of the active ATD tube samples to the concentrations calculated from the mass flow controller measurements. Three of the passive samplers showed a low bias for MEK, but that may also be attributable to a high bias in the active sampler results.

Table 26a: Mean C/Co values for the low concentration laboratory tests

Mean C/Co (passive/active)	ATD / Carbopack B	ATD / Tenax	WMS	Radiello	SKC	Active/ Calculated
111TCA	**0.72**	**0.67**	**1.15**	**0.95**	**0.80**	0.79
124TMB	**0.73**	**0.69**	0.54	**1.13**	**0.69**	0.89
12DCA	0.60	**0.67**	**0.86**	**0.83**	**0.75**	0.87
BEN	1.71	**1.07**	**0.99**	**0.90**	**0.95**	0.72
CT	**0.82**	**0.67**	**1.18**	**0.81**	0.55	0.98
HEX	**1.12**	0.55	**1.15**	**0.80**	**0.70**	0.86
MEK	0.21	**1.00**	**1.12**	0.62	0.46	1.33
NAPH	**0.90**	**0.98**	0.17	2.26	0.36	0.82
PCE	**1.15**	**0.85**	**0.72**	**1.02**	**0.98**	0.94
TCE	**0.91**	0.62	**0.80**	**0.91**	**0.87**	0.91

Mean C/Co is the average of 24 passive/active concentration ratios (one for each chamber test)
boldface: average C/Co values of 0.63 to 1.58, which meet the success criteria: RPD < +/-45%
Active ATD tube data was compared to concentrations calculated from mass flow controllers

The precision success criteria (COV <30%) was met for almost all of the passive sampler/compound combinations for the average of the COV values for the three replicates within each of the 24 chamber tests (Table 26b), except for MEK with the ATD/Carbopack B sampler. The SKC Ultra II was marginal for 124TMB and MEK. The passive samplers had a lower COV than the active control (pumped ATD tubes) in 68% (34/50) cases and 80% of the cases where the SKC Ultra II is not included. This demonstrates that the passive samplers have a high precision and provide very reproducible results under a certain set of conditions.

Table 26b: Mean Intra-Chamber COV values for the low concentration laboratory tests

Mean intra-chamber COV	ATD / Carbopack B	ATD / Tenax	WMS	Radiello	SKC	Active ATD/ Calculated
111TCA	**7%**	**3%**	**7%**	**5%**	**14%**	**13%**
124TMB	**5%**	**5%**	**7%**	**4%**	**22%**	**7%**
12DCA	**8%**	**3%**	**6%**	**4%**	**12%**	**9%**
MEK	47%	**5%**	**13%**	**11%**	**23%**	**15%**
CT	**4%**	**6%**	**8%**	**4%**	**8%**	**12%**
HEX	**7%**	**2%**	**7%**	**7%**	**16%**	**7%**
BENZ	**5%**	**6%**	**12%**	**3%**	**10%**	**6%**
NAPH	**6%**	**12%**	**7%**	**6%**	**16%**	**7%**
PCE	**2%**	**3%**	**6%**	**3%**	**6%**	**5%**
TCE	**3%**	**2%**	**5%**	**3%**	**16%**	**5%**

Mean intra-chamber COV is the average of 24 COV values, from three replicates in each chamber
boldface: COV value meets the success criteria: < 30%

The COV can also be calculated for all 24 chamber tests as a single population (Table 26c), which results in higher COV values because the high and low values of the test chamber factors (sample duration, face velocity, temperature, humidity and concentration) caused additional variability or bias in the passive sampler data. Calculated in this way, even the active (pumped) ATD tubes showed a COV that was marginal compared to the success criteria (<30%). The passive samplers showed generally higher COV values and a wider range between compounds, which shows they are more sensitive than the pumped ATD tubes to the test conditions.

Table 26c: Mean Inter-Chamber COV values for the low concentration laboratory tests

Mean inter-chamber COV	ATD / Carbopack B	ATD / Tenax	WMS	Radiello	SKC	Active ATD/ Calculated
111TCA	**24%**	**27%**	**26%**	35%	51%	**18%**
124TMB	**12%**	**16%**	42%	**25%**	55%	**17%**
12DCA	31%	32%	35%	**28%**	61%	**23%**
MEK	88%	69%	116%	70%	65%	**19%**
CT	**25%**	**26%**	31%	**28%**	59%	**19%**
HEX	37%	45%	56%	**28%**	39%	**27%**
BENZ	**25%**	31%	**26%**	**16%**	40%	**19%**
NAPH	**18%**	**25%**	128%	46%	58%	**17%**
PCE	**13%**	**14%**	34%	**27%**	**26%**	**18%**
TCE	**11%**	**17%**	34%	**30%**	51%	**16%**

Inter-chamber COV is the COV of 24 average C/Co values, one from each chamber test
boldface: COV value meets the success criteria: < 30%

The information from the low concentration laboratory chamber tests can be used to improve the application of passive samplers in the future. The average C/Co values (Table 26a) can be multiplied by the initial uptake rates (Table 3) to derive improved uptake rates for the 10 target analytes (Table 26d) for the compounds and sorbents tested. For the centerpoint conditions (temperature of 21 ^{o}C, relative humidity of about 60%, 0.23 m/s face velocity, 4 day sample duration, and concentrations of about 50 ppbv), most of the samplers provided data that met the

success criteria for precision (COV<30%, as shown on Figure 34), and with better-calibrated uptake rates (Table 26d), the results would meet similar data quality objectives as conventional active Suma canister/TO-15 or active (pumped) ATD tube/TO-17. Combinations of samplers and analytes that did not meet the success criteria even at the centerpoint conditions (indicated by a double asterisk in Table 26d) should be supported by inter-method duplicates regardless of the field sampling conditions if the highest level of data quality is needed. Compound/sampler combinations that showed high variability when the chamber conditions were at high or low levels of the 5 factors (not boldfaced in Table 26c and marked with a single asterisk in Table 26d) would also benefit from inter-method duplicates when field sampling conditions are not similar to the midpoint levels. For compounds not listed on Table 26d, of for other samplers or sorbents, the accuracy will depend on the level of calibration effort for the particular compound and sampler.

Table 26d: Recommended revised Uptake Rates for Compounds, Samplers and Sorbents used in the Low Concentration Laboratory Tests

	Recommended Revised Uptake Rate (mL/min)				
	WMS	**Radiello**	**SKC Ultra**	**ATD Tube**	**ATD Tube**
Analyte	1.8 mL vial and Anasorb 747	White body and Charcoal	Ultra II and Carbopack X	Carbopack B	Tenax TA
1,1,1-Trichloroethane	1.5	59*	11*	0.36	0.34
1,2,4-Trimethylbenzene	7.0*	57	9.0*	0.45	0.43
1,2-Dichloroethane	2.2*	64	9.8*	0.30*	0.34*
2-Butanone (MEK)	1.5*	**49****	7.8*	**0.11****	0.50*
Benzene	2.2	72	15*	0.60	0.37*
Carbon Tetrachloride	1.8*	54	7.2*	0.41	0.34
n-Hexane	1.5*	53	9.8*	0.56*	0.28*
Naphthalene	**4.4****	**57****	4.7*	0.45	0.49
Tetrachloroethene	3.9*	60	13	0.47	0.35
Trichloroethene	2.6*	63	13*	0.46	0.31
** - Field calibration is recommended * - Consider field calibration if temperature, humidity, velocity, duration or concentration are considerably different than 21^{o}C, 60%RH, 0.2 m/s, 4 days and 50 ppbv, respectively					

Statistical analysis of the low concentration laboratory test data using analysis of variance (ANOVA) are presented in Appendix I and summarized in Table 27. The highlighted p-values identify the main effects that are statistically significant at the 5% level of significance. The fact that the chambers were very well controlled during these experiments resulted in low experimental variability, which increases the probability that a main effect will show a difference that can be statistically resolved when compared to the intrinsic variance. In many cases, the statistically significant effects are consistent with expectations:

- Temperature and humidity showed significant effects less frequently than other factors, but this may be attributable to the fact that these factors were the most challenging to control (higher variability makes it less likely that an effect will be statistically significant by comparison).

- Temperature had a significant effect for 8/10 compounds for the Radiello and no more than 3 compounds for any of the other samplers. The uptake rate for the Radiello depends mostly on the diffusion coefficient for each compound, and the diffusion coefficient changes with temperature, so this is not unexpected. The fact that temperature is significant for the Radiello more frequently than other samplers could be because the higher uptake rate provides more sensitivity to changes. The Radiello also showed very low variability, which increases the likelihood that any trends will be significant statistically.

- Humidity had a significant effect for MEK and 12DCA (the two most soluble compounds) in the SKC Ultra and Radiello samplers, but not the WMS (which has a PDMS membrane that inhibits water uptake by the sorbent) and ATD-Tenax (Tenax is extremely hydrophobic).

- Sample duration (or exposure time) showed significant effects for the ATD-Tenax sampler for all compounds tested. Tenax has lower recommended maximum sample volumes than Carbopack B, so this is attributable to poor retention in the 4-day and 7-day samples. For example, the RMSVs for 111TCA, 12DCA, BENZ, CT and TCE are 0.2, 1, 1, 0.2 and 1 L, respectively (Supeloco, 2013). The product of the uptake rate and the sample duration (the equivalent sample volume) for these compounds for the 7 day samples was 5, 5, 3.5, 5 and 5 L, respectively. RMSVs are not available for MEK, HEX and NAPH, but of the other compounds, 55 of the 64 cases of C/Co<0.63 (i.e., failing the accuracy success criteria with a low bias) had an equivalent sample volume (UR x t) greater than the RMSV. This is further supported by the fact that the only two compounds that had a p value greater than 0.0001 were naphthalene and 124TMB, which were the two compounds with the highest K_{oc} values (i.e., most strongly sorbed). Sample time was also significant for 7/10 compounds for the passive ATD sampler with Carbopack B, and the compounds with the lowest p-values (111TCA, 12DCA, CTET and TCE) had the smallest RMSVs (20, 5, 20 and 20 L, respectively). The Radiello and WMS samplers showed the fewest compounds having a significant effect from sample time, which is consistent with expectations because these samplers both used very strong sorbents (charcoal and Anasorb 747, respectively).

- Face velocity had less effect on the ATD tubes than the other samplers. This may be because they have the lowest uptake rates of the samplers tested, and therefore less likely to experience low bias from the starvation effect at low air velocities.

- Concentration had a significant effect for MEK on all sampler types, but was otherwise comparable for all samplers and not consistently significant for any other compounds.

Table 27: Results of ANOVA analysis (p-values) of low concentration lab tests (main effects)

Sampler Type	Analyte	Relative Humidity	Temperature	Face Velocity	Exposure Time	Concentration
ATD Carbopack	1,1,1-Trichloroethane	0.0778	0.0281	0.0106	0.0003	<.0001
ATD Carbopack	1,2,4-Trimethylbenzene	0.3181	0.0009	0.1245	0.5664	0.0011
ATD Carbopack	1,2-Dichloroethane	0.0012	0.6819	0.7406	<.0001	0.1371
ATD Carbopack	2-Butanone (MEK)	0.0693	0.4097	0.0603	0.7378	0.0119
ATD Carbopack	Hexane	0.7999	0.2913	0.4002	0.0272	0.1177
ATD Carbopack	Benzene	0.4718	0.2468	0.0547	0.0023	0.0331
ATD Carbopack	Carbon tetrachloride	0.0434	0.2975	0.3501	<.0001	<.0001
ATD Carbopack	Naphthalene	0.2629	0.6088	0.293	0.007	0.0778
ATD Carbopack	Trichloroethene	0.0113	0.2781	0.0002	<.0001	0.9484
ATD Carbopack	Tetrachloroethene	0.8513	0.004	0.0071	0.8484	0.0727
ATD Tenax	1,1,1-Trichloroethane	<.0001	0.2715	0.0021	<.0001	<.0001
ATD Tenax	1,2,4-Trimethylbenzene	0.9169	0.8868	0.0121	0.0296	0.2864
ATD Tenax	1,2-Dichloroethane	0.9154	0.8908	0.4733	<.0001	<.0001
ATD Tenax	2-Butanone (MEK)	0.7719	0.0799	0.1479	<.0001	<.0001
ATD Tenax	Hexane	0.6362	0.21	0.6114	<.0001	0.1148
ATD Tenax	Benzene	0.8106	0.0059	0.438	<.0001	0.0442
ATD Tenax	Carbon tetrachloride	<.0001	0.0229	0.0159	<.0001	<.0001
ATD Tenax	Naphthalene	0.311	0.2147	0.565	0.025	0.0347
ATD Tenax	Trichloroethene	0.5875	0.0002	0.0153	<.0001	0.475
ATD Tenax	Tetrachloroethene	0.3221	0.4522	0.11	<.0001	0.9827
RADIELLO	1,1,1-Trichloroethane	0.1005	0.0261	0.003	0.0899	0.0548
RADIELLO	1,2,4-Trimethylbenzene	0.6688	0.0007	<.0001	0.1133	0.0451
RADIELLO	1,2-Dichloroethane	0.0005	0.054	0.0002	0.0327	<.0001
RADIELLO	2-Butanone (MEK)	<.0001	0.5801	0.0003	0.0738	<.0001
RADIELLO	Hexane	0.1795	0.0066	0.0021	<.0001	0.0035
RADIELLO	Benzene	0.0047	0.0496	0.0012	<.0001	0.6113
RADIELLO	Carbon tetrachloride	0.4994	0.0143	0.0513	0.1724	0.9018
RADIELLO	Naphthalene	0.6635	0.0008	0.933	0.1183	0.0005
RADIELLO	Trichloroethene	0.001	0.0032	<.0001	0.0002	0.0169
RADIELLO	Tetrachloroethene	0.2158	0.0023	<.0001	0.3477	0.9109
SKC	1,1,1-Trichloroethane	0.0906	0.1691	0.0055	0.0096	0.0001
SKC	1,2,4-Trimethylbenzene	0.1362	0.3054	0.0012	0.0004	<.0001
SKC	1,2-Dichloroethane	<.0001	0.5187	0.1033	0.9879	0.6424
SKC	2-Butanone (MEK)	<.0001	0.2819	0.3914	0.0073	0.0028
SKC	Hexane	0.0006	0.0398	0.012	0.4921	0.1584
SKC	Benzene	0.0318	0.0551	0.9085	0.0218	0.0125
SKC	Carbon tetrachloride	0.0223	0.2682	0.032	<.0001	<.0001
SKC	Naphthalene	0.1182	0.1437	0.6579	<.0001	0.1122
SKC	Trichloroethene	<.0001	0.9977	0.0306	0.5618	<.0001
SKC	Tetrachloroethene	0.4868	0.0368	0.018	0.0097	0.1261
WMS	1,1,1-Trichloroethane	0.0224	0.9489	0.0042	0.6355	0.4719
WMS	1,2,4-Trimethylbenzene	0.7716	0.7992	<.0001	0.1467	0.0194
WMS	1,2-Dichloroethane	0.7347	0.1749	0.0054	0.0325	0.1887
WMS	2-Butanone (MEK)	0.5881	0.3369	0.14	0.0319	0.0027
WMS	Hexane	0.6198	0.4942	0.022	0.0003	0.0001
WMS	Benzene	0.5712	0.9017	0.0328	0.0012	0.0099
WMS	Carbon tetrachloride	0.0016	0.3838	0.0035	0.0766	0.0553
WMS	Naphthalene	0.9025	0.4298	<.0001	0.5432	0.006
WMS	Trichloroethene	0.6289	0.0325	0.0006	0.8376	0.0124
WMS	Tetrachloroethene	0.5923	0.1477	<.0001	0.9894	0.0074

red highlighted cells indicate statistical significance when alpha=0.05, therefore, p-value<0.05 = significant

One general interpretation of the low concentration laboratory test data is that the uptake rates of passive samplers vary in response to the conditions under which testing is performed and the variability is compound-specific. The trends are in many cases consistent with theoretical expectations, but there is not yet enough information available to predict or mathematically model the uptake rates for any given set of site conditions, compounds and sampler(s). Therefore, it is sensible to include some frequency of inter-method verification samples in a passive sampling campaign (i.e., collect one active sample beside every 10^{th} passive sampler) to provide data that can be used to derive "field-calibrated" uptake rates for a particular set of environmental conditions. The high precision of the passive samplers under any particular set of conditions (Table 26b) provides confidence in the consistency of the uptake rate for other passive samplers collected under the same conditions as the inter-method duplicate.

Another general interpretation is that the sample duration should be considered when selecting a sorbent and a passive sampler for a given compound of interest. A shorter sample duration requires a high uptake rate sampler to provide good sensitivity (low concentration reporting limits), but longer sample durations may benefit from a low-uptake rate sampler to avoid poor retention. Stronger sorbents are also advisable for longer sample durations.

7.2 High Concentration Laboratory Tests

The accuracy of the passive samplers in the high concentration tests is summarized in Table 28a, which shows the relative concentration (C/C_0), where C is the average passive sampler concentration and C_0 is the average Summa canister concentration for each compound, sampler and concentration. The C/C_0 values were within the range of 0.6 to 1.7 (which meets the success criteria for soil gas sampling of an RPD of 50% of a C/Co range of 0.5 to 1.67) in 114 out of 140 (81%) of the sampler / compound / concentration combinations. Of the 26 combinations where the accuracy did not meet the success criteria, 7 were because of non-detect results, 8 were for MEK (the most soluble compound) and 7 were for NAPH or 124TMB (the most sorptive compounds).

High humidity is known to reduce the adsorptive capacity of activated carbon or charcoal (Abiko et al., 2010), and the OVM, Radiello and SKC samplers used activated carbon or charcoal as the adsorbent, which may explain the low bias for MEK, although the 30 minute sample duration was very short, relative to the range of typical sample durations, so the total uptake of water vapor would still be relatively small. The OVM Technical Data Bulletin (3M, 2013b) and Harper (2000) indicate that MEK concentrations are lower at 80% RH compared to <40% RH for an 8 hour sample , but the effect is smaller when samples are refrigerated, which was not performed, so the root cause of low bias for MEK may also have been degradation during shipping and storage. Note that for the 1 ppmv tests, Carbograph 5 was used in the SKC Ultra sampler, and the results showed an average C/Co of 1.9 for MEK. Carbograph 5 is a hydrophobic sorbent and has been shown to provide good retention even in high humidity air (Brancaleonia et al., 1999). Tenax is also hydrophobic and the WMS sampler has a hydrophobic membrane, and both samplers performed better for MEK than the other samplers.

The C/C_0 values were generally higher for the 100 ppmv tests, which might be attributable to the fact that the chamber was allowed to re-equilibrate for 5 minutes between samples.

Table 28a: Average relative concentrations (C/Co) for high concentration tests

C/Co for 1ppm	MEK	NHEX	12DCA	111TCA	BENZ	CTET	TCE	PCE	124TMB	NAPH
WMS Anasorb 747	ND	**1.4**	**0.63**	**0.60**	**0.50**	**0.60**	**0.70**	**0.66**	**0.55**	0.12
ATD Tenax TA	ND	**1.0**	**0.61**	0.45	1.7	**0.63**	**1.2**	**0.82**	**0.55**	**1.1**
Radiello Charcoal	0.41	**0.80**	**0.77**	**0.89**	**0.80**	**0.73**	**0.85**	**0.75**	0.28	ND
3M OVM 3500	0.21	**0.65**	**0.60**	**0.64**	**0.83**	**0.62**	**0.73**	**0.82**	**0.63**	ND
SKC Carbograph 5	1.9	**0.76**	**0.66**	**0.63**	**0.96**	**0.49**	**0.58**	**0.58**	**0.60**	1.1
C/Co for 10ppm										
WMS Anasorb 747	**0.54**	**0.70**	**0.68**	**0.65**	**0.75**	**0.69**	**0.74**	**0.71**	**0.83**	0.35
ATD Tenax TA	ND	**1.0**	**0.89**	**0.60**	**1.6**	**0.79**	**1.2**	**0.96**	**0.88**	**1.3**
Radiello Charcoal	0.47	**0.78**	**0.73**	**0.82**	**0.77**	**0.70**	**0.83**	**0.77**	0.35	ND
3M OVM 3500	0.22	**0.70**	**0.68**	**0.68**	**0.68**	**0.74**	**0.85**	**0.96**	**0.95**	0.46
SKC Charcoal	0.40	**1.1**	**1.1**	**1.0**	**0.98**	**0.99**	**1.0**	**1.2**	**1.2**	ND
C/Co for 100ppm										
WMS Anasorb 747	**0.80**	**0.86**	**0.92**	**0.82**	**1.0**	**0.90**	**1.0**	**1.2**	NT	NT
ATD Tenax TA	**1.0**	**1.4**	**1.4**	**1.2**	2.7	**1.2**	2.1	1.9	NT	NT
Radiello Charcoal	**0.58**	**1.1**	**1.1**	**1.3**	**1.2**	**1.1**	**1.4**	**1.4**	NT	NT
3M OVM 3500	0.30	**0.86**	**0.88**	**0.94**	**0.86**	**0.96**	**1.2**	**1.4**	NT	NT
SKC Charcoal	0.37	**1.2**	**1.4**	**1.3**	**1.1**	**1.3**	**1.4**	1.8	NT	NT

boldface: average C/Co values of 0.50 to 1.67, which meet the success criteria: RPD < +/-50%

The precision of the passive samplers and Summa canisters is summarized in Table 28b, which shows the COV for all the compound and sampler combinations. The COV values for the passive samplers were less than or equal to the COV values for the Summa canister samples in 69% of the cases (91/132). The COV for the passive samplers was less than the success criteria of 30% in all but one case (n-hexane for the WMS sampler). The COV values were generally lower at the 10 and 100 ppmv levels where the mass was more readily resolved against reporting limits (except for the Radiello, which had highest COV values at 10 ppmv). The Summa canister had an average COV over 20% for 124TMB and NAPH.

The results of the high concentration laboratory tests indicate that passive samplers provide comparable accuracy and precision to active samplers across a broad range of concentrations, and that the uptake rates derived for longer sample durations typical of indoor air quality monitoring provide reasonably accurate results for shorter-term (30 minute) samples appropriate for higher concentrations common in the subsurface. Highly soluble compounds (like MEK) or highly sorptive compounds (like 124TMB and NAPH) appear to be more challenging to quantify accurately than other compounds, which is consistent with observations made during the low concentration laboratory tests.

Table 28b: Coefficient of variation (COV) measured in high concentration tests

COV at 1 ppm	MEK	NHEX	12DCA	111TCA	BENZ	CTET	TCE	PCE	124TMB	NAPH
WMS Anasorb 747	ND	32%	**3%**	**6%**	**6%**	**5%**	**0%**	**5%**	**6%**	**18%**
ATD Tenax TA	ND	**4%**	**7%**	**10%**	**8%**	**13%**	**4%**	**5%**	**15%**	NC
Radiello Charcoal	**3%**	**14%**	**9%**	**11%**	**12%**	**9%**	**11%**	**15%**	**19%**	ND
3M OVM 3500	**3%**	**9%**	**12%**	**8%**	**20%**	**11%**	**8%**	**9%**	**8%**	ND
SKC Carbograph 5	**5%**	**13%**	**16%**	**18%**	**5%**	**21%**	**18%**	**18%**	**19%**	**14%**
Summa Canister	**17%**	**15%**	**17%**	**16%**	**18%**	**14%**	**17%**	**20%**	**26%**	**29%**
COV at 10 ppm										
WMS Anasorb 747	**11%**	**5%**	**4%**	**6%**	**5%**	**4%**	**2%**	**1%**	**4%**	**12%**
ATD Tenax TA	ND	**2%**	**0%**	**7%**	**2%**	**7%**	**0%**	**1%**	**2%**	**9%**
Radiello Charcoal	**17%**	**14%**	**14%**	**14%**	**14%**	**14%**	**15%**	**15%**	**18%**	ND
3M OVM 3500	**4%**	**8%**	**8%**	**6%**	**6%**	**7%**	**8%**	**6%**	**6%**	**7%**
SKC Charcoal	**18%**	**14%**	**2%**	**4%**	**4%**	**3%**	**4%**	**4%**	**5%**	NC
Summa Canister	**6%**	**3%**	**4%**	**3%**	**4%**	**7%**	**6%**	**9%**	**17%**	**22%**
COV at 100 ppm										
WMS Anasorb 747	**10%**	**9%**	**6%**	**5%**	**9%**	**7%**	**6%**	**6%**	NT	NT
ATD Tenax TA	**5%**	**5%**	**4%**	**4%**	**4%**	**4%**	**5%**	**5%**	NT	NT
Radiello Charcoal	**14%**	**3%**	**3%**	**3%**	**3%**	**2%**	**3%**	**10%**	NT	NT
3M OVM 3500	**1%**	**3%**	**3%**	**2%**	**0%**	**3%**	**6%**	**5%**	NT	NT
SKC Charcoal	**12%**	**12%**	**9%**	**10%**	**7%**	**9%**	**11%**	**12%**	NT	NT
Summa Canister	**11%**	**3%**	**6%**	**3%**	**5%**	**4%**	**6%**	**14%**	NT	NT

boldface: COV value meets the success criteria: < 30%

NC – Not Calculated (too few detections or two different sorbent)

ND – Not Detected

NT – Not Tested

7.3 Indoor and Outdoor Air Sampling

At OTC, most of the indoor and outdoor air concentrations were below the reporting limit, except for TCE in indoor air, which showed excellent accuracy and precision for all of the passive samplers except the SKC Ultra, which showed a low bias attributable to poor retention from an unfortunate selection of a weak sorbent.

At CRREL, the indoor air data met the accuracy success criteria of +/-45% RPD (C/Co between 0.63 and 1.58) in 77% (49/64) of cases. The relative concentrations (average of three replicates by passive sampler divided by average of three replicates by Summa canister) and COV (standard deviation divided by mean for three replicates samples by each sampler for each compound in each location) are shown in Table 29.

Table 29: C/Co and COV for indoor air samples at CRREL

Location	Sampler Type	TCE (C/C_o)	Toluene (C/C_o)	Ethyl-benzene (C/C_o)	m,p-Xylene (C/C_o)	o-Xylene (C/C_o)	1,2,4-TMB (C/C_o)
IA-1	ATD/CPB	**0.85**	1.95	1.62	**1.42**	1.8	**1.56**
	OVM	**0.72**	**1.29**	**0.99**	**0.91**	**1.21**	**0.75J**
	Radiello	**1.09**	**1.18**	**1.17**	**0.98**	1.81	**1.24**
	WMS	0.6	**1.18**	**0.75**	0.36	**0.73**	0.48
	SKC	**0.89**	3.38	**1.38**	**1.02**	**1.35**	**0.96**
IA-2	ATD/CPB	**0.74**	**1.54**	**1.5**	**1.42**	**1.48**	**1.51**
	OVM	0.58	**0.99**	**0.84**	**0.8**	**0.95**	0.61J
	Radiello	**0.86**	**0.87**	**1.01**	**0.91**	**1.32**	**1.22**
	WMS	0.56	**0.88**	**0.68**	0.35	0.57	0.47
	SKC	**0.79**	1.69	**1.07**	**0.99**	**1.08**	**0.98**
IA-3	ATD/CPB	**0.95**	ND	ND	ND	ND	ND
	OVM	**0.68**	ND	ND	ND	ND	ND
	Radiello	**1**	ND	ND	ND	ND	ND
	WMS	**0.63**	ND	ND	ND	ND	ND
	SKC	ND	ND	ND	ND	ND	ND

boldface: average C/Co values of 0.63 to 1.58, which meet the success criteria: RPD < +/-45%

Location	Sampler Type	TCE (COV)	Toluene (COV)	Ethyl-benzene (COV)	m,p-Xylene (COV)	o-Xylene (COV)	1,2,4-TMB (COV)
IA-1	Summa	**16%**	**18%**	**8%**	**10%**	64%	**3%**
	ATD/CPB	**4%**	**16%**	**2%**	**2%**	**2%**	**7%**
	OVM	**6%**	**19%**	**5%**	**7%**	**4%**	**18%**
	Radiello	**2%**	**3%**	**2%**	**1%**	**3%**	**14%**
	WMS	**1%**	**18%**	**9%**	**12%**	**10%**	**13%**
	SKC	**21%**	73%	**12%**	**23%**	**19%**	**24%**
IA-2	Summa	**12%**	**9%**	**14%**	**8%**	**9%**	**12%**
	ATD/CPB	**7%**	**11%**	**5%**	**5%**	**9%**	**8%**
	OVM	**4%**	44%	**4%**	**4%**	**3%**	**6%**
	Radiello	**5%**	**5%**	**3%**	**3%**	**3%**	**7%**
	WMS	**2%**	**23%**	**5%**	**7%**	**7%**	**13%**
	SKC	**7%**	39%	**2%**	**1%**	**4%**	**3%**
IA-3	Summa	**16%**	ND	ND	ND	ND	ND
	ATD/CPB	**21%**	ND	ND	ND	ND	ND
	OVM	**18%**	ND	ND	ND	ND	ND
	Radiello	**20%**	ND	ND	ND	ND	ND
	WMS	**10%**	ND	ND	ND	ND	ND
	SKC	ND	ND	ND	ND	ND	ND

boldface: COV value meets the success criteria: < 30%, ND – not detected, J - estimated

The COV values met the precision success criteria of 30% or less in 94% (60/64) of cases, and in most cases, the passive samplers had lower COV values than the Summa canisters (SKC excepted). The instances where the passive samplers did not meet the success criteria at CRREL appear to be attributable to inaccuracies in the uptake rate. For example, the C/C_o values for the WMS sampler for locations 1 and 2 were 0.36 and 0.35 for o-xylene and 0.48 and 0.47 for 124TMB. These results are very consistent. The uptake rates for o-xylene and 124TMB for the WMS sampler (Table 3) were calculated to be 6.2 and 13 mL/min, respectively; however, based on the indoor air sampling results at CRREL, the field-calibrated values would have been 2.2 mL/min for o-xylene and 6.2 for 124TMB. This is an example of the usefulness of some inter-method samples during the conduct of a passive sampling campaign. The uptake rate may be different than expected because of site-specific temperature, humidity, face velocity, sample duration or concentrations, but inter-method samples will allow the uptake rate to be calibrated to the field conditions. Once the site-specific uptake rate is known, the accuracy of all samples collected under similar conditions will be improved because the passive samplers show very good precision.

At MCAS 137, indoor and outdoor air data met the accuracy success criteria of +/-45% RPD in 67% (64/96) of the available comparisons, after excluding the data for the WMS and Radiello with poorly retained compounds (cDCE, tDCE, 11DCA, 11DCE and 12DCA). The excluded compounds all showed low bias attributable to poor retention (i.e., where the uptake rate multiplied by the sample duration was much greater than the recommended maximum sampling volume). If the Summa canister data were used to calculate "field-calibrated" uptake rates, only 9 of 50 uptake rates would have changed by a factor of 2 or more and only 3 of 50 would have changed by a factor of 3 or more, so even where the results did not meet the accuracy success criteria, they were within a range that is relatively narrow compared to intrinsic temporal variability in indoor air concentrations. Where there were sufficient detections, the COV for each compound in each indoor air location for each sampler was calculated and the average of all the COV values was calculated for all five passive samplers and the Summa canisters. The Summa canisters had an average COV of 5% and the passive samplers ranged from 6% to 9%, which is very similar to the conventional method and within the success criteria for precision.

7.4 Passive Soil Vapor Sampling

The passive soil vapor sampling data collected in this demonstration program span a wide range of operating conditions: sample durations from 20 minutes to 11.7 days, concentrations from about 100 to about 60,000 $\mu g/m^3$, uptake rates from about 0.05 to 80 mL/min, several different chlorinated VOCs, 2.4 to 10 cm (1 to 4 inch) diameter and 2.5 to 46 cm (1 to 18 inch) tall void spaces, ambient temperatures during sample collection from about 15 to about 30 °C, analysis by several different laboratories and different extraction methods for each of several different types of sorbent media. This breadth of testing demonstrated several trends, many of which were consistent with theoretical expectations.

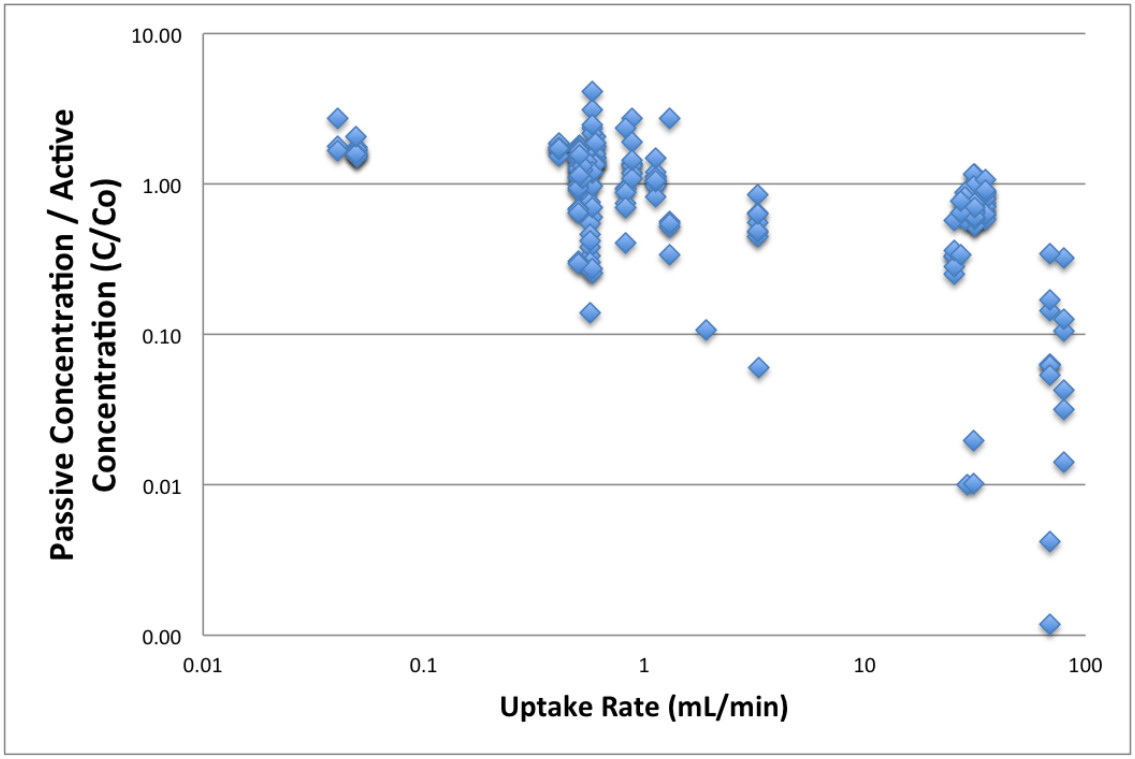
Low bias was observed for combination of adsorbents and analytes with a small recommended maximum sampling volume, particularly for longer-term sample s, specifically the ATD tube sampler and 11DCE/Carbopack B, 11DCE/Tenax TA and TCE/Tenax TA at the Layton house.

This is attributable to poor retention and can be avoided by selecting adsorbents with higher recommended maximum sampling volumes for the compounds of concern.

Low bias was more common for samplers with high uptake rates. Figure 54a shows the relative concentration (C/C_o = passive concentration / active sample concentration) as a function of the uptake rate for all the passive soil gas and sub-slab samples in this study. Starvation was minimal on average for samplers with uptake rates of about 1 mL/min or less. Some samplers with higher uptake rates showed good accuracy, but only for relatively short sample durations.

Low bias was more common for cases where the samplers were deployed in void spaces that were smaller than the product of the sampler uptake rate and sample time (UR x t), as shown in Figure 54b. In these cases, the mass of vapors in the void-space is not sufficient to satisfy the needs of the sampler so vapors must diffuse into the void-space from the surrounding soil during the passive sampling interval to avoid starvation, and diffusion through the surrounding soil is a much slower process than diffusion to the sampler though the air inside the void space. This challenge can be avoided either by: 1) designing a void space larger than (UR x t) and purging after placement of the passive sampler, 2) by using low-uptake rate samplers that will not induce starvation even if the void-space is small, or 3) using a short sample duration if the vapor concentrations are high enough to obtain a detectable result.

The passive soil vapor concentrations that were measured with low uptake rates, strong adsorbents and (UR x t) values similar to or less than the void volume and recommended maximum sample volume show a better correlation to active sampler results than any previously published comparisons that the authors are aware of.



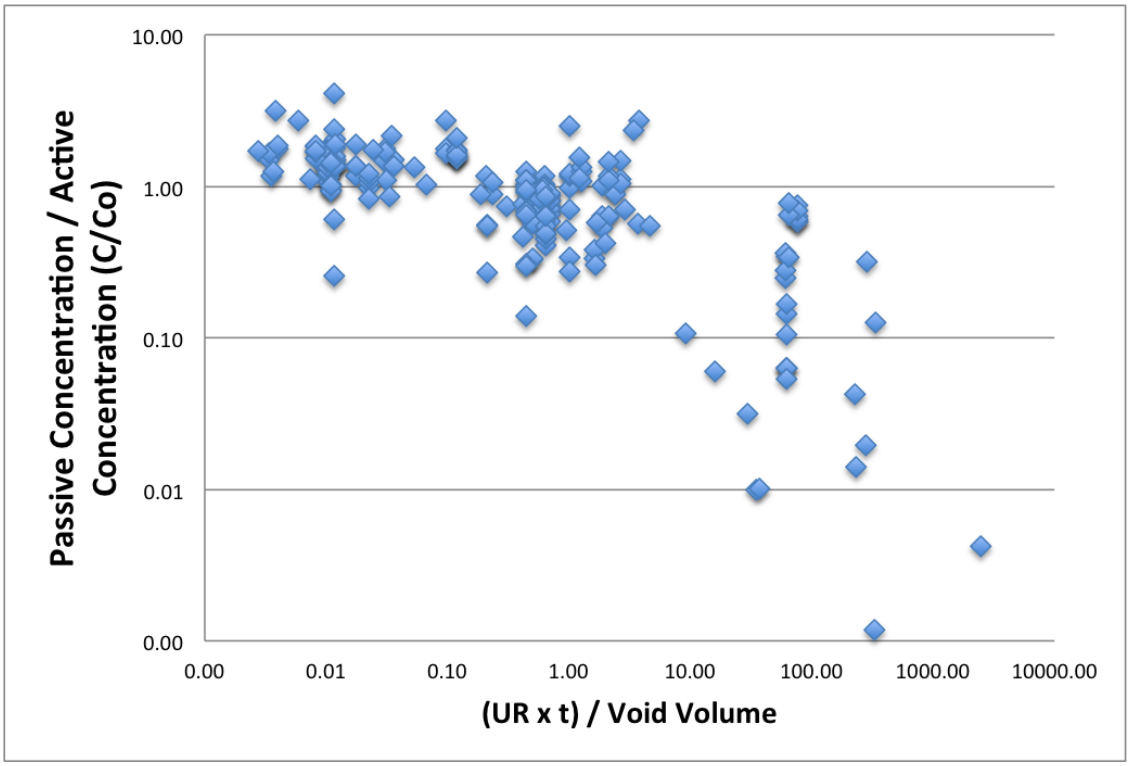


Figure 54a,b: Relative concentrations measured with passive samplers in sub-slab and soil vapor samples as a function of the uptake rate (top) and the equivalent sample volume (UR x t) divided by the void volume (bottom)

Additional testing is warranted to evaluate a wider range of site conditions. In the near term, the confidence in the accuracy of passive soil vapor sampling can be improved with some on-going benchmark testing via collection of side-by-side duplicate samples (e.g., one conventional active soil gas sample for every ~10 passive-diffusive samples). The comparison between the active sample data and the passive sampler data can be used to derive site-specific and media–specific uptake rates for the compounds that are detectable in both samples. The low variability of the passive samplers is encouraging and other benefits such as simplicity, ease of shipping, and lower cost provide sufficient incentive to justify the calibration/benchmarking effort required to provide accuracy in the process.

7.5 Flow-Through Cell Sampling

The flow-through cell test showed that the passive samplers provide good accuracy on average, but the variability was higher than for most of the other types of sampling. This may be feasible to improve with additional design effort. The low flow rate (80 mL/min) and short duration (10 min) conditions showed a notable low bias for the passive samplers relative to the Summa canisters. To explore the root cause further, the results (C/C_o, passive/Summa) were plotted versus the number of volumes purged through the cell (the product of the flow rate and sample duration divided by the 500 mL volume of the flow-through cell). The smallest purge volume samples showed a low bias for all but one of the samplers (SKC). The low bias is attributable to insufficient purging of indoor air entrained in the flow-through cell at the time of deployment of the sampler, which would dilute the soil vapor TCE concentrations.

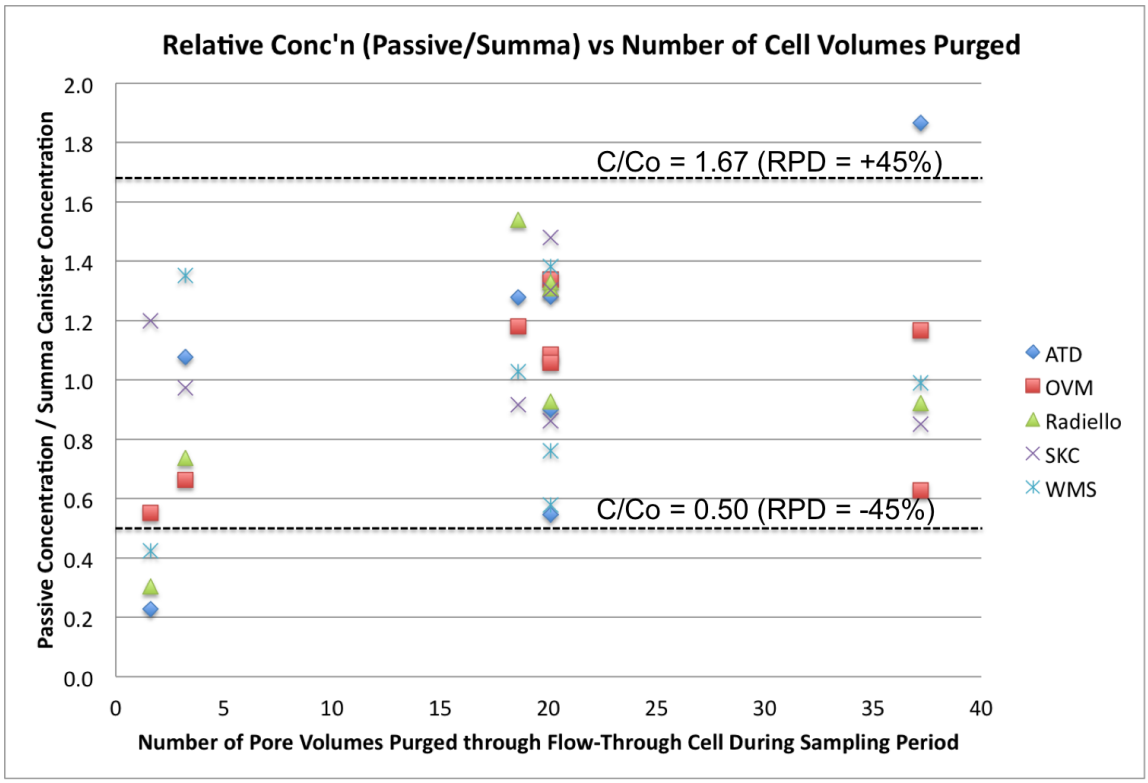


Figure 55: Relative concentration of TCE versus number of pore volumes purged through the flow-through cell during the sample period

Passive samplers can show a low bias via the starvation effect when the uptake rate is high compared to the face velocity (velocity of air flow measured at the face of the sampler). This was evaluated by plotting the relative concentration (passive/Summa) versus the ratio of the uptake rate divided by the face velocity for the flow-through cell test data (Figure 56). With the exception of the highest uptake rate samplers in the lowest velocity conditions (OVM 3500 and Radiello at flow rate of 80 mL/min), the average relative concentration was 1.05 (passive sampler concentration 5% higher than Summa canister concentration), so there is no indication of a starvation effect for the majority of the data collected.

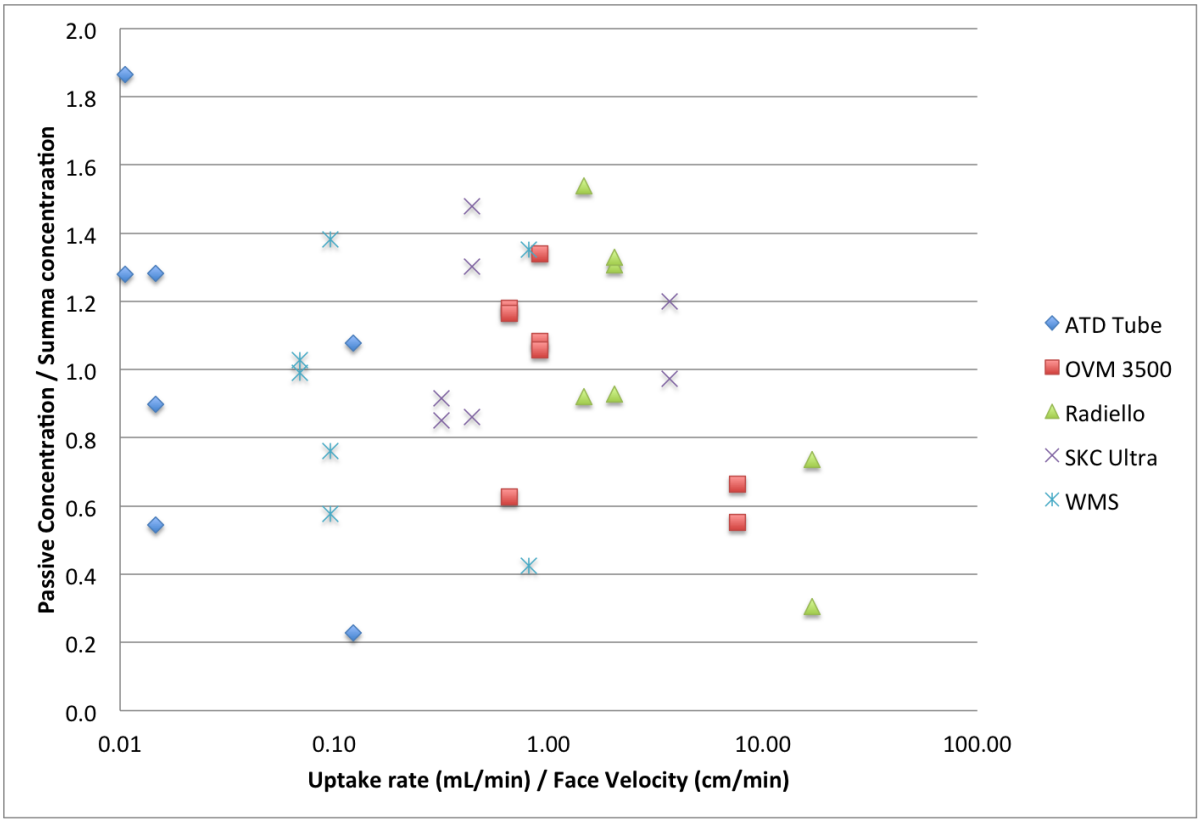


Figure 56: Relative concentration of TCE versus uptake rate divided by face velocity

The flow-through cell tests showed that 31 of 35 (89%) of the passive sampler measured concentrations met the success criteria of 50% RPD (C/Co in the range of 0.5 to 1.67) compared to the Summa canister concentration. The low flow rate and short duration tests showed a low bias attributable to insufficient purging of indoor air from the cell. The passive samplers showed average accuracy within about 10% of the Summa canisters. The WMS and SKC samplers had a similar coefficient of variability to the Summa canister samples and met the precision success criteria of COV<30% (Table 25).

The volume of the test cell was large enough to accommodate the largest of the passive samplers, but this resulted in a low bias for the low flow rate and short duration tests because of insufficient purging of indoor air entrained during sampler deployment in the cell. This could be resolved either using a longer sample duration, higher flow rate or exposure chamber

custom-fit to the passive sampler to reduce the dead volume inside the chamber. The high uptake rate samplers (OVM 3500 and Radiello) appeared to show a slight low bias at the low flow rate, which may be attributable to the starvation effect. This can be managed by selecting a flow rate that is higher, or using a smaller diameter flow-through cell, which would reduce the volume of the cell and increase the rate at which the volume of the chamber is exchanged during the sampling period.

A three-way analysis of variance (ANOVA) was run on the concentration values using sampler type, flow rate and sample duration as the three factors of interest and the results are shown in Table 30. No first or second order interaction terms were included in the analysis. The data consisted of 72 observations and were run as an unbalanced design using the PROC GLM function in SAS 9.2. The overall F-test was not significant (F=1.88, p = 0.0789), indicating that there was no statistically significant difference in the TCE concentrations between the Summa canisters and the passive samplers or between the different types of passive samplers at the 5% significance level (alpha =0.05). The analysis of individual factors showed that the sampler type and sample duration was also not significant at the 5% level (p=0.6356 and p=0.4987, respectively); however, there was a statistically significant effect for the flow rate at the 5% level (p=0.0014). This is because of the low bias experienced due to insufficient purging and removal of indoor air entrained in the cell with the low flow/short duration exposure conditions.

Table 30: Results of ANOVA analysis results of flow-through cell tests

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	8	1470185958	183773245	1.88	0.0789
Error	63	6156962319	97729561		
Corrected Total	71	7627148277			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Sampler Type	5	335354902	67070980	0.69	0.6356
Flow Rate	1	1091813566	1091813566	11.17	**0.0014**
Sample duration	1	45255510	45255510	0.46	0.4987

7.6 Ease of Use

Each of the passive samplers has aspects that result in slight differences in their ease of use relative to one another. This section describes the ease of use of each of the samplers for indoor air, outdoor air and soil gas sampling, along with any differences or challenges that might influence the selection of one sampler over another.

3M OVM 3500

The 3M OVM 3500 comes in a container that is easily opened and the initiation of sampling is nearly effortless and immediate. At the end of the sample sample period, the porous plastic cap must be pried off and replaced with a solid plastic cap, which requires a certain amount of force and may be a challenge for individuals with low grip strength. The OVM3500 is also the

largest diameter sampler and has only a high uptake rate variety, so it is not well-suited to soil gas or sub-slab sampling because of the extra effort to create a large diameter hole and the increased risk of a low bias from the starvation effect.

Radiello

The Radiello requires some assembly because the sorbent medium comes separately packaged from the white or yellow body in which it resides during deployment. The operator must be aware that the cylinder of stainless steel mesh should be handled to minimize contamination with skin oil, perfumes, moisturizer, sun-screen, or other potential contaminants. The Radiello requires a shield for outdoor air sampling to protect against wind and rain.

Waterloo Membrane Sampler

The WMS sampler is easily opened and the initiation of sampling is straightforward. Both the 1.8 mL and 0.8 mL vial sizes are very small and therefore discrete, easy to ship and handle and fit in small diameter holes for soil gas and sub-slab sampling. The operator must be aware not to touch the membrane with contaminants, but the membrane is small relative to the rest of the sampler, so this is easily accomplished. The sampler is resistant to water and wind, so protection is not specifically needed for outdoor applications.

SKC Ultra and Ultra II

The SKC Ultra comes pre-loaded with the sorbent media and is simple to use; however, the Ultra II requires the user to transfer the sorbent into the housing at the start of the sampling event, and transfer the sorbent back into the shipping vial at the end and the laboratory then needs to transfer the sorbent into an ATD tube prior to analysis. The additional sorbent transfer steps for the Ultra II create a potential for positive bias from compounds adsorbed during transfer or negative bias from sorbent losses during transfer, or desorption of weakly-held compounds during the transfer process.

ATD Tubes

The ATD tubes are shipped with compression-fit caps on both ends and one must be removed and replaced with a slip-on cap (regular or low-uptake) before the sampling period begins. This may require the use of wrenches for people with low grip strength. This is the only sampler tested with no membrane or porous plastic barrier to reduce the risk of high bias from turbulent uptake in high face velocity environments, so protection from wind and rain would be appropriate in outdoor sampling.

Comparison to Summa Canisters (TO-15)

Indoor air sampling is slightly more complex with Summa canisters because the canister vacuum must be measured before and after sample collection, the vacuum gauge and flow controller must be attached and detached using compression fitting and wrenches, and the

canisters can't be hung from a thread, they are heavy and generally need to be supported by some piece of furniture (which is not always readily-available).

Sub-slab and soil gas sampling is substantially more complex with Summa canisters because the permeability of the geologic material is often unknown in advance of sampling and can vary over 10 or more orders of magnitude. As a result, the applied vacuum required to sustain the flow-rate of the flow controller (which is usually set in advance and seldom adjusted in the field) is also unknown. If the geologic material has a low permeability, the risk of a small leak in the probe seal or any of the (usually multiple) fittings can contribute a significant fraction of the total sample drawn by the canister. Tracer tests are often used or required to verify whether any such leak is significant, which involves extra equipment (e.g., shroud, helium cylinder, helium meter, lung-box and pump) and several additional procedural steps, all of which require training and practice to perform with minimal operator bias or error. With passive samplers, the primary process is diffusion, not advection, so leaks and leak testing are not necessary.

Passive sampling requires some consideration of the most appropriate sampler, sorbent, sample duration and method of analysis (solvent extraction vs thermal desorption) prior to use. The uptake rates should be known for all the target analytes, and this may not be the case for all passive samplers, so it may be necessary to estimate the uptake rates from comparison of diffusion coefficients or permeation constants. The sample duration must be long enough to result in a reporting limit lower than an appropriate target level to meet data quality objectives. Where the product of the uptake rate multiplied by the sample duration is greater than the recommended maximum sample volume, it may be appropriate to consider using a stronger adsorbent, or be aware that there may be a low bias from poor retention for the compounds with the lowest recommended maximum sample volumes. A trip blank should be included with each shipment of passive samplers, which is not necessary with Summa canisters because the potential for canister contamination during shipment can be tested with canister vacuum measurements in the field and laboratory before and after shipment in each direction.

Comparison to Pumped ATD Tubes (TO-17)

Active sampling with pumped ATD tubes includes many of the same initial design considerations as passive samplers (sorbent selection, flow rate, sample duration), with the additional consideration of using multiple sorbents in series and a second ATD tube in series to assess the potential for breakthrough. The pumps have a limited battery life (usually 24 hours or less), so it may be necessary to plug the pumps into an electrical socket, which may require an extension cord, and is generally more challenging for outdoor air sampling. In dusty environments, the dust may accumulate and impose a resistance to flow that could change the flow rate and make it difficult to estimate the total volume of gas drawn through the ATD tube. Therefore, the passive samplers are considered to be easier to use than pumped ATD tubes. In cases where soil vapor concentrations are high enough to allow a short sample duration for passive samplers, purging of the void-space may be appropriate, which adds an increment of effort, however, the purging flow rate usually does not need to be as tightly controlled as the flow rate for an active TO-17 sample, so the passive sampling is still considered easier.

7.7 Overall Performance

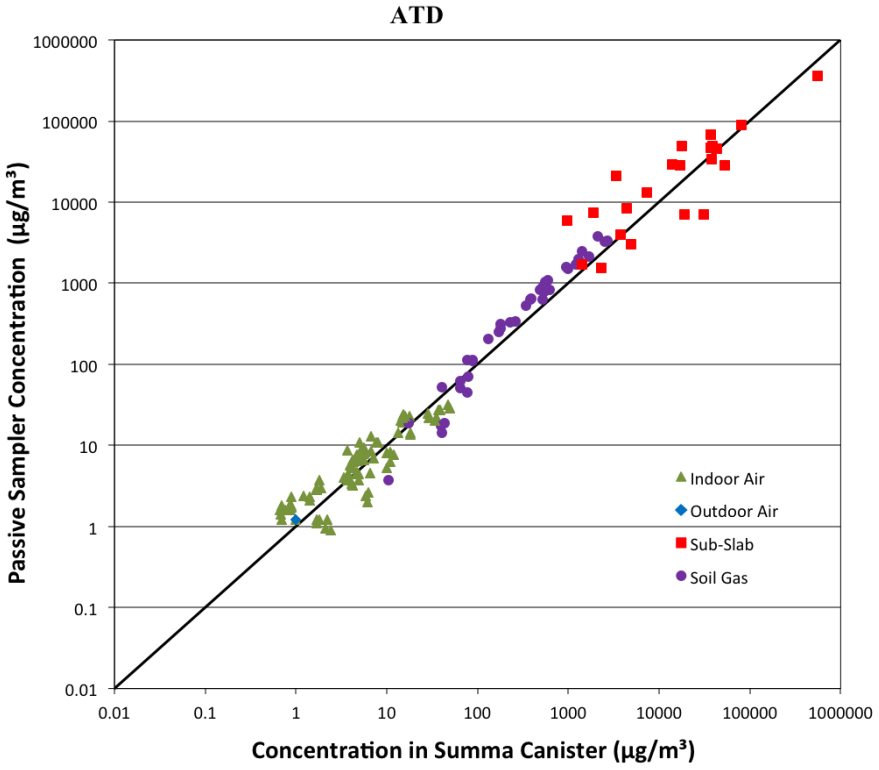
The data for each sampler type for indoor air, outdoor air, sub-slab gas, and/or soil gas from all five field sites were compiled to evaluate the overall performance. These plots (Figure 57) exclude the results with easily explained biases, specifically:

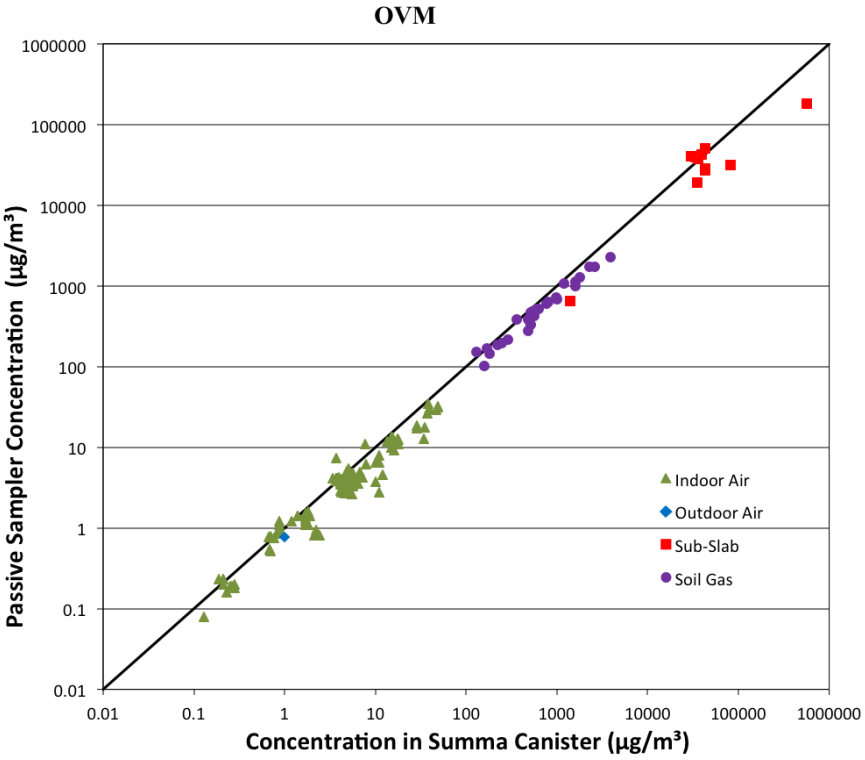
- The passive sub-slab samples from OTC were collected before the Study Team understood the importance of using low uptake rates and strong sorbents and all showed negative bias, so they were not included in Figure 57.
- Results for which the equivalent sample volume was much larger than the recommended maximum sample volume showed low bias attributable to poor retention, so they were not included either. This applies to the dichlorinated ethenes and ethanes in indoor air at Cherry point for the Radiello and WMS samplers, the ATD tube with Tenax in soil gas samples at Hill AFB and the ATD with Carbopack B for 11DCE only in soil gas samples at Hill AFB, and the cDCE results for indoor air at OTC3 with the SKC, and
- Results for which the uptake rate was higher than the expected diffusive delivery rate from the surrounding soil showed a negative bias attributable to starvation and were also not included. This applied to the Radiello sampler at Hill AFB.

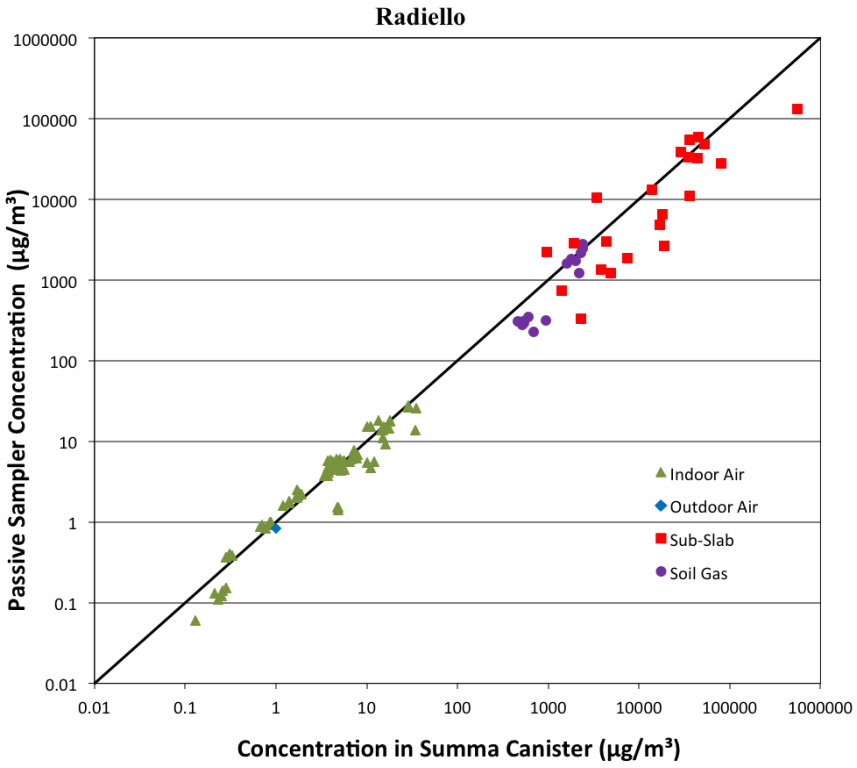
Each of these plots includes a line from the lower left to the upper right corners representing the ideal correlation.

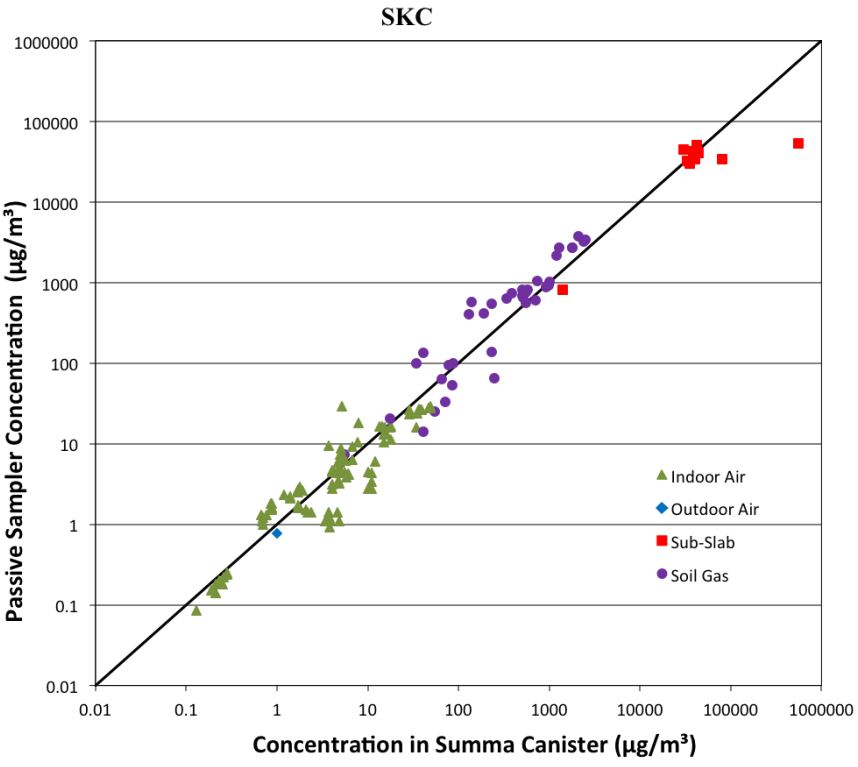
There are some outliers in the correlation, which may be attributable to individual compounds for which the uptake rate for a particular sampler may be poorly known or calculated, so there are opportunities for improved data quality over time as more studies are conducted and the uptake rates become supported with more data.

The passive samplers showed precision comparable to or better than conventional pumped ATD tube or Summa canister samples for a given set of conditions, but more sensitivity to changes in the conditions. The precision also varied by compound. For example, NAPH and 124TMB are highly sorptive compounds, which can lead to issues with competitive sorption or poor recovery; whereas 12DCA is weakly sorbed, which can lead to losses in long duration samples with weaker sorbents. MEK was challenging for the less hydrophobic sorbents, which may have been a result of reactions.


ATD
Passive Sampler Concentration (µg/m³)
Concentration in Summa Canister (µg/m³)
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
10000
100000
1000000
Indoor Air
Outdoor Air
Sub-Slab
Soil Gas


OVM
Passive Sampler Concentration (µg/m³)
Concentration in Summa Canister (µg/m³)
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
10000
100000
1000000
Indoor Air
Outdoor Air
Sub-Slab
Soil Gas


Radiello
Passive Sampler Concentration (µg/m³)
Concentration in Summa Canister (µg/m³)
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
10000
100000
1000000
Indoor Air
Outdoor Air
Sub-Slab
Soil Gas


SKC
Passive Sampler Concentration (µg/m³)
Concentration in Summa Canister (µg/m³)
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
10000
100000
1000000
Indoor Air
Outdoor Air
Sub-Slab
Soil Gas

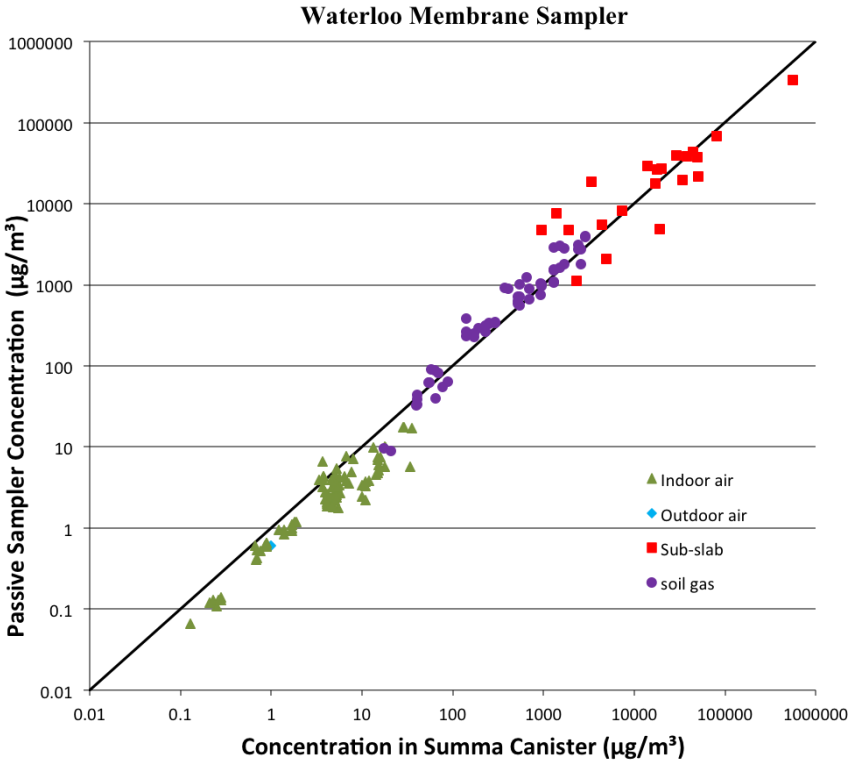


Figure 57: Correlations for all passive samplers in all field demonstrations

8 COST ASSESSMENT

This section presents the results of a cost assessment to implement site investigation and monitoring using passive samplers. Section 8.1 describes a cost model that was developed for different scenarios for site investigation and monitoring using passive samplers and an analysis of the cost model; Section 8.2 presents an assessment of the cost drivers for the application of passive samplers.

8.1 Cost Model and Cost Analysis

A cost model was developed to assist remediation professional in understanding costs associated with passive sampling versus active sampling. The cost model is easiest to understand when compared to active sampling. The cost model identified the major cost elements required to implement passive sampling under four different scenarios.

The cost model was developed for the following scenarios:

- Scenario 1 – collection of seven (7) sub-slab soil gas samples, seven (7) indoor air samples, and two (2) outdoor air samples at a single building (Table 29a);
- Scenario 2 – the collection of fifty (50) sub-slab soil gas samples, fifty (50) indoor air samples, and twelve (12) outdoor air samples at several large buildings (Table 29b); and
- Scenario 3 – a contaminated groundwater plume is migrating beneath a residential community adjacent to a DoD facility. Soil gas probes are installed and sampled to map the subsurface vapor distribution (approximately 100 samples) and the indoor and sub-slab samples are collected in buildings over the areas of elevated soil vapor concentrations (approximately 50 each). Two rounds of sampling are conducted to assess seasonal variations. This scenario assumes that the building occupants are cooperative and willing to watch the passive sampling collection procedures during the first sampling event and deploy their own indoor air and outdoor air samples during the second sampling event (much as is the case with many radon samplers in domestic applications) (Table 29c).

The cost of using passive samplers in the above scenarios is similar to or less than the cost of using active samplers, as shown in Table 31a,b and c. The costs are similar to conventional methods for small sampling programs because there is an initial effort required to select the appropriate sampler, sorbent and sample duration for a given list of target chemicals and desired reporting limits. For larger sampling programs, the initial effort is more than compensated by the reduced labor costs for sample deployment and reduced shipping costs. Actualy costs will depend on the quoted costs of analyses of individual laboratories. Summa canister/TO-15 laboratory fees have decreased in the past few years with increasing competition, and this may occur with passive samplers as the demand increases.

Table 31a: Cost comparison for Scenario 1

Scenario 1

The first cost scenario consists of the collection of seven sub-slab soil gas samples (6 samples and 1 duplicate), seven (7) indoor air samples (6 samples and 1 duplicate), and two (2) outdoor air samples at a single building. The cost comparison between the five passive and one active sampler types are provided below.

Item	Unit Cost	Unit	Number of Units		Conventional Summa/TO-15		WMS		Radiello		ATD		OVM		SKC	
			Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab
LABOR COSTS																
Active (Conventional Summa/TO-15)																
Laboratory coordination, planning	$125	/hour	2	2	$250	$250										
Indoor and outdoor sample collection (deployment and retrieval)	$85	/hour	4		$340											
Sub-slab sample collection (deployment and retrieval)	$85	/hour		9		$765										
Soil gas sample collection (deployment and retrieval)	$85	/hour														
Passive																
Laboratory coordination, planning	$125	/hour	4	4			$500	$500	$500	$500	$500	$500	$500	$500	$500	$500
Indoor and outdoor sample collection (deployment and retrieval)	$85	/hour	4				$340		$340		$340		$340		$340	
Sub-slab sample collection (deployment and retrieval)	$85	/hour		3				$255		$255		$255		$255		$255
Soil gas sample collection (deployment and retrieval)	$85	/hour														
LABORATORY COSTS*																
1 Liter Summa Canister (Batch Certified for soil gas/sub-slab)	$20	/each		8		$160										
Flow Controller (100 mL/min for soil gas/sub-slab)	$15	/each		8		$120										
Modified EPA TO-15 (open scan for soil gas/subslab)	$140	/each		8		$1,120										
6 Liter Summa Canister (Individually Certified for indoor/outdoor air)	$30	/each	9		$270											
Flow controller (24 hr for indoor/outdoor air)	$10	/each	9		$90											
Modified EPA TO-15 SIM and scan (for indoor/outdoor air)	$180	/each	9		$1,620											
WMS™ Sampler	$25	/each	10	8			$0	$200								
WMS™ Analysis (solvent extraction for soil gas/sub-slab)	$150	/each		8				$1,200								
WMS™ Analysis (thermal desorption for indoor/outdoor air)	$200	/each	10				$2,000									
Radiello Sampler	$30	/each	10	8					$300	$240						
Radiello Analysis (modified EPA TO-17)	$150	/each	10	8					$1,500	$1,200						
ATD Tube	$30	/each	10	8							$300	$240				
ATD Tube Analysis (modified EPA TO-17)	$200	/each	10	8							$2,000	$1,600				
3M OVM 3500 Badge	$20	/each	10	8									$200	$160		
3M OVM 3500 Badge Analysis	$150	/each	10	8									$1,500	$1,200		
SKC Ultra II Sampler	$75	/each	10	8											$750	$600
SKC Ultra II Sampler Analysis (modified EPA TO-17)	$200	/each	10	8											$2,000	$1,600
EXPENSES																
Federal Express (Standard Overnight) - 16 Summa canisters (6L)	$950	/shipment	9		$534											
Federal Express (Standard Overnight) - 16 Summa canisters (1L)	$238	/shipment		8		$119										
Federal Express (Standard Overnight) - 16 passive samplers	$60	/shipment	10	8			$38	$30	$38	$30	$38	$30	$38	$30	$38	$30
Concrete coring contractor (SKC and OVM only)	$500	/day		1										$500		$500
Hammer drill (conventional Summa, WMS, Radiello and ATD only)	$200	/week		1		$200		$200		$200		$200				
Helium detector	$350	/week		1		$350										
Helium cylinder	$150	/each		1		$150										
Sub-slab probe parts (stainless steel) (conventional Summa sampling)	$25	/each		6		$150										
1 inch rubber stoppers, aluminum foil and Teflon tape (passive sampling)	$1	/each		6				$6		$6		$6		$6		$6
Soil gas probe materials (passive)	$25	/each														
Soil gas probe materials (active)	$50	/each														
Subtotal					$3,104	$3,384	$2,878	$2,391	$2,678	$2,431	$3,178	$2,831	$2,578	$2,651	$3,628	$3,491
TOTAL					$6,488		$5,269		$5,109		$6,009		$5,229		$7,119	

Notes:

*passive sampler laboratory analytical costs assume an analyte list of 20 compounds or less.

Table 31b: Cost comparison for Scenario 2

Scenario 2

The second cost scenario consists of the collection of fifty (45 samples and 5 duplicates) sub-slab soil gas samples, fifty indoor air samples (45 samples and 5 duplicates) , and twelve outdoor air samples (11 samples and 1 duplicate) at several large buildings. The cost comparison between the five passive and one active sampler types are provided below.

Item	Unit Cost	Unit	Number of Units		Conventional Summa/TO-15		WMS		Radiello		ATD		OVM		SKC	
			Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab
LABOR COSTS																
Active (Conventional Summa/TO-15)																
Laboratory coordination, planning	$125	/hour	2	2	$250	$250										
Indoor and outdoor sample collection (deployment and retrieval)	$85	/hour	29		$2,465											
Sub-slab sample collection (deployment and retrieval)	$85	/hour		75		$6,375										
Soil gas sample collection (deployment and retrieval)	$85	/hour														
Passive																
Laboratory coordination, planning	$125	/hour	4	4			$500	$500	$500	$500	$500	$500	$500	$500	$500	$500
Indoor and outdoor sample collection (deployment and retrieval)	$85	/hour	29				$2,465		$2,465		$2,465		$2,465		$2,465	
Sub-slab sample collection (deployment and retrieval)	$85	/hour		25				$2,125		$2,125		$2,125		$2,125		$2,125
Soil gas sample collection (deployment and retrieval)	$85	/hour														
LABORATORY COSTS*																
1 Liter Summa Canister (Batch Certified for soil gas/sub-slab)	$20	/each		50		$1,000										
Flow Controller (100 mL/min for soil gas/sub-slab)	$15	/each		50		$750										
Modified EPA TO-15 (open scan for soil gas/subslab)	$140	/each		50		$7,000										
6 Liter Summa Canister (Individually Certified for indoor/outdoor air)	$30	/each	62		$1,860											
Flow controller (24 hr for indoor/outdoor air)	$10	/each	62		$620											
Modified EPA TO-15 SIM and scan (for indoor/outdoor air)	$180	/each	62		$11,160											
WMS™ Sampler	$25	/each	63	51			$0	$1,275								
WMS™ Analysis (solvent extraction for soil gas/sub-slab)	$150	/each		51				$7,650								
WMS™ Analysis (thermal desorption for indoor/outdoor air)	$200	/each	63				$12,600									
Radiello Sampler	$30	/each	63	51					$1,890	$1,530						
Radiello Analysis (modified EPA TO-17)	$150	/each	63	51					$9,450	$7,650						
ATD Tube	$30	/each	63	51							$1,890	$1,530				
ATD Tube Analysis (modified EPA TO-17)	$200	/each	63	51							$12,600	$10,200				
3M OVM 3500 Badge	$20	/each	63	51									$1,260	$1,020		
3M OVM 3500 Badge Analysis	$150	/each	63	51									$9,450	$7,650		
SKC Ultra II Sampler	$75	/each	63	51											$4,725	$3,825
SKC Ultra II Sampler Analysis (modified EPA TO-17)	$200	/each	63	51											$12,600	$10,200
EXPENSES																
Federal Express (Standard Overnight) - 16 Summa canisters (6L)	$950	/shipment	62		$3,681											
Federal Express (Standard Overnight) - 16 Summa canisters (1L)	$238	/shipment		50		$742										
Federal Express (Standard Overnight) - 16 passive samplers	$60	/shipment	63	51			$236	$191	$236	$191	$236	$191	$236	$191	$236	$191
Concrete coring contractor (SKC and OVM only)	$500	/day		2										$1,000		$1,000
Hammer drill (conventional Summa, WMS, Radiello and ATD only)	$200	/week		2		$400		$400		$400		$400				
Helium detector	$350	/week		2		$700										
Helium cylinder	$150	/each		7		$1,050										
Sub-slab probe parts (stainless steel) (conventional Summa sampling)	$25	/each		50		$1,250										
1 inch rubber stoppers, aluminum foil and Teflon tape (passive sampling)	$1	/each		50				$50		$50		$50		$50		$50
Soil gas probe materials (passive)	$25	/each														
Soil gas probe materials (active)	$50	/each														
Subtotal					$20,036	$19,517	$15,801	$12,191	$14,541	$12,446	$17,691	$14,996	$13,911	$12,536	$20,526	$17,891
TOTAL					$39,553		$27,993		$26,988		$32,688		$26,448		$38,418	

Notes:

*passive sampler laboratory analytical costs assume an analyte list of 20 compounds or less.

Table 31c: Cost comparison for Scenario 3

Scenario 3

The third cost scenario represents a site with a contaminated groundwater plume migrating beneath a residential community adjacent to a DOD facility. Soil gas probes are installed and sampled to map the subsurface vapor distribution (approximately 100 samples) and the indoor and sub-slab samples are collected in buildings over the areas of elevated soil gas concentrations (approximately 50 each). Two rounds of sampling are conducted to assess seasonal variations. This scenario assumes that the building occupants are cooperative and willing to watch the passive sampling collection procedures during the first sampling event and deploy their own indoor air and outdoor air samples during the second sampling event (much as is the case with many radon samplers in domestic applications). The cost comparison between the five passive and one active sampler types are provided below.

			Number of Units		Conventional Summa/TO-15		WMS		Radiello		ATD		OVM		SKC	
Item	**Unit Cost**	**Unit**	**Indoor & Outdoor**	**Sub-slab**	**Indoor & Outdoor**	**Sub-slab**	**Indoor & Outdoor**	**Sub-slab**	**Indoor & Outdoor**	**Sub-slab**	**Indoor & Outdoor**	**Sub-slab**	**Indoor & Outdoor**	**Sub-slab**	**Indoor & Outdoor**	**Sub-slab**
LABOR COSTS																
Active (Conventional Summa/TO-15)																
Laboratory coordination, planning	$125	/hour	2	2	$250	$250										
Indoor and outdoor sample collection (deployment and retrieval)	$85	/hour	50		$4,250											
Sub-slab sample collection (deployment and retrieval)	$85	/hour		150		$12,750										
Soil gas sample collection (deployment and retrieval)	$85	/hour		450		$38,250										
Passive																
Laboratory coordination, planning	$125	/hour	4	4			$500	$500	$500	$500	$500	$500	$500	$500	$500	$500
Indoor and outdoor sample collection (deployment and retrieval)	$85	/hour	35				$2,975		$2,975		$2,975		$2,975		$2,975	
Sub-slab sample collection (deployment and retrieval)	$85	/hour		50				$4,250		$4,250		$4,250		$4,250		$4,250
Soil gas sample collection (deployment and retrieval)	$85	/hour		250				$21,250		$21,250		$21,250		$21,250		$21,250
LABORATORY COSTS*																
1 Liter Summa Canister (Batch Certified for soil gas/sub-slab)	$20	/each		300		$6,000										
Flow Controller (100 mL/min for soil gas/sub-slab)	$15	/each		300		$4,500										
Modified EPA TO-15 (open scan for soil gas/subslab)	$140	/each		300		$42,000										
6 Liter Summa Canister (Individually Certified for indoor/outdoor air)	$30	/each	100		$3,000											
Flow controller (24 hr for indoor/outdoor air)	$10	/each	100		$1,000											
Modified EPA TO-15 SIM and scan (for indoor/outdoor air)	$180	/each	100		$18,000											
WMS™ Sampler	$25	/each	100	300			$0	$7,500								
WMS™ Analysis (solvent extraction for soil gas/sub-slab)	$150	/each		300				$45,000								
WMS™ Analysis (thermal desorption for indoor/outdoor air)	$200	/each	100				$20,000									
Radiello Sampler	$30	/each	100	300					$3,000	$9,000						
Radiello Analysis (modified EPA TO-17)	$150	/each	100	300					$15,000	$45,000						
ATD Tube	$30	/each	100	300							$3,000	$9,000				
ATD Tube Analysis (modified EPA TO-17)	$200	/each	100	300							$20,000	$60,000				
3M OVM 3500 Badge	$20	/each	100	300									$2,000	$6,000		
3M OVM 3500 Badge Analysis	$150	/each	100	300									$15,000	$45,000		
SKC Ultra II Sampler	$75	/each	100	300											$7,500	$22,500
SKC Ultra II Sampler Analysis (modified EPA TO-17)	$200	/each	100	300											$20,000	$60,000
EXPENSES																
Federal Express (Standard Overnight) - 16 Summa canisters (6L)	$950	/shipment	100		$5,938											
Federal Express (Standard Overnight) - 16 Summa canisters (1L)	$238	/shipment		300		$4,453										
Federal Express (Standard Overnight) - 16 passive samplers	$60	/shipment	100	300			$375	$1,125	$375	$1,125	$375	$1,125	$375	$1,125	$375	$1,125
Concrete coring contractor (SKC and OVM only)	$500	/day		10										$5,000		$5,000
Hammer drill (conventional Summa, WMS, Radiello and ATD only)	$200	/week		4		$800		$800		$800		$800				
Helium detector	$350	/week		7		$2,450										
Helium cylinder	$150	/each		37		$5,550										
Sub-slab probe parts (stainless steel) (conventional Summa sampling)	$25	/each		50		$1,250										
1 inch rubber stoppers, aluminum foil and Teflon tape (passive sampling)	$1	/each		50				$50		$50		$50		$50		$50
Soil gas probe materials (passive)	$25	/each		100				$2,500		$2,500		$2,500		$2,500		$2,500
Soil gas probe materials (active)	$50	/each		100		$5,000										
Subtotal					$32,438	$123,253	$23,850	$82,975	$21,850	$84,475	$26,850	$99,475	$20,850	$85,675	$31,350	$117,175
TOTAL					$155,691		$106,825		$106,325		$126,325		$106,525		$148,525	

Notes:

*passive sampler laboratory analytical costs assume an analyte list of 20 compounds or less.

8.2 Cost Drivers

Passive samplers can reduce costs because the protocols for sampling are simpler, and as a result the costs of training and labor for field personnel are lower than in conventional sampling methods. The passive samplers are also smaller and lighter than Summa canisters, so shipping costs are lower. Passive samplers are also capable of collecting samples over a longer period of time than conventional samplers, so fewer samples may be needed to provide data over a given period.

Passive samplers incur more effort in the initial design process because it takes time to select the best sampler, sorbent and sample duration for a given set of target chemicals and target reporting limits. This process can be automated to a significant degree, but should be reviewed by an experienced analytical chemist. Inter-method verification samples are a valuable quality assurance/quality control element that allows uptake rates to be derived or verified for site-specific field sampling conditions, which would add a small increment to the overall cost for sampling campaigns, but add a level of quality control and assurance where the highest level of accuracy is desired.

The cost differential between the various types of passive samplers is relatively small, so the selection between the passive sampling options should be based primarily on technical considerations. One exception is if sub-slab sampling is included, because the larger diameter of the SKC and OVM samplers would require a larger diameter hole, and the cost of coring is higher than the cost of using a hammer-drill to make a smaller diameter hole sufficient to accommodate the ATD, Radiello or WMS samplers.

9 IMPLEMENTATION ISSUES

9.1 Potential Biases

Most of the passive samplers provided data that met the success criteria for most compounds under most conditions. Exceptions were generally attributable to one of the following causes:

- Poor retention causes a low bias in the passive sampler concentration results. This condition was observed in cases where the sampler uptake rate multiplied by the sample duration (referred to here as an "equivalent sample volume") was larger than the recommended maximum sampling volume (RMSV) for a particular compound and adsorbent. The RMSV is specific for each chemical and adsorbent (Supelco, 2013). To reduce the risk of poor retention, a stronger adsorbent may be selected with a larger RMSV for the compounds of interest. The uptake rate or sample duration may also be reduced to reduce the equivalent sample volume; however, this will increase the reporting limit, so it is important to verify that the reporting limits are still lower than the applicable risk-based screening levels.

- Poor Recovery causes a low bias in the passive sampler results. This condition was not common, but may explain some of the low bias and/or variability for NAPH and 124TMB, the two most strongly sorbed compounds and MEK in high humidity environments where activated carbon is the sorbent. Laboratories routinely test the recovery of various chemicals from various sorbents by both thermal desorption and solvent extraction, so close communication with the analytical chemist during the sampler and sorbent selection stage can usually assure that recoveries are sufficient.

- Starvation also causes a low bias, and occurs in cases where the uptake rate is high relative to the face-velocity of gas in the vicinity of the sampler. Starvation is exacerbated in subsurface (sub-slab and soil gas) sampling, where the face velocity is typically very low. Low uptake rate versions of several passive samplers were developed during the conduct of this research, and tended to minimize this effect. The optimal uptake rate for soil vapor sampling appears to be in the range of about 0.1 to 1 mL/min depending on the rate of transport of vapors through soil, as supported by transient and steady-state models (Section 6.7.1) as well as empirical data (Figure 54a).

- Uptake Rate Uncertainty can cause high or low bias in the passive sampler results. The uptake rate varies between compounds, samplers, sampling conditions (temperature, humidity, face velocity, sample duration and concentration), and sorbents to varying degrees. For most samplers and most VOCs, the accuracy of the vendor-supplied uptake rates was within a factor of about 2 or 3 for the conditions tested. Considering natural spatial and temporal variability in soil vapor and indoor air quality data, this may be acceptable for many monitoring purposes. Where improved accuracy is required or desired, a field-calibrated uptake rate can be calculated if a selected number of samples are collected using a inter-method verification samples (e.g., a select number of conventional Summa canisters beside passive samplers). The comparison between the Summa canister data and the passive sample data can be used to derive site-specific and media-specific uptake rates for the

compounds that are detectable in both samples. The laboratory and field data both showed that the precision of the passive samplers is generally similar to or better than the active samplers; therefore, with proper calibration/benchmarking, the performance of the passive samplers is expected to be comparable to or better than conventional methods. Some chemicals are more challenging than others, and there are many compounds of potential concern for vapor intrusion that were not evaluated in this study. The laboratory testing program was designed to include chemicals spanning a wide range of properties and to include compounds expected to be challenging (MEK and NAPH), so the study results indicate that passive samplers are likely to be able to provide good quality (accurate and precise) concentration data for many or most VOCs of concern for vapor intrusion.

- Blank contamination causes a high bias and can be identified and corrected using travel blanks, which are recommended for all adsorptive sampling methods.

- The SKC Ultra II showed indications of variability attributable to the transfer of the sorbent into and out of the sampler (see letter from CAS in Appendix F).

9.2 Considerations for Sampler Selection

Selection of the most appropriate sampler for a particular application depends on the:

1. Target compounds: not all sampler types have measured uptake rates for all chemicals;

2. Target concentrations: some samplers have better sensitivity than others for a given sample duration;

3. Ambient gas flow velocities: low uptake rate samplers are preferable in low velocity environments;

4. Desired sample duration: weaker sorbents suffer from poor retention over longer deployment intervals, but longer deployment intervals provide better sensitivity (ability to detect lower concentrations), which may be needed to meet data quality objectives (including reporting limits lower than screening levels). Furthermore, in wet soils, the diffusive delivery rate may be the rate-limiting step in the sampling procedure, in which case, a long sample duration is likely to be needed and the uptake rate may need to be estimated from measurement of the soil moisture and application of the steady-state model described is Section 5.6.2; and

5. Convenience: drilling a 2-inch diameter hole in a concrete slab is much more work than drilling a 1-inch diameter or smaller hole, and some sample durations required to meet screening levels may be longer than desired.

With the various combinations of each sampler type (high and low uptake versions, and various types of adsorbents), the selection process requires some specialized knowledge, and should be reviewed carefully by an experienced professional. One important consideration for sampler selection is the reporting limit, which varies inversely with sample duration. Table 30 shows an

example of how this might affect the selection of a sampler. In Table 30, the residential indoor air screening level corresponding to a 1×10^{-6} incremental lifetime cancer risk (USEPA, 2013) is listed for comparison and the sample duration required for each of the passive samplers to achieve a reporting limit equal to the screening level is also shown. The sample duration may be longer than practical for compounds with very low screening levels (e.g., chloroform, VC, 1122PCA). There are some blanks in Table 30 where the uptake rate is not well known or the specific compound is not suited for use with a specific sorbent.

Table 30: Sample duration required for each of the passive sampler with either solvent or thermal analysis to achieve a reporting limit equal to the residential indoor air screening level corresponding to a 1×10^{-6} incremental lifetime cancer risk.

Compound	Residential Indoor Air Screening Level (µg/m3)	WMS		ATD Tube		Radiello		SKC Ultra		3M OVM
		Solvent Extraction	Thermal Desorption	Tenax TA	Carbopack B	Solvent Extraction	Thermal Desorption	Solvent Extraction	Thermal Desorption	Solvent Extraction
		Sample Time (hr)	Sample Time (hr)	Sample Time (hr)	Sample Time (hr)	Sample Time (hr)	Sample Time (hr)	Sample Time (hr)	Sample Time (hr)	Sample Time (hr)
1,1,1-Trichloroethane	5,200	0.13	0.01	0.03	0.03	0.01	<0.01	0.03	0.00	0.01
1,1,2,2-Tetrachloroethane	0.042	2800	190							
1,1,2-Trichloroethane	0.15	1700	180	1200	1200			1200	27	280
1,1-Dichloroethane	1.5	470	19	89	90					25
1,1-Dichloroethene	210	19	0.19	0.56	0.56	0.10	<0.01	1.8	0.01	0.36
1,2,4-Trimethylbenzene	7.3	9.1	0.46			4.6	0.23			
1,2-Dichlorobenzene	210	0.27	0.03							0.21
1,2-Dichloroethane	0.094	3400	140	1400	1400	230	4.6	1250	25	400
1,3,5-Trimethylbenzene	--									
1,3-Dichlorobenzene	--									
1,4-Dichlorobenzene	0.22	290	35	140		150				200
2-Butanone	5,200	0.13	0.15	0.14		0.04		0.02	0.01	0.01
4-Methyl-2-pentanone	3,100	0.17	0.03							
Acetone	32,000	0.08	0.01			<0.01		0.01	0.00	0.00
Benzene	0.31	2500	400	130		130	34	670	54	230
Carbon Tetrachloride	0.41	1400	84			61				100
Chlorobenzene	52	3.0	0.14			0.47				0.82
Chloroform	0.11	3900	190			200				340
Chloromethane	94	77								
cis-1,2-Dichloroethene	--									
Cyclohexane	6,300	0.06	0.00	0.01						0.01
Ethylbenzene	0.97	130	5.7	37	250	253	5.0	130	2.9	47
Heptane	--									
Hexane	730	1.1	0.40					0.16	0.03	0.05
m,p-Xylene	100	1.3	0.06		2.4	0.24	0.12	1.3	0.03	
MTBE	9.4	72	2.6			2.7		13	2.3	4.3
Naphthalene	0.072	450	23	45		930				700
o-Xylene	100	1.2	0.05		2.4	0.26	0.13	1.4	0.03	
Propylbenzene	1,000	0.09	0.04			0.03				
Styrene	1,000	0.12	0.01	0.04		0.03	0.01	0.16		0.04
Tetrachloroethene	0.41	380	26	100	670	70	3.4	330	13	
Toluene	5,200	0.04	0.00	0.01	0.01	<0.01	0.00	0.02	0.00	0.01
trans-1,2-Dichloroethene	63	20	0.40	2.4	2.4	0.43	0.01	3.6	0.04	1.4
Trichloroethene	1.2	210	11	150	150	20	1.01	93	2.5	33
Vinyl Chloride	0.16	43000	200	400						770

Note: Reporting limits depend on laboratory sensitivity, which may change from time-to-time

Samples of outdoor air should use passive samplers with high uptake rates and/or long sample times, to minimize the risk of non-detect results. It is vital when collecting outdoor air samples with passive samplers that a trip blank be included. The sorbent used in passive sampler

fabrication should also be blank-tested to identify any chemicals that may contribute to blank contamination.

9.3 Research Needs

Further research is needed to evaluate the performance of passive samplers for other chemicals. The 10 VOCs tested in the laboratory clearly showed that there are differences in passive sampler performance attributable to the properties of the chemicals, but the different samplers are not all equally susceptible to bias and variability for all compounds. Controlled chamber tests with a wider range of compounds would be valuable.

Further research is needed to evaluate the combinations of samplers and sorbents that are most reliable for long-term passive sampling. In the radon field, a 30-day sample is referred to as a "short-term" sample. Controlled chamber tests over a longer duration would be valuable. Passive samplers with strong sorbents are most likely to be needed. It may also be appropriate to use low-uptake varieties to avoid sorbent saturation.

Field-calibrated uptake rates would provide insight into the degree of variability from site-to-site, which can be assessed with inter-method duplicate samples at a specified frequency (e.g., 1 for every 10 investigative samples). Further testing to assess the limitations of passive soil vapor sampling in wet soil conditions is also warranted. A repository for such information would be valuable and may eventually provide sufficient information to allow better prediction of uptake rates as a function of site-specific conditions, which would reduce or eliminate the need for on-going field calibration.

More than 100 compounds can potentially pose a risk via the vapor intrusion pathway (OSWER, 2002), and they have a wide range of properties that are not all well-suited for a single sorbent. Weakly sorbed compounds like vinyl chloride, chloromethane and other low boiling point, low molecular weight compounds require a strong sorbent to avoid low bias attributable to poor retention, and strongly sorbed compounds like PAHs, PCB, and other SVOCs require a weaker sorbent to avoid low bias attributable to poor recovery. Testing designed to specifically improve the understanding of the ranges of compounds that will yield good retention and good recovery for several different sorbent/sampler combinations would be valuable.

Several compounds of potential concern have very low risk-based screening levels of about 0.1 $\mu g/m^3$ or less (e.g., 1,3-butadiene, chloroform, 1,2-dichloroethane, hexachlorobenzene, hexachlorobutadiene, all of the polycyclic aromatic hydrocarbons and polychlorinated biphenyls, 1,1,2,2-tetrachloroethane, 1,1,2-trichloroethane, and vinyl chloride), so if any of these compounds is a site-specific compound of concern, they will likely dictate the sample duration needed to achieve reporting limits as low or lower than risk-based screening levels. In some cases, that may result in oversaturation of the sorbent with compounds that may be more abundant (e.g., limonene, pinene and other fragrances, hydrocarbons, aerosols, and other chemicals from background sources). Further testing to verify the performance of passive samplers at very low reporting limits for these compounds would be valuable.

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APPENDIX A

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Dr. Paul Johnson	Arizona State University PO Box 875506 Tempe, AZ 85287-5506	480.965.9235 480.965.4000 Paul.c.johnson@asu.edu	Co-Principal Investigator
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Geosyntec
consultants

APPENDIX B

Process Flow Diagrams for the Low Concentration Laboratory Test Apparatus

May 2015

G–801
HUMIDIFIER

T–701A/B
SUPPLY GAS TANKS

T–702A/B
EXPOSURE CHAMBERS
WITH FUME HOODS

OIL LESS
COMPRESSOR

DRYER

ACTIVATED
CHARCOAL
FILTER

G–801

HOT PLATE/STIRRER

HUMID LINE

DRY AIR LINE

ROTOMETERS

CONDENSER/CHILLER
LINES WRAPPED AROUND
TUBING & CHAMBERS

10
L/MIN

RH/T

SP

T–702A

CHILLER TUBING COILED
AROUND CHAMBERS

FUME HOOD

FUME HOOD

T–702B

PRV

10–100
mL/MIN

MASS FLOW
CONTROLLERS

T–701A

T–701B

CONDENSERS/
CHILLERS

ROOM AIR TEMPERATURE CONTROLLER
(HVAC SYSTEM (A/C)) + AMCOR A/C
FLOOR UNIT FOR ROOM

LEGEND:

- A — AIR SUPPLY
- G — SPECIALTY GAS SUPPLY
- SG — SOURCE GAS SUPPLY
- MASS FLOW CONTROLLER
- SP — SAMPLE PORT
- PRESSURE REGULATOR VALVE

**Process Flow Diagram -
Cold Conditions**

Geosyntec consultants

Guelph | November 2010

Figure
B1

P:\PRJ\Projects\TR0309 - ESTCP Passive Samplers\AutoCAD\Update\TR0309 F01 - Cold&Hot Conditions.dwg

G–801
HUMIDIFIER

T–701A/B
SUPPLY GAS TANKS

T–702A/B
EXPOSURE CHAMBERS
WITH FUME HOODS

OIL LESS
COMPRESSOR

DRYER

ACTIVATED
CHARCOAL
FILTER

HUMID LINE

G–801

HOT PLATE/STIRRER

DRY AIR LINE

ROTOMETERS

HEATING TAPE

10
L/MIN

10
L/MIN

PRV

10–100
mL/MIN

PRV

10–100
mL/MIN

MASS FLOW
CONTROLLERS

T–701A

T–701B

FUME HOOD

RH/T

SP

T–702A

HEATING TAPE /
INSULATED CHAMBERS

FUME HOOD

RH/T

SP

T–702B

CONDENSERS/
CHILLERS

ROOM AIR TEMPERATURE
CONTROLLER (HVAC SYSTEM)

LEGEND:

- A — AIR SUPPLY
- G — SPECIALTY GAS SUPPLY
- SG — SOURCE GAS SUPPLY
- MASS FLOW CONTROLLER
- SP — SAMPLE PORT
- PRESSURE REGULATOR VALVE

**Process Flow Diagram -
Hot Conditions**

Geosyntec consultants

Guelph | November 2010

Figure
B2

P:\PRJ\Projects\TR0309 - ESTCP Passive Samplers\AutoCAD\Update\TR0309 F01 - Cold&Hot Conditions.dwg

Geosyntec
consultants

APPENDIX C

Protocols for Passive Samplers and Summa Canisters for Indoor and Outdoor Air

May 2015

Leading Science. Lasting Solutions

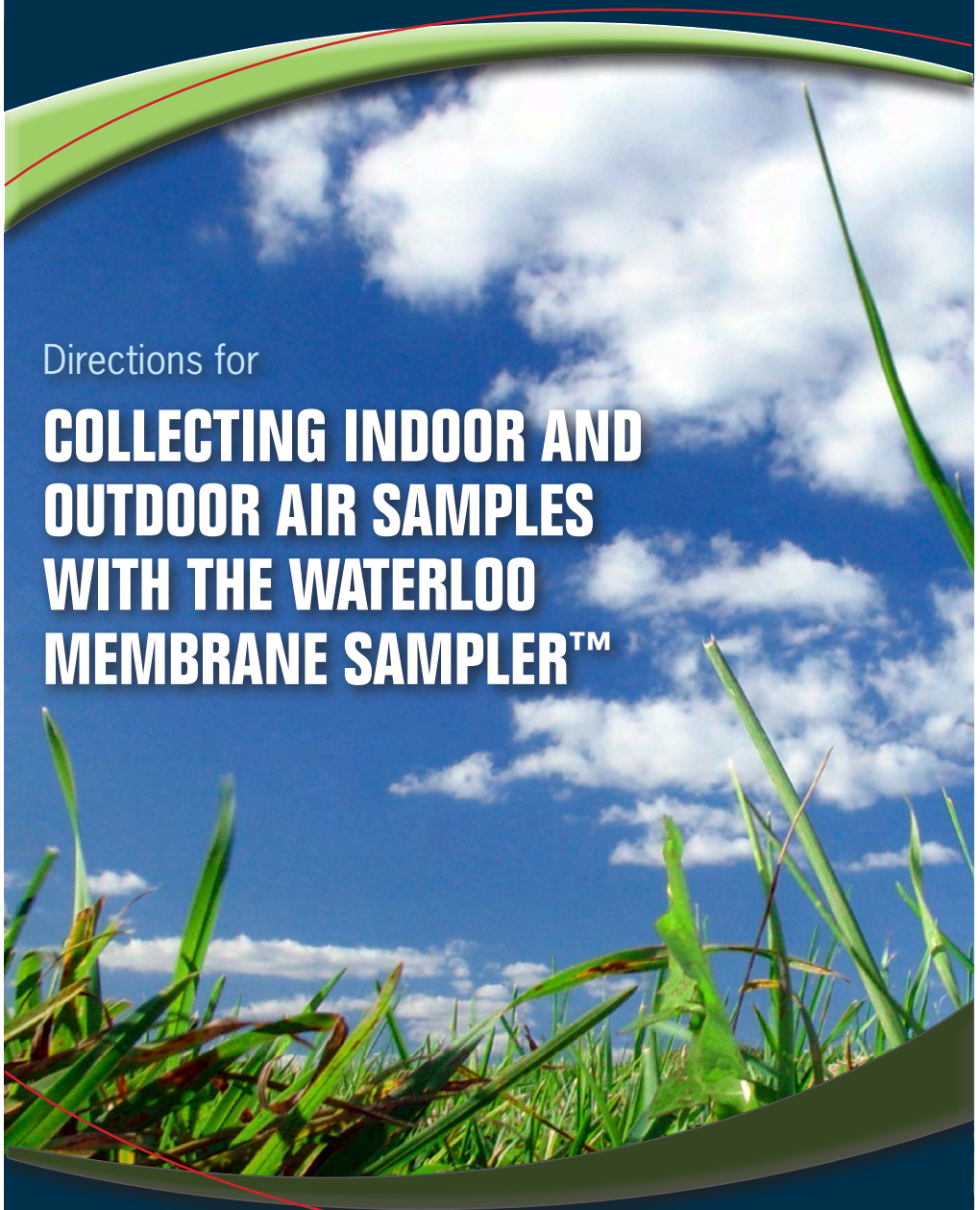
SIREM

130 Research Lane, Suite 2
Guelph, ON N1G 5G3
Ph: (519) 822-2265
Toll Free: 1-866-251-1747

www.siremlab.com

Directions for

COLLECTING INDOOR AND OUTDOOR AIR SAMPLES WITH THE WATERLOO MEMBRANE SAMPLER™



SIREM

OVERVIEW

The sampler is shipped inside a dedicated glass overpack vial, an unsealed bubble pack, and sealed plastic bag to prevent exposure to chemicals during shipment (Figure 1). Do not remove the sampler from the packaging until deployment.

Avoid wearing perfume, using felt markers, and touching the membrane of the samplers, and minimize use of volatile organic chemicals during the sampler deployment period.



Figure 1: *WMS™ sampler with glass overpack vial, unsealed bubble pack and plastic bag.*

WMS™ DEPLOYMENT

1 Remove the Teflon tape seal from the white cap of the glass overpack vial (Figure 2), open the cap and remove the sampler. REMOVE THE SMALL WHITE PACKET OF ABSORBENT, AND PLACE IT IN THE BUBBLE PACK. Keep glass overpack vial closed and sealed inside the plastic bag with the bubble pack in a secure and clean location while the sampler is deployed.

2 The sampler has a plastic hanger (Figure 2) which is used to deploy the sampler (membrane facing down) at the location of interest (Figure 3). Generally, indoor and outdoor air samples should be located about 1 to 2 m above ground (breathing zone height).



Figure 2: *Close-up of WMS™ sampler in its glass overpack shipping vial*





Figure 3: *Photo of deployed WMS™ Sampler hanger (left), and close-up of the membrane on a sampler (right).*



Figure. 4: *WMS™ Sampler after deployment. Absorbent packet is now in bubble pack, NOT in glass overpack.*

3 Record the date, start-time, location and sampler identification number on the sampling form provided with the WMS™ samplers. Do not disturb the sampler until the sample has been collected. It is often useful to photograph the deployed sampler to assist in describing and evaluating the sample location.

4 At the end of the sampling time period, record the sampler collection date and time and complete the rest of the sampling form. Return the sampler to its dedicated glass overpack vial (same sampler code). Wrap the threads of the overpack vial with new Teflon tape, screw the cap securely onto the overpack vial, and then wrap the outside of the cap with more Teflon tape (see Figure 2).

5 Put the sealed glass overpack into the bubble pack containing the white absorbent packet, (Figure 4) and close the bubble pack by removing the white strip on the flap and folding the flap over the pack's opening. Put the pack inside the plastic bag, and seal the plastic bag.

6 Complete the chain-of-custody form. Ship the samplers (including one unopened sampler to be analyzed as a trip blank), and the chain-of-custody to:

Sample Reception
Air Toxics Ltd.
180 Blue Ravine Road, Suite B
Folsom, California, 95630
Phone: 916-985-1000 | toll free: 800-985-5955

7 **Questions?**
Contact Hester Groenevelt at: 519-822-2265 x 252 or toll free: 866-251-1747 or hgroenevelt@siremlab.com.

SUPELCO
SUPELCO • 595 North Harrison Road
Bellefonte, PA 16823-0048, USA
800-359-3041 or 814-359-3041

This Data Sheet Contains Important Information About The Product.

PerkinElmer™
instruments.
710 Bridgeport Avenue
Shelton, CT 06484
1-800-762-4000

Users Guide for Unconditioned Thermal Desorption Tubes

Tube Description	Glass TD Tubes			Stainless Steel TD Tubes		
	PerkinElmer		Supelco	PerkinElmer		Supelco
Carbotrap™ 300	N9307064	❑	28952-U	N9307056	❑	28937-U
Air Toxics™	N9307058	❑	28953-U	N9307050	❑	28938-U
Carbopack™ B	N9307059	❑	28954-U	N9307051	❑	28939-U
Carbosieve™ S-III	N9307060	❑	28956-U	N9307052	❑	28942-U
Tenax® GR	N9307061	❑	28957-U	N9307053	❑	28946-U
Tenax TA	N9307062	❑	28958-U	N9307054	❑	28947-U
Chromosorb® 106	N9307063	❑	28965-U	N9307055	❑	28948-U
Carbotrap 349	N9307066	❑	28966-U	N9307057	❑	28949-U
Carbotrap 202	N9307065	❑	28967-U	—		—

Lot Number 11967

Tube Serial Numbers:

1 G0126233
2 G0126205
3 G0128694
4 G0126202
5 G0126216
6 G0128639
7 G0128610
8 G0128681
9 G0128623
10 G0128666

Thermally Conditioning the Tubes Before Use

These tubes must be thermally conditioned before use. See Table 1 for the recommended conditioning temperatures. Position the tubes in the tube conditioner so the gas stream enters the sampling outlet and exits at the sampling inlet (opposite of the "P" in PerkinElmer label affixed on the tube). Condition the tubes using clean dry, helium, or nitrogen at a flow rate of 30-100 mL/min. The necessary time to condition the tubes may vary since these tubes have not been pre-conditioned. It may take anywhere from 30 minutes to 8 hours depending on your desired application. Conditioning may be done in a TurboMatrix™, ATD-400 or ATD-50 thermal desorption instrument. Please refer to the instrument users guide for detailed instructions.

Tube Storage

The purpose of the PTFE caps included with these tubes is to protect the tubes from dust and to protect the ends of the glass tubes. These caps do not provide sufficient sealing capabilities to keep contaminants from entering the tube during storage. To maintain the integrity of the tube after it has been conditioned, we recommend the tubes be sealed in a TDS[3] storage container or brass endcaps using PTFE ferrules.

Figure A

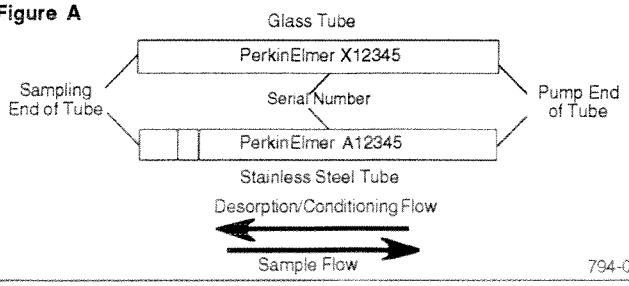


Table 1

Sample Tube	Recommended Conditioning Temperature	Maximum Recommended Temperature	Recommended Desorption Temperature	Approximate Analyte Volatility Range	Typical Analytes
Carbotrap 202	350 °C	400 °C	330 °C	n-C5 to n-C30	Offgassing polymers
Carbotrap 300	350 °C	400 °C	330 °C	n-C3 to n-C30	EPA TO-1, TO-2, TO-3
Carbotrap 349	350 °C	400 °C	330 °C	n-C3 to n-C16	NIOSH Method 2549
Air Toxics	350 °C	400 °C	330 °C	n-C3 to n-C12	EPA TO-14 compounds
Carbopack B	350 °C	400 °C	330 °C	n-C5 to n-C12	Wide range of VOCs
Carbosieve S-III	350 °C	400 °C	330 °C	n-C2 to n-C6	Very volatile compounds
Tenax TA	320 °C	350 °C	300 °C	n-C7 to n-C26	Aromatics except benzene, apolar compounds (BP>100 °C) and less volatile compounds
Tenax GR	320 °C	350 °C	300 °C	n-C7 to n-C30	Alkyl benzenes, PAH, PCBs; same for Tenax TA
Chromosorb 106	240 °C	250 °C	220 °C	n-C5 to n-C12	Wide range of VOCs including hydrocarbons from n-C5 to n-C12. Also volatile oxygenated compounds

Trademarks
Air Toxics, TurboMatrix – PerkinElmer Corp.
Carbopack, Carbosieve, Carbotrap, SPB – Sigma-Aldrich Co.
Chromosorb – Celite Corp.
Tenax – BUCHEM BV

Tube Conditioning Recommendations Using ATD

ATD 400

1. Remove the PTFE caps and fit standard PTFE tube storage caps (L427 0122).
2. Place the tubes on the ATD 400 carousel such that the ends closer to the "P" in PerkinElmer (the sampling ends, as shown in Figure A) are nearer the rear of the instrument.
3. Set the following parameters:

Mode	1
Desorb	30 mins.
Valve	175 °C

4. Set the oven to the temperature the tubes were conditioned at prior to shipment, as described in Table 1. This conditioning temperature is usually 10 °C or more above the recommended desorption temperature for most applications. If your application requires a higher desorption temperature, condition the tubes for one hour at 10 °C above the desorption temperature you will use. NEVER EXCEED THE MAXIMUM TEMPERATURE FOR THE LEAST STABLE ADSORBENT IN THE TUBE (Table 1).
5. Using the flow meter to measure the flow, set the needle valves at the top left side as follows:

   Desorb flow 50 mL/min.
   Inlet split flow 75 mL/min.

NOTE: In Mode 1 the trap is not heated, and therefore, during tube conditioning the values entered for the trap and transfer line are not important.

ATD 50

1. Remove the PTFE caps and fit standard analytical end caps, ensuring that the flanged outer analytical end cap is fitted to the end of the tube closer to the "P" in PerkinElmer (the sampling end, as shown in Figure A).
2. Place the tubes on the ATD 50 turntable such that the ends closer to the "P" in PerkinElmer (the sampling ends, as shown in Figure A) are nearer the outer edge of the turntable.
3. Set the following parameters:

Mode	2
Desorb	15 mins.
Box	150 °C
CTL	30 °C
CTH	to suit trap packing

4. Set the oven to 5 °C below the lowest maximum temperature of the adsorbents in the tube (Table 1).

   If the maximum temperatures of all the adsorbents in the tube are above 250 °C, select 250 °C. Never exceed the maximum temperature of the least stable adsorbent in the tube.
5. Using a flow meter to measure the flows, set the needle valves on the multiple splitter accessory as follows:

Inlet split flow	100 mL/min.
Purge flow	5 mL/min.
Outlet split flow	100 mL/min.
Column flow	1 mL/min.

NOTE: If the multiple splitter accessory is not fitted to the ATD 50, set the split flow to 100 mL/min. If a splitter is not installed, set the flow through the column to 50 mL/min.

Sample Collection

Samples should be collected through the end of the tube nearer to the "P" in PerkinElmer on the tube label (see Figure A).

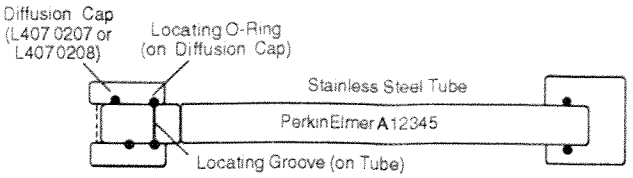
While sampling, the tubes must be protected from extreme weather conditions and must not be allowed to come into contact with aerosol or particulate material without appropriate filters.

Thermal Desorption of the Sample

When thermally desorbing the tube, the direction of flow is opposite of the sampling direction. See Table 1 for recommended desorption temperatures. The typical desorption time is for 5-10 minutes. The optimal desorption time may vary depending on the desorption flow rate and type of sample that is adsorbed on the tube.

NOTE: Do not overtighten the screw caps because this can damage the tubes. When the PTFE ferrules are new, the caps should be tightened by hand until they touch the ferrule. Tighten a further 1/2 to 3/4 of a turn. Do not tighten beyond this. The ferrules may be re-used, but the required rotation of the cap will be less the more times the ferrules are used. Usually, if the cap does not fall off the tube, it has been tightened sufficiently.

Figure B. Schematic Showing Locating O-Ring and Groove for Diffusion Caps



Diffusion caps available from PerkinElmer

794-0802

Diffusive (Passive) Sampling

Stainless steel sampling tubes may be used as diffusive samplers (sometimes called passive samplers) if they are packed with a single adsorbent only. For diffusive sampling, a standard diffusion cap (L407 0207) or a diffusion cap with membrane (L407 0208) must be fitted to the grooved end of the tube. The latter is recommended when hydrophilic adsorbents are used, or for sampling in high humidity atmospheres. To ensure that the diffusion gap is set correctly, the first (locating) O-ring in the diffusion cap must engage in the first (locating) groove on the tube (Figure B). This sets the diffusive path length to 15 mm. Diffusive sampling cannot be used when the tube is packed with more than one adsorbent. A list of diffusive uptake rates for some common analytes is given in PerkinElmer's Thermal Desorption Data Sheet 2. Further details on diffusive sampling are given in PerkinElmer's Thermal Desorption Data Sheet 11.

Pumped Sampling

Stainless steel and glass tubes may be used for pumped sampling. The pump should be attached to the end closer to the serial number (see Figure A) and the sample collected at the end closer to the "P" in PerkinElmer. The pump flow rate should be measured with the tube attached before sampling commences. Further details for pumped sampling are given in PerkinElmer's Thermal Desorption Data Sheet 14.

Analysis of Sample Tubes

To reduce chromatographic interference from adsorbent artifacts, wherever possible use lower desorption temperatures for sample analysis than those used for tube conditioning. Always desorb the tubes in the backflush mode, that is, with the carrier gas flow in the opposite direction from that used during air sampling. This is achieved by placing the tubes on the ATD carousel or turntable in the orientation described earlier for tube conditioning.

After analysis, we recommend that sample tubes be re-desorbed at a temperature 10% higher than the desorption temperature, to ensure that all adsorbed species were removed. When you know that the tubes are clean, they can be used again for sampling. Cap the tubes with the screw caps and PTFE ferrules until they are to be used again.

NOTE: Do not overtighten the screw caps because this can damage the tubes. When the PTFE ferrules are new, the caps should be tightened by hand until they touch the ferrule. Tighten a further 1/2 to 3/4 of a turn. Do not tighten beyond this. The ferrules may be re-used but the required rotation of the cap will be less the more times the ferrules are used. Usually, if the cap does not fall off the tube it has been tightened sufficiently (brass caps not included).

If care is taken with the sample tubes, they should be capable of at least 100 cycles of sample collection and thermal desorption before the adsorbent material needs changing. Adsorbent degradation is usually indicated by a reduced retention volume for one or more analytes. A test for retention volume is outlined in PerkinElmer's Data Sheet 8.

For guidance on sample collection procedures (pumped or diffusive), system calibration, tube packing and practical aspects of ATD operation, please consult the ATD 400 User's Manual or the ATD 50 Operator's Manual and the following PerkinElmer Thermal Desorption Data Sheets:

TDD9	Calibrating Thermal Desorption Systems
TDD10	A Guide to Adsorbent Selection
TDD11	Principles of Diffusive Monitoring and Sampler Design
TDD12	Compliance with Personal Exposure Limit Levels — A Guideline
TDD13	Thermal Desorption Troubleshooting
TDD14	Practical Aspects of Pumped Air Monitoring Using PerkinElmer Sample Tubes
TDD15	Model ATD 400 — Multiple Splitter Operation
TDD16	Model ATD 50 — Multiple Splitter Operation
TDD17	Packing Thermal Desorption Sample Tubes

How to use 3M Passive Diffusion Monitors – Organic Vapor Monitors

3M OVM 3500 passive sampling devices (PSDs) are small, noiseless, light-weight passive samplers which can be deployed inconspicuously throughout a building or as relatively unobtrusive personal samplers and can operate without supervision for the desired sampling period.

DEPLOYMENT

1 The sampler and its shipping cap are supplied in an aluminum transport container with a pull-top lid. To expose the sampler, remove and keep the white plastic lid, then open the metal container by pulling on the ring atop the lid of the metal cup. This initiates sampling. Record the date and time (to the nearest minute).



A



B



C

2 Remove the sampler from the can by means of its metallic clip. Do not touch the thin white screen (diffusion barrier). Hold the badge at the edges or by the metal clip as seen in photo D.



D

3 Record the sampler ID number, start date, and time. Also record this information on the lid of the container. Keep the aluminum transport container, white plastic lid, and the clear plastic shipping cap and small clear plastic tube within the container, for return of the exposed sampler to the analytical laboratory.

4 Clip the sampler to an appropriate support device (string, wire etc.) in the selected sampling area.

5 Repeat the above procedures (steps 1 to 4) for any replicate area sampler.

RETRIEVAL

6 After the sampling period has ended, remove the badge from its support, again handling it by its edges or by its metal clip.

7 Remove the plastic retainer ring and white film from the badge as in photo E & F. A coin or key can be used to pry this ring loose from the main badge body. The black membrane below, inside the badge, is the adsorbent sampling medium – do not touch this.



E



F

8 Take the clear plastic shipping cap that is supplied in the transport container and snap it firmly onto the sampler body as in photos G, H & I. Work your thumbs around the edges of the clear plastic cap to ensure that cap is securely in place. Do this carefully so as not to disturb the two port plugs atop the clear cap; if the plugs do come loose, ensure that the two port plugs atop the clear cap are firmly sealed. If they are not sealed closed, the sample will be invalid when received at the lab.



G



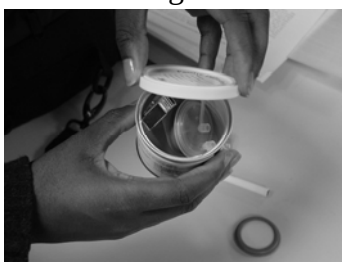
H



I

9 Sampling is now terminated. Record the time (to nearest minute).

10 Place the sampler badge in the transport container and close the container with its white plastic lid. – photos J & K. As an added security measure, you can seal around the edge of the lid with Teflon tape.



J



K

11 Verify that all information has been properly recorded, and ship the badges back to the analytical laboratory for analysis.

Field Blank: a sampler should be opened, the white screen & retainer ring removed immediately, and the clear plastic shipping cap immediately put in place. Ship to lab with the other samples.

Standard Practice for Determination of Concentration Levels of Selected Volatile Organic Compounds (VOCs) with Passive Sampling Devices (PSDs)

3M OVM 3500 PSDs are small, noiseless, light-weight passive samplers which can be deployed inconspicuously throughout a building or as relatively unobtrusive personal samplers and can operate without supervision for the desired sampling period.

Sampling Instructions for Area Monitoring

1 The sampler and its shipping cap are supplied in an aluminum transport container with a pull-top lid. To expose the sampler, open the metal container by pulling on the ring atop the lid. This initiates sampling. Record the date and time (to the nearest minute).

2 Remove the sampler from the can by means of its metallic clip. Do not touch the thin white film (diffusion barrier) or the adsorbent medium (inside the badge). Record the sampler ID number on the Sample Custody Form and on the lid of the container. Keep the aluminum transport container, and the small plastic tube within it, for return of the exposed sampler to the analytical lab.

3 For indoor samples, place the sampler on an appropriate support device (e.g., table, desk, etc) in the selected area. Ensure that the sampling location is more than 1 m from windows, vents or other sources of direct drafts. If an area close to a wall is selected, then avoid corner locations.

Place the samplers so that they are unobstructed and at least 0.5 m from walls or other large objects. Place sampler approximately 1.5 m above floor or ground level to be representative of breathing zone exposures.

Try to position the sampler to minimize possible interference from occupants. This can occur either by brushing against the sampler unintentionally or by direct contact. Indicate to occupants the importance of carrying on with normal activities and of avoiding contact with the sampler.

4 Complete the Sample Custody Form. If possible, record the indoor temperature and relative humidity values at the time of exposure of the sampler.

5 Repeat the above procedures (1 to 4) for any replicate indoor area sampler. Similar procedures can be followed for outdoor samples, but samplers need to be protected from weather. Complete a separate Sample Custody Form for each sampler.

7 After the sampling period has ended, remove the area sampler from its support.

8 Remove the plastic ring and white film from the PSD (using a coin). Snap the shipping cap firmly onto the sampler body. Ensure that the two port plugs are firmly sealed. Sampling is now terminated. Record the time (to nearest minute).

9 Place the sampler in the container and close the container with its white plastic lid. Seal around the edge of the lid with Teflon tape.

10 Record the indoor temperature and relative humidity on the Sample Custody Form when sampling is terminated.

11 Verify that all information has been properly recorded.

Edition 01/2006

how to use *radiello*

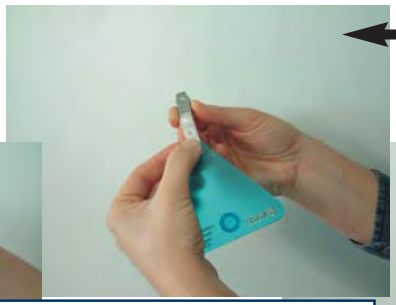
before sampling

assembling the supporting plate

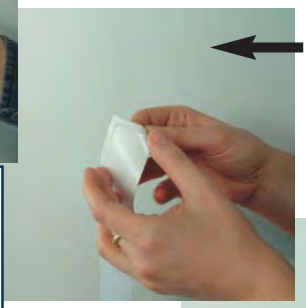
Before using ***radiello***, you have to assemble the supporting plate with the clip, necessary to suspend it, and the adhesive label pocket.

1 insert the clip strip in the slot, with the peg facing upwards





2 ply the strip and insert the peg into the hole



3 peel off the transparent pocket

user tip

assemble the supporting plate in your laboratory before the sampling campaign: on the field they are useless time-consuming.

4 and stick it onto the plate in a central position;

if you prefer, the pocket can be applied to the rear of the plate, but BE CAREFUL, always with the label insertion slot on the side (otherwise, if it starts raining the label can get wet)



on-field

to start the sampling

1 open the plastic bag, draw the cartridge out from the tube and put it in the diffusive body. ***Keep the glass or the plastic tube and stopper in the original plastic bag.***



The lower part of the diffusive body holds a seat for the central positioning of the cartridge. **A correctly centered cartridge should not stick out even by half a millimeter. If it is not so, the cartridge is not correctly positioned and is out of axis.**
As a consequence, when the diffusive body is screwed onto the supporting plate the cartridge is bent, the geometry of the sampler is disturbed and the results obtained become unreliable.
To place the cartridge centrally you need only to tap on the diffusive body.



2 keeping the diffusive body in a vertical position, screw it onto the supporting plate

BE CAREFUL: do not hold the diffusive body horizontally when you screw it onto the plate, otherwise the cartridge could come out from its seat and stick out.

user tip

Do not touch the cartridge with your fingers if possible, particularly if it is impregnated with reactive



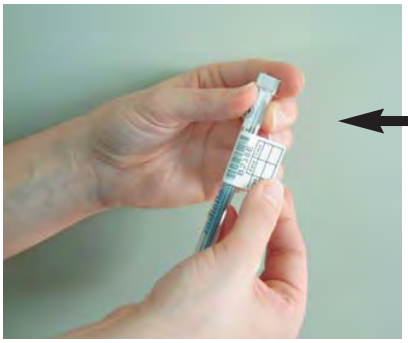
3 Insert a label in the pocket without peeling it off. Keep note of the date and time and expose ***radiello***. Sampling has started.

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user tip

even if you can write date and time of the sampling start and end on the adhesive label, we suggest you to keep note of these parameters also separately: after a week exposure with bad weather conditions, your writings could become illegible!

DO NOT USE MARKING PENS to write on the label: they contain solvents that are sampled by ***radiello***!



4

after the sampling

Keep note of the date and time of the end of exposure.

Place the cartridge into the tube, peel off the label and stick it onto the tube **such that the barcode is parallel to the axis of the tube.**

If you have performed the sampling of different polluting compounds at the same time, ***BE CAREFUL NOT TO MIX UP THE TUBES***: place the exposed cartridge in its original tube, identified by the code printed on the plastic bag.

IMPORTANT

Always stick the label such that the barcode is parallel to the axis of the tube: any other position will compromise the barcode automated reading by the optic reading device.

radiello maintenance

When exposed outdoors or in a workplace environment, the diffusive body may get dirty from airborne dust. Fine particles (PM_{10}) are especially harmful to yellow diffusive bodies since they can obstruct the pores. When the diffusive bodies are dirty you can wash them as follows.
Immerse the diffusive bodies in a beaker with a soapy solution (e.g. dish detergent) and sonicate them for 20 minutes. As the diffusive bodies float, you may make them sink by putting a smaller beaker on them, with water inside enough to dip it a few centimeters.

Rinse the diffusive bodies with plenty of water and then deionized water; let them finally dry in the air.

IMPORTANT: NEVER USE SOLVENTS TO CLEAN THE DIFFUSIVE BODIES!!!

After four or five washings, diffusive bodies need replacing: repeatedly adsorbed dust may have penetrated the pores such deeply to be undisturbed by washing.

The following table shows the advised washing schedule:

PM_{10} concentration ($\mu g \cdot m^{-3}$)	<30	40	>50
Washing after days of exposure	45	30	15



Edition 01/2006

Volatile organic compounds (VOCs)

chemically desorbed with CS_2

Radiello components to be used:

White diffusive body code 120
Supporting plate code 121
Vertical adapter code 122 (optional)
Adsorbing cartridge code 130

Or: *radiello-ready-to-use* code 123-1

Principle

Code 130 cartridge is a stainless steel net cylinder, with 100 mesh grid opening and 5.8 mm diameter, packed with 530 ± 30 mg of activated charcoal with particle size 35-50 mesh. Volatile organic compounds are trapped by adsorption and recovered by carbon disulfide displacement, analysis is performed by FID gas chromatography.

Sampling rates

The table on page D2 lists sampling rate values at 298 K (25 °C) and 1013 hPa, experimentally measured in a standard atmosphere chamber. For other compounds, whose diffusion coefficient[1] is known, sampling rate can be calculated according to equation [5] on page A2, taking into account that white diffusive body and code 130 cartridge give the geometric constant of radiello the value of 14.145 ± 0.110 cm. Several experiments performed in the standard atmosphere chamber demonstrate that the calculated sampling rates seldom deviate by more than ± 10% from the experimentally measured values.

Effect of temperaure, humidity and wind speed

Sampling rates varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation

$$Q_K = Q_{298} \left(\frac{K}{298}\right)^{1.5}$$

where Q_K is the sampling rate at the temperature **K** and Q_{298} is the reference value at 298 K. This produces a variation of ± 5% for 10 °C variation (upwards or downwards) from 25 °C.

Sampling rate is invariant with humidity in the range 15-90% and with wind speed between 0.1 and 10 $m \cdot s^{-1}$.

[1]Lugg G.A.: Diffusion Coefficients of Some Organic and Other Vapours in Air. *Anal. Chem.* **40-7**:1072-1077 (1968).

Calculations

The listed sampling rate values already take into account for the desorption efficiency with carbon disulfide. **The average concentration over the exposure time interval is therefore calculated from the mass of analyte found onto the cartridge and exposure time <u>without introducing any corrective factor</u>**, apart from corrections due to average temperature different from 25 °C.

Average concentration over the whole exposure time is calculated according to the following expression

$$C\ [\mu g \cdot m^{-3}] = \frac{m\ [\mu g]}{Q_K\ [ml \cdot min^{-1}] \cdot t\ [min]}\ 1{,}000{,}000$$

where:
m = mass of analyte in µg
t = exposure time in minutes

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Sampling rate values at 25°C (298 K)

	sampling rate $ml \cdot min^{-1}$	linearity range $\mu g \cdot m^{-3} \cdot min$	uncertainty at 2σ %	notes
acetone	77	$10{,}000\text{-}600 \cdot 10^6$	7.0	**a**
acetonitrile	73	$10{,}000\text{-}6 \cdot 10^6$	8.2	**b**
acrylonitrile	75	$1{,}000\text{-}50 \cdot 10^6$	2.2	
benzyl alcohol	37	$1{,}000\text{-}800 \cdot 10^6$	6.5	
amyl acetate	52	$1{,}000\text{-}800 \cdot 10^6$	3.4	
benzene	80	$500\text{-}500 \cdot 10^6$	1.8	
bromochloromethane	70	$50{,}000\text{-}1{,}000 \cdot 10^6$	1.4	
butanol	74	$1{,}000\text{-}500 \cdot 10^6$	5.0	
sec-butanol	64	$1{,}000\text{-}300 \cdot 10^6$	5.2	
tert-butanol	62	$1{,}000\text{-}300 \cdot 10^6$	5.5	
butyl acetate	60	$1{,}000\text{-}1{,}000 \cdot 10^6$	3.0	
2-butoxyethanol	56	$1{,}000\text{-}100 \cdot 10^6$	5.7	
2-butoxyethyl acetate	41	$1{,}000\text{-}100 \cdot 10^6$	5.5	
carbon tetrachloride	67	$100{,}000\text{-}60 \cdot 10^6$	9.0	
cyclohexane	54	$500\text{-}500 \cdot 10^6$	4.5	
cyclohexanone	68	$5{,}000\text{-}120 \cdot 10^6$	4.2	
cyclohexanol	54	$5{,}000\text{-}120 \cdot 10^6$	4.5	
chlorobenzene	68	$1{,}000\text{-}1{,}000 \cdot 10^6$	3.6	
chloroform	75	$100{,}000\text{-}60 \cdot 10^6$	9.7	**a**
n-decane	43	$500\text{-}1{,}000 \cdot 10^6$	1.1	
diaceton alcohol	43	$500\text{-}1{,}000 \cdot 10^6$	4.5	
1,4-dichlorobenzene	51	$1{,}000\text{-}1{,}000 \cdot 10^6$	7.7	
1,2-dichloroethane	77	$1{,}000\text{-}500 \cdot 10^6$	8.2	
1,2-dichloropropane	66	$500\text{-}250 \cdot 10^6$	4.5	
dichloromethane	90	$500\text{-}60 \cdot 10^6$	8.7	
N,N-dimetylformamide	82	$1{,}000\text{-}200 \cdot 10^6$	14.5	**c**
1,4-dioxane	68	$1{,}000\text{-}600 \cdot 10^6$	5.5	
n-dodecane	8	$1{,}000\text{-}1{,}000 \cdot 10^6$	4.7	
n-heptane	58	$5{,}000\text{-}1{,}500 \cdot 10^6$	3.0	
n-hexane	66	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.5	
1-hexanol	52	$5{,}000\text{-}120 \cdot 10^6$	5.5	
ethanol	102	$10{,}000\text{-}500 \cdot 10^6$	7.5	**a-b**
diethyl ether	78	$5{,}000\text{-}500 \cdot 10^6$	12.0	**a**
ethyl acetate	78	$1{,}000\text{-}1{,}000 \cdot 10^6$	1.5	
ethylbenzene	68	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.4	
2-ethyl-1-hexanol	43	$5{,}000\text{-}500 \cdot 10^6$	10.1	
2-ethoxyethanol	55	$500\text{-}50 \cdot 10^6$	6.7	**b**
2-ethoxyethyl acetate	54	$10{,}000\text{-}100 \cdot 10^6$	2.5	
ethyl-*tert*-butyl ether (ETBE)	61	$500\text{-}200 \cdot 10^6$	3.0	
isobutanol	77	$1{,}000\text{-}300 \cdot 10^6$	2.5	
isobutyl acetate	63	$1{,}000\text{-}1{,}000 \cdot 10^6$	5.2	
isooctane	55	$500\text{-}1{,}000 \cdot 10^6$	3.2	
isopropanol	52	$10{,}000\text{-}400 \cdot 10^6$	12.0	**b**
isopropyl acetate	66	$1{,}000\text{-}1{,}000 \cdot 10^6$	9.9	
isopropylbenzene	58	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.7	
limonene	43	$1{,}000\text{-}1{,}000 \cdot 10^6$	10.0	
methanol	125	$10{,}000\text{-}250 \cdot 10^6$	9.2	**a-b**
methyl acetate	80	$1{,}000\text{-}1{,}000 \cdot 10^6$	12.0	
methyl-*ter*-butyl ether (MTBE)	65	$500\text{-}200 \cdot 10^6$	2.5	

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	sampling rate $ml \cdot min^{-1}$	linearity range $\mu g \cdot m^{-3} \cdot min$	uncertainty at 2σ %	notes
methylcyclohexane	66	$1{,}000\text{-}1{,}000 \cdot 10^6$	6.5	
methylcyclopentane	70	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.5	
methylethylketone	79	$1{,}000\text{-}500 \cdot 10^6$	1.6	
methylisobutylketone	67	$1{,}000\text{-}250 \cdot 10^6$	8.7	
methyl metacrylate	68	$1{,}000\text{-}500 \cdot 10^6$	2.5	
2-methylpentane	70	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.5	
3-methylpentane	70	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.5	
2-methoxyethanol	35	$5{,}000\text{-}100 \cdot 10^6$	11.0	**b**
2-methoxyethyl acetate	56	$2{,}000\text{-}100 \cdot 10^6$	3.0	
1-methoxy-2-propanol	55	$1{,}000\text{-}350 \cdot 10^6$	6.0	
1-methoxy-2-propyl acetate	60	$2{,}000\text{-}350 \cdot 10^6$	6.2	
naphtalene	25	$1{,}000\text{-}1{,}000 \cdot 10^6$	7.0	
n-nonane	48	$1{,}000\text{-}1{,}000 \cdot 10^6$	5.4	
n-octane	53	$500\text{-}1{,}000 \cdot 10^6$	3.2	
pentane	74	$1{,}000\text{-}1{,}000 \cdot 10^6$	1.9	
α-pinene	53	$1{,}000\text{-}1{,}000 \cdot 10^6$	7.0	
propyl acetate	65	$500\text{-}1{,}000 \cdot 10^6$	7.5	
propylbenzene	57	$1{,}000\text{-}1{,}000 \cdot 10^6$	2.9	
styrene	61	$1{,}000\text{-}500 \cdot 10^6$	3.0	
tetrachloroethylene	59	$10{,}000\text{-}500 \cdot 10^6$	2.5	
tetrahydrofuran	74	$2{,}000\text{-}250 \cdot 10^6$	11.0	**b**
toluene	74	$500\text{-}1{,}000 \cdot 10^6$	1.5	
1,1,1-trichloroethane	62	$5{,}000\text{-}1{,}000 \cdot 10^6$	5.5	
trichloroethylene	69	$5{,}000\text{-}1{,}000 \cdot 10^6$	2.4	
1,2,4-trimethylbenzene	50	$500\text{-}1{,}000 \cdot 10^6$	6.6	
n-undecane	24	$1{,}000\text{-}1{,}000 \cdot 10^6$	10.0	
m-xylene	70	$500\text{-}1{,}000 \cdot 10^6$	2.5	
o-xylene	65	$500\text{-}1{,}000 \cdot 10^6$	2.5	
p-xylene	70	$500\text{-}1{,}000 \cdot 10^6$	2.5	

Notes:

a = weakly adsorbed compound. If its concentration is higher than the TLV for the workplace environments it may be partially displaced by other compounds that are more strongly trapped if their concentration is also high. If this is the case, it is advisable to reduce sampling time under 8 hours.

b = prolonged exposure of charcoal cartridges at relative average humidity higher than 80% causes adsorption of up to 100 mg of water. Water does not interfere with adsorption mechanisms but is displaced by carbon disulfide and gives raise to a separate layer. Some very water soluble polar compounds will distribute between the two solvents, thus provoking an underestimation of the actual air concentration since only the carbon disulfide is injected in the gas chromatograph. When the concentration of polar compounds has to be determined, the calibration curve should be prepared by spiking 50 µl of water in each tube containing the cartridge and the 2 ml of carbon disulfide standard solution (see Analysis).

c = better reproducibility obtained by use of methanol as extraction solvent instead of carbon disulfide.

Limit of quantitation

The limit of quantitation depends on the instrumentation and on the analytical conditions. The minimum revealable environmental concentration can be estimated on the basis of the equation on page D1, where ***m*** is the minimum revealable mass, experimentally measured for each compound. Under the analytical conditions described on page D4, the limit of quantitation for 7 days exposure usually ranges from 0.05 to 1 $\mu g \cdot m^{-3}$, depending on the compound.



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Exposure

Code 130 cartridge has a very large loading capacity: about 80 mg, corresponding to an overall VOCs concentration of 3,000-3,500 mg·m^{-3} sampled for 8 hours or 70,000-80,000 µg·m^{-3} sampled for 14 days. Neverthless, if the quantified overall adsorbed mass should be near 80 mg, sampling rate could have deviated from linearity. If this is the case, it is advisable to repeat the sampling experiment reducing exposure time.

Workplace environment

In workplace environments complex mixtures of airborne solvent vapours are often found at concentrations of 2,000-3,000 mg·m^{-3}. The outstanding adsorbing capacity of code 130 cartridges allows you to sample them for the whole working shift of 8 hours. On the other hand, the very high values of sampling rates for a variety of compounds allow you to perform accurate concentration measurements even after very short exposures. For example, 15 minutes are enough to measure 0.1 mg·m^{-3} of benzene.

radiello can therefore be employed to evaluate both *TWA* and *STEL* concentrations.

Other indoor sampling experiments and outdoor campaigns

High sampling rates of ***radiello*** ensure very low limits of detection also for short exposure time intervals. For example, you may measure benzene concentrations as low as 2 µg·m^{-3} with an error not exceeding 4% after 8 hours of exposure. If ***radiello*** is exposed for 7 days, limit of quantitation becomes 0.1 µg·m^{-3}.

Generally speaking, we suggest exposure time duration ranging from 8 hours to 30 days, the ideal value being 7 days.

Storage

The activated charcoal cartridges have undergone a complex conditioning process that ensures an outstanding chromatographic blank level, never exceeding three times the instrumental noise of a FID detector at the lowest attenuation.

Kept in a cool place and away from volatile organic compounds, the cartridges mantain unchanging blank level and adsorbing capacity for at least two years. Expiry day and lot number are printed onto the plastic bag wrapping each cartridge: its integrity stands as warranty seal.

After exposure the cartridges, well capped and kept in a cool and solvent-free place, mantain their content unalterated for at least six months.

Analysis

Extraction

Introduce 2 ml of CS_2 and 100 µl of internal standard solution (see next page) directly in the ***radiello*** glass tube without drawing out the cartridge. **Always use class A volumetric pipettes or dispensers.** Stir from time to time for 30 minutes. If analysis is not performed soon after, draw out the cartridge and discard it.

IMPORTANT

always use high purity grade CS_2, for example Fluka code 84713 or Aldrich code 34,227-0

BE CAREFUL

even refrigerated, CS_2 permeates the tube plastic cap: its volume decreases by 4-5% a day. If the internal standard has been added, it is only matter of unpleasant odour...

Calibration

Outdoor environment sampling

If benzene, toluene, ethylbenzene and xylenes (BTEX) have to be analyzed, prepare three or four standard solutions in CS_2 having decreasing concentrations of the analytes in the following ranges (in mg·l^{-1}):

benzene	0.04-17.6	ethylbenzene	0.04-17.7
toluene	0.09-34.8	m-xylene	0.04-17.2
o-xylene	0.04-17.6	p-xylene	0.04-17.2

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It is advisable to proceed via consecutive dilutions, starting for example from a stock solution containing 1 ml of each compound in 100 ml. Always use class A volumetric glassware. Introduce 2 ml of each standard solution, along with 100 µl of internal standard, onto a blank code 130 cartridge in its glass tube.

Analysis of unknown samples

Identify the sample that has been exposed for the longest time or at the highest expected concentration. Introduce 2 ml of CS_2 but do not add the internal standard, stir and let the sample stand for 30 minutes. Without discarding the cartridge, inject the CS_2 solution in the gas chromatograph with FID detector (see below), identify the compounds appearing in the chromatogram and make an estimation of the order of magnitude of their concentrations.

Prepare a CS_2 solution of the identified compounds with doubled concentration with respect to the sample. Dilute this solution in order to obtain standard solutions of concentration respectively about 0.1, 0.5 and 1 times the concentration estimated in the sample. Introduce 2 ml of each standard solution onto a blank code 130 cartridge in its glass tube, along with the chosen internal standard solution.

The chosen **internal standard** should have a retention time that does not interfere with other compounds in the chromatogram. Compatibly with this requirements, we suggest to employ a solution of **2-fluorotoluene** (e.g. Aldrich F 1,532-3) in CS_2 with concentration of 100 $\mu l \cdot l^{-1}$ for outdoor samples and 2 $ml \cdot l^{-1}$ for workplace samples.

Add 2 ml of CS_2 and the internal standard to all of the samples, stir, let the samples stand for 30 minutes and discard the cartridges prior to the analysis.

USER TIP

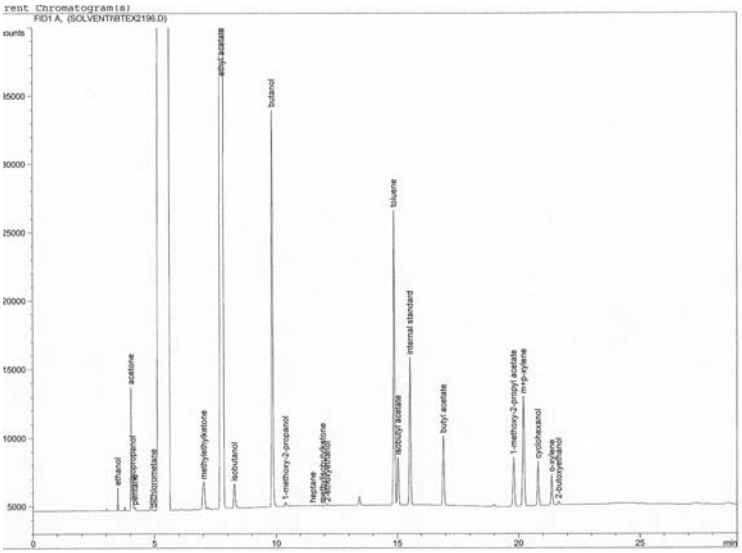
For a very accurate calibration we offer the **preloaded cartridges code 405** (outdoor environment) and **code 406** (workplace environment).

Instrumental analysis (advised)

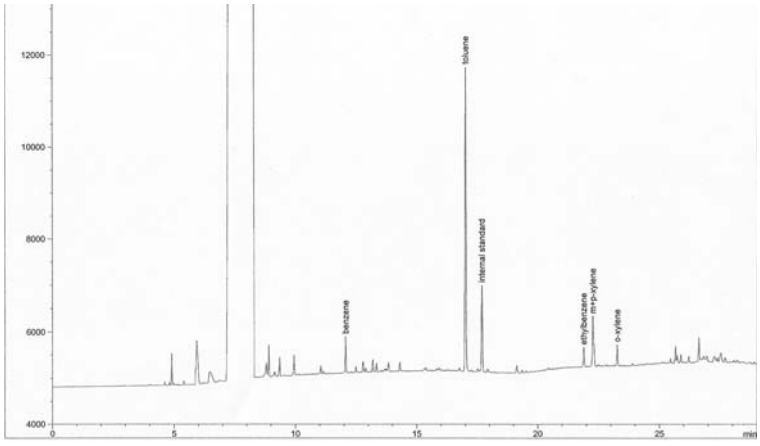
Capillary gas chromatography with FID detection

outdoor environment samples: 100% dimethylpolysiloxane column 0.2 mm·50 m, film thickness 0.5 µm; split injection of 2 µl; split ratio 25:1; nitrogen carrier gas at constant pressure of 20 psi; injector temperature 240 °C; oven initial temperature 35 °C for 5 minutes, 5 °C/min up to 90 °C, maintain for 3 minutes, 10 °C/min up to 220 °C, final isotherm for 5 minutes.

workplace samples: 100% dimethylpolysiloxane column 0.2 mm·50 m, film 0.5 µm; split injection of 3 µl, split ratio 100:1; carrier N_2 at constant pressure of 20 psi; injector temperature 240 °C; oven initial temperature 50 °C for 5 minutes, 5 °C/min up to 80 °C, 15 °C/min up to 135 °C, 20 °C/min up to 220 °C, final isotherm 10 minutes. Total time: 29 minutes. The retention times for several compounds analyzed under the described conditions are listed in the table on next page.



On top: *FID chromatogram of a real workplace sample*



on the left: *chromatogram of a real urban outdoor sample*

USER TIP

If you perform several analyses, a barcode reader will greatly improve productivity in your laboratory and will also minimize the possibility of errors in the copying of sample labels.

Please contact us to help you in the implementation of the reader.

We have also developed software solutions for the analytical data processing and automated production of analysis reports.

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	retention time (minutes)
methanol	4.834
ethanol	5.340
acetone	5.712
isopropanol	5.835
pentane	6.121
methyl acetate	6.346
dichloromethane	6.405
2-methylpentane	7.559
methylethylketone	7.719
3-methylpentane	7.941
ethyl acetate	8.331
n-hexane	8.402
isobutanol	8.763
methylcyclopentane	9.350
1,1,1-trichloroethane	9.636
butanol	9.956
isopropyl acetate	9.978
benzene	10.203
1-methoxy-2-propanol	10.424
cyclohexane	10.580
1,2-dichloropropane	11.285
trichloroethylene	11.625
isooctane	11.667
2-ethoxyethanol	11.831
propyl acetate	11.868
n-eptane	12.068
1-ethoxy-2-propanol	12.775
methylcyclohexane	12.912
methylisobutylketone	13.258
isobutyl acetate	14.005
toluene	14.055
butyl acetate	15.279
n-octane	15.435
tetrachloroethylene	15.601
diaceton alcohol	15.915
1-methoxy-2-propyl acetate	16.609
ethylbenzene	16.997
m+p-xylene	17.241
cyclohexanone	17.436
cyclohexanol	17.436
styrene	17.716
o-xylene	17.832
2-buthoxyethanol	17.880
n-nonane	18.186
α-pinene	19.129
n-decane	20.334
n-undecane	22.142

What make the code 130 cartridge incomparable?

the container



The container is made of stainless steel cloth AISI 316 with 100 mesh grid opening. It is electric welded with no supply of foreign materials. It has tolerance of ± 0.05 mm diameter and of ± 0.1 mm length.

the contents

The cartridge is packed with vegetal activated charcoal with a very large adsorbing surface. Its exceptionally low blank is obtained by conditioning it in a nitrogen stream fluidised bed at 450 °C for 16 hours. The fluidised bed technique does not only guarantee the thorough purification of adsorbing material but also performs an accurate selection of its granulometry, by ventilation separations of the fraction under 50 mesh and over 35 mesh.

the production

The cartridge is filled up with charcoal by a very complex automated apparatus that was designed and realised in our laboratory. It avoids any contamination of the adsorbing material during the delicate process of cartridge production and ensures a very accurate dosing of the material itself, providing a variability of less than 2% of the weight of the activated charcoal among the cartridges.





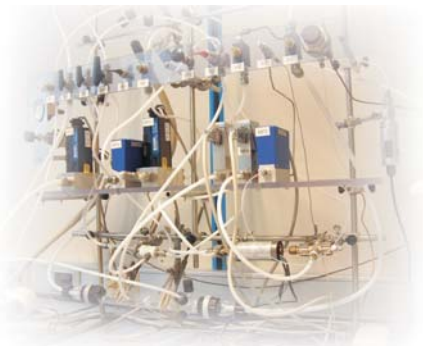
the quality control

Each cartridge batch undergoes statistical quality control of the blank level. If amounts higher than 20 ng of each of the BTEX compounds are found, the entire lot is discarded.

the sampling rate measurements

The sampling rate is measured in a standard atmosphere chamber unique in Italy (and one of the few found all over Europe) that allows the dynamic generation of high flows of controlled concentration gas mixtures from 1 $\mu g \cdot m^{-3}$ to 1,000 $mg \cdot m^{-3}$ (dynamic range from 1 to 10^6) of each investigated compound alone or mixed with others. The chamber allows temperature control from -20 to 60 °C, relative humidity control from 5% to 100% and air speed variation from 0.1 to 10 $m \cdot s^{-1}$.

All of the gas flows are measured as mass flows and have therefore the properties of primary standards. All of the operating parameters (gas flows, temperature, relative humidity, ...) are recorded and the records are available along with the certification documents.



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Edition 01/2006

Volatile organic compounds (VOCs)

thermally desorbed

Radiello components to be used:

Yellow diffusive body code 120-2
Supporting plate code 121
Vertical adapter code 122 (optional)
Adsorbing cartridge code 145

Principle

Code 145 is a stainless steel net cylinder, with 3x8 µm mesh grid opening and 4.8 mm diameter, packed with 350 ± 10 mg of graphitised charcoal (Carbograph 4), particle size is 35-50 mesh.

Volatile organic compounds are trapped by adsorption and recovered by thermal desorption, analysis is performed by capillary gas chromatography and FID or MS detection.

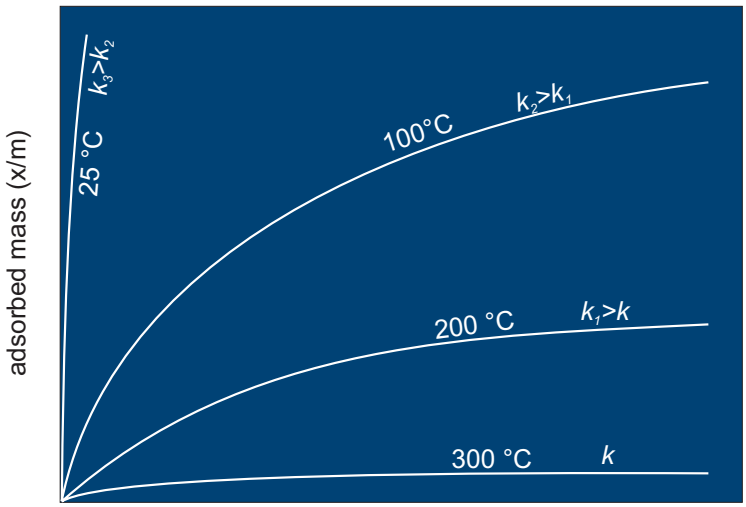
General considerations

Thermal desorption is an easy-to-use technique, but it implies some precautions and is of less general use than chemical desorption.

The recovery of adsorbed compounds is based onto the different shape of adsorption isotherms at different temperatures. Since quantitative desorption of trapped molecules should ideally be accomplished at moderate temperatures, only weak adsorbing media are employed, with active adsorbing surface between 10 and 50 times smaller than that of activated charcoal.

Use of thermal desorption requires therefore an accurate preliminary investigation about the adsorbed compound - adsorbing medium pair. Stronger adsorbents are suitable for very volatile compounds, but will yield only partial desorption of heavier compounds.

Anyway, *backdiffusion* (see page A3) is always lying in wait: due to the adsorbing medium weakness heavier compounds will eventually displace the more volatile ones. Once you have made an accurate choice of the adsorbing material, therefore, you should bear in mind that a real atmosphere is composed by a variety of compounds apart from those you are analyzing at unpredictable concentrations. As a consequence, sampling times can not be as long as those allowed by activated charcoal, otherwise lighter compounds will be lost. With the purpose of allowing reasonable sampling times (up to two weeks) the sampling rate has been dramatically reduced by changing the diffusive body from the white type (code 120) to the yellow one (code 120-2). Smaller average pore size and



When in contact with a solid adsorbing medium, a gaseous compound will be adsorbed following the Freundlich isotherm*, that is to say the adsorbed mass will be* $x/m=kC^{1/n}$*, where* x *is the mass of gaseous compound adsorbed by the mass m of the solid adsorbent and C is the concentration of the gaseous compound at the equilibrium in the gas phase. K and n depend on temperature and on the adsorbate - adsorbing medium pair. K increases with decreasing temperature and n is the closer to 1 the stronger the adsorbent.*

At low temperatures, x/m *depends almost linearly on the concentration in air (see the curve at 25 °C): this allows diffusive sampling. At high temperatures, the adsorbent mass is very low whatever the concentration in the gas phase: this allows the recovery of adsorbed compounds by heating (see the curve at 300 °C).*

To ensure the best possible recovery yields, k and n have to be small. This, however, will compromise sampling efficiency. In other words, compounds strongly adsorbed at room temperature will be only partially recovered by thermal desorption. On the other hand, compounds that are easily desorbed by heating will be sampled at room temperature with low efficiency.



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thicker diffusive membrane make the diffusive path longer and, as a consequence, sampling rates are reduced to less than one third compared to those obtained with white diffusive bodies.



Some compounds, moreover, are thermally unstable. Thermal degradation of such compounds will cause an underestimation of their concentration or the appearance of ghost peaks.

Thermal desorption is neverthless an outstanding analytical technique because it is easy to perform, it does not require the use of toxic solvents as carbon disulfide, it ensures very low limits of detection, is suited to mass spectrometric detection and allows the recovery of the adsorbing cartridges. Basing on our experience, we have chosen Carbograph 4 as the best compromise between sampling efficiency and recovery yields for a wide range of organic compounds.

Sampling rates

Sampling rate values at 298 K (25 °C) and 1013 hPa are listed in table on page ***E3***. All of the values shown have been experimentally measured. Exposure tests have been performed up to the levels shown (in $\mu g \cdot m^{-3} \cdot min$) and sampling rates are guaranteed to be linear up to the limit values and for overall concentration of volatile organic compounds in air not exceeding 2,000 $\mu g \cdot m^{-3}$.

Effect of temperature, humidity and wind speed

Sampling rates varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation

$$Q_K = Q_{298} \left(\frac{K}{298}\right)^{1.5}$$

where Q_K is the sampling rate at the temperature **K** and Q_{298} is the reference value at 298 K. This produces a variation of ± 5% for 10 °C variation (upwards or downwards) from 25 °C.

Sampling rate is invariant with humidity in the range 15-90% and with wind speed between 0.1 and 10 $m \cdot s^{-1}$.
Do not expose directly ***radiello*** to rain: even if small amounts of water are adsorbed by Carbograph 4, they can neverthless interfere with analysis.

Calculations

The listed sampling rate values take already into account the recovery yields of adsorbed compounds. **The average concentration over the sampling period is therefore calculated from sampled mass of analyte and exposure time <u>without introducing any other corrective factor</u>,** apart from temperature variations of Q.

Average concentration ***C*** in $\mu g \cdot m^{-3}$ over the whole exposure time is calculated according to the following expression:

$$C\ [\mu g \cdot m^{-3}] = \frac{m\ [\mu g]}{Q_K\ [ml \cdot min^{-1}] \cdot t\ [min]}\ 1{,}000{,}000$$

where:
m = mass of analyte in µg
t = exposure time in minutes

Exposure

Workplace environment

The use of ligth adsorbing media is not recommended in the workplace environment.



Other indoor sampling experiments and outdoor campaigns

Thermal desorption is exceptionally suited for long exposure times at low concentrations, as in outdoor campaigns and some indoor environments (e.g. homes, schools, etc...), particularly if the subsequent analysis is performed by HRGC-MS.

The recommended exposure times range from 8 hours to the upper limits shown in the table below. It is advisable to reduce sampling time if the estimated overall VOCs concentration is higher than 2,000 $\mu g \cdot m^{-3}$.

Sampling rate values at 25°C (298 K)

	sampling rate $ml \cdot min^{-1}$	exposure time upper limit	linear up to $\mu g \cdot m^{-3} \cdot min$	uncertainty (2σ) %	limit of detection[1] $\mu g \cdot m^{-3}$
benzene	27.8	7	410,000	8.3	0.05
benzene	26.8	14	410,000[2]	7.5	0.05
butyl acetate	24.5	14	580,000	12.4	0.05
2-butoxyethanol	19.4	14	550,000	9.7	0.1
cyclohexane	27.6	7	470,000	14.7	0.1
n-decane	22.3	14	450,000	22.4	0.1
1,4-dichlorobenzene	22.0	14	650,000	9.5	0.1
dimethyl disulfide	23.7	7	500,000	9.1	0.04
n-heptane	25.3	14	420,000	7.6	0.05
n-hexane	25.5	7	420,000	10.9	0.05
ethylbenzene	25.7	14	550,000	9.1	0.01
2-ethyl-1-hexanol	14.3	14	550,000	17.4	0.07
2-ethoxyethanol	26.0	14	570,000	7.7	0.05
2-ethoxyethyl acetate	20.9	14	600,000	8.0	0.05
isopropyl acetate	25.8	7	540,000	9.6	0.1
limonene	12.8	14	550,000	24.8	0.2
2-methoxyethanol	4.0	7	1,000,000	--	1.0
2-metoxyethyl acetate	21.0	7	1,000,000	--	0.1
1-methoxy-2-propanol	26.6	7	600,000	11.6	0.2
n-nonane	21.0	14	440,000	11.8	0.07
n-octane	24.1	14	440,000	13.4	0.07
α-pinene	6.4	14	550,000	29.5	0.2
styrene	27.1	14	550,000	24.0	0.01
tetrachloroethylene	25.4	7	1,000,000	8.9	0.02
toluene	30.0	14	550,000	8.3	0.01
1,1,1-trichloroethane	20.0	7	300,000	13.0	0.1
trichloroethylene	27.1	7	800,000	9.5	0.02
1,2,4-trimethylbenzene	21.9	14	550,000	9.6	0.05
n-undecane	12.0	14	520,000	32.7	0.05
m-xylene	26.6	14	550,000	11.3	0.01
o-xylene	24.6	14	550,000	9.1	0.01
p-xylene	26.6	14	550,000	11.3	0.01

[1]after 7 days exposure and with MS detection; analytical conditions as described in the Analysis paragraph
[2]for overall VOCs concentrations not exceeding 500 $\mu g \cdot m^{-3}$

Storage

The cartridges have undergone a complex conditioning procedure that ensures an outstanding chromatographic blank level. If kept in a cool place without VOCs contamination, blank level and adsorbing capacity stay unaltered for at least eighteen months.

After exposure the cartridges, well capped and kept in a cool and solvent-free place, are stable for at least three months.

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Analysis

The analytical methods hereafter described have been set up with the Perkin-Elmer Turbomatrix thermal desorber and Agilent 5973 MSD mass spectrometer detector. They may be implemented on other instruments by introducing minor adjustements as suggested by the analyst's experience and characteristics of employed instrumentation.

In the following we propose two methods, one for **BTEX** analysis and another for **VOCs**. The former is suited to outdoor sampling in urban monitoring, where investigation is usually focussed onto benzene, toluene, ethylbenzene and xylene isomers. The latter is conceived for indoor monitoring, allowing quantification of all the compounds listed on page E3 and also extended qualitative analysis. The two methods differ by a few details, such as the higher desorption temperature for VOCs and the higher cryofocusing temperature for BTEX. The latter caution is introduced to avoid freezing of excess humidity gathered during the sampling in the cryofocusing trap.

Desorption

The thermal desorber is equipped with 1/4" s.s. sample tubes, they have to be hollow and free: discard the stainless steel gauze disk which is fitted to the groove and discard also the springs if present.

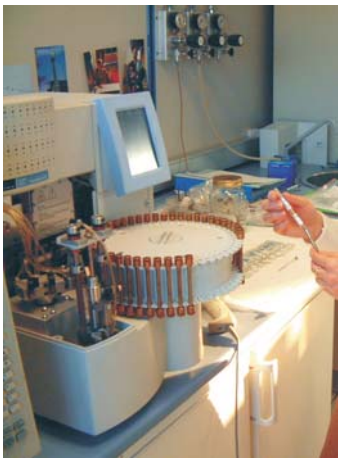
Code 145 cartridge has been dimensioned to fit the diameter of Turbomatrix thermal desorption tubes. Its length is such that, when the cartridge is introduced into the tube and is stopped by the groove, it is positioned exactly centrally with respect to the tube length.

Inner diameter of Perkin-Elmer tubes is not always exactly the same; it may be the case therefore that a cartridge code 145 does not slide easily into the tube. Some pushing tool may be helpful then, such as a 500 µl syringe piston, a glass bar or an iron wire 2-3 mm thick.

In some cases the tube inner diameter is sligthly larger than the cartridge outer diameter: the cartridge can therefore be pushed out from the tube during desorption due to the desorption gas pressure. If this is the case, make use of the springs provided along with the tubes.

Once capped, the Turbomatrix steel tube has to be positioned in the carousel with the grooves on the bottom.

The described conditions have been optimized for seven days exposures to typical concentrations of urban atmospheres and indoor environments. Shorter exposure times or considerably higher concentrations would require different settings of split flows, with the purpose of ensuring good analytical sensitivity or linearity of response.



Usually, the cartridge enters into the Turbomatrix tube by simple pouring. If it does not occur, use a pushing tool to press the cartridge till the nick on the tube.

BTEX

Temperatures and timing

- ✓ Desorption: 320 °C for 10 minutes
- ✓ Cryofocusing trap (Tenax TA): during primary desorption mantain 2 °C, secondary desorption at 99 °C/sec up to 290 °C, 1 minute at 290 °C
- ✓ Six port valve: 150 °C
- ✓ Transfer line: 200 °C

Flows

- ✓ Carrier gas: helium, 24 psi
- ✓ Desorption flow: 100 ml·min^{-1}
- ✓ Inlet split: 90 ml·min^{-1}
- ✓ Outlet split: 30 ml·min^{-1}

VOCs

Temperatures and timing

- ✓ Desorption: at 370 °C for 15 minutes
- ✓ Cryofocusing trap (Tenax TA): during primary desorption mantain at -20 °C, secondary desorption at 99 °C/sec up to 290 °C, 1 minute at 290 °C
- ✓ Six port valve: 150 °C
- ✓ Transfer line: 200 °C

Flows

- ✓ Carrier gas: helium, 24 psi
- ✓ Desorption flow: 100 ml·min^{-1}
- ✓ Inlet split: 90 ml·min^{-1}
- ✓ Outlet split: 30 ml·min^{-1}



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Instrumental analysis

Analytical parameters for BTEX and VOCs are the same, apart from the duration of chromatographic run and final temperature.

We recommended the following conditions:

Column

100% dimethylpolysiloxane, length 50 m, i.d. 0.2 mm, film thickness 0.5 µm; the column is directly fitted to the six-port valve of Turbomatrix apparatus.

Temperatures

- ✓ GC oven: 40 °C for 3 minutes, 8 °C/min up to 80 °C, mantain for 1 minute, 20 °C/min up to 250 °C for BTEX and up to 280 °C for VOCs, final isotherm 1.5 minutes for BTEX and 3 minutes for VOC
- ✓ GC-MS interface: 270 °C

USER TIP

If you perform several analyses, a barcode reader will greatly improve productivity in your laboratory and will also minimize the possibility of errors in the copying of sample labels.

Please contact us to help you in the implementation of the reader.

We have also developed software solutions for the analytical data processing and automated production of analysis reports.

Flows

- ✓ Carrier gas: helium, 0.8 ml·min^{-1}

USER TIP

For a very accurate BTEX calibration we offer the **preloaded cartridges code 407.**

On page E6 we display two total ion current chromatograms from an outdoor urban site and an indoor sampling respectively.

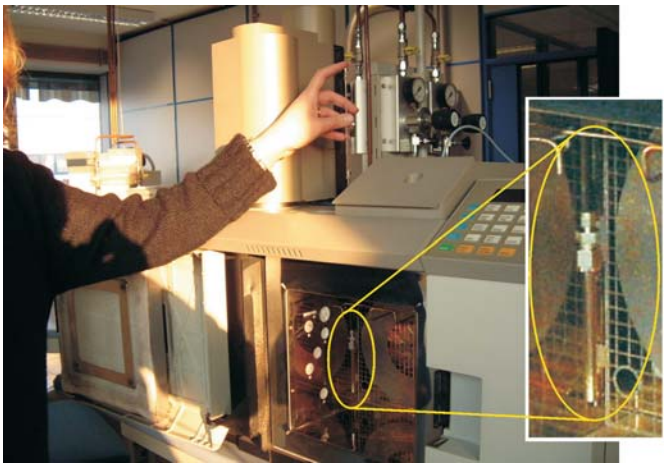
In the first case, the benzene peak corresponds to an average concentration of 2.2 µg·m^{-3}; in the second the concentration of 1,4-dichlorobenzene was 14 µg·m^{-3}. Despite the low concentration values, the signal-to-noise ratio is very high in both cases. As a consequence, very reliable mass spectral identification is possible.

Calibration

Calibration curves are obtained by gas-phase injection of methanol solutions of the target compounds onto blank cartridges. Injections are performed through a GC injector, where a short piece (10 cm) of wide-bore (0.53 i.d.) deactivated uncoated column is installed. The other end bears a Swagelock reducing connection (1/16”-1/4”). The 1/4” Swagelock nut has to be equipped with a PTFE *ferrule* instead of the original steel one (use PTFE ferrules that come along with the Turbomatrix caps).

Introduce a blank cartridge in a Turbomatrix tube and fit the tube to the Swagelock nut. Mantain the injector at 200 °C but do not heat the oven. Inject slowly 1 µl of each calibration solution under nitrogen flow (50 ml/min) and let the system purge for 2 minutes. Analyze the cartridge as you would do with a sample.

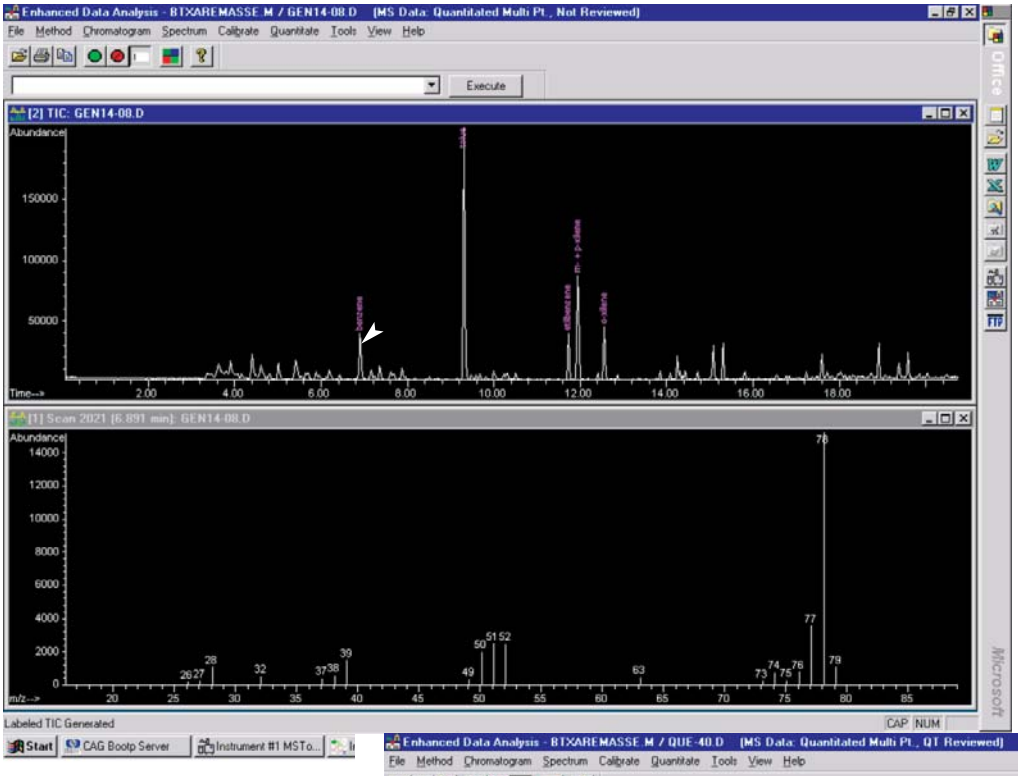
We suggest you to prepare a complete set of calibration solutions by subsequent dilutions such as they contain, for example, 8, 4, 2, 1, 0.04, 0.02 and 0.01 µg·µl^{-1} of each compound.



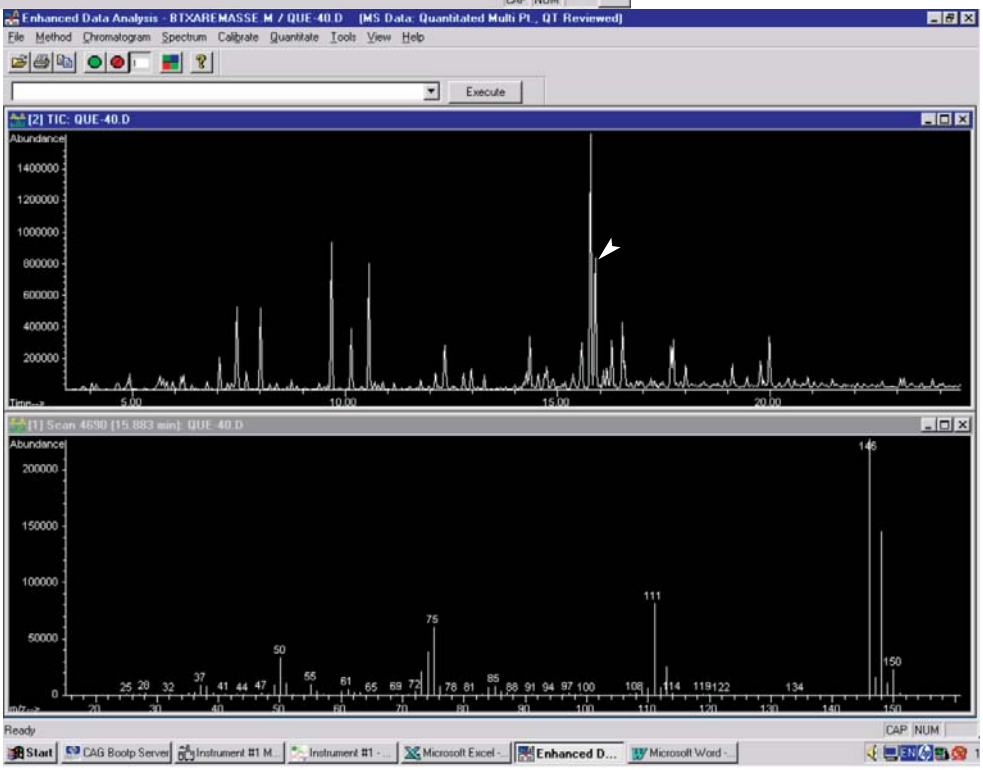
To prepare the calibration standards fit a 1/16”-1/4” Swagelock reducing connection to the GC injector by a short piece (10 cm) of wide-bore deactivated uncoated column.



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TIC chromatograms of an outdoor urban sampling (left) and of indoor air (bottom). Mass spectra of benzene and of 1,4-dichlorobenzene are shown on the bottom of each picture, at concentrations of 2.2 and 14 µg·m^{-3} respectively. Despite the low concentration values, the signal-to-noise ratio is very high in both cases.
As a consequence, very reliable mass spectral identification is possible by comparison with mass spectral data libreries with no need of further processing.



Cartridge recovery

In principle, the thermal desorption analysis leaves a conditioned cartridge that can be used as it is for another sampling. Actually this is not the case since the desorption yield, even if very high, is never quantitative, particularly for compounds with more than six carbon atoms. We recommende therefore to re-condition the cartridges after analysis, keeping them at 350 °C for eight hours under nitrogen flow.

Graphitized charcoal is a fragile material that exhibits a tendency to turn to dust under mechanical stress during the use on field and in the laboratory. Even if the stainless steel net mesh grid opening is a few micrometers, dust is lost anyway and the cartridge will eventually become empty. As soon as the mass of graphitized charcoal is reduced by 20% the cartridge has to be discarded. Basing onto our experience, this will occur after at least twenty sampling-and-analysis cycles.

radiello is patented by FONDAZIONE SALVATORE MAUGERI-IRCCS
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SKC®

Operating Instructions

863 Valley View Road, Eighty Four PA 15330 USA
Tel: 724-941-9701 Fax: 724-941-1369 e-mail: skctech@skcinc.com

Ultra II Passive Samplers
for Thermal Desorption

Introduction

SKC Ultra II Passive (diffusive) Samplers provide reliable sampling and highly sensitive detection of ppt and low ppb-level volatile organic compounds (VOCs) through thermal desorption and GC analysis.

Ultra II Samplers are packaged as empty sampler housings that the user fills with cleaned/purged sorbent provided in glass vials with Teflon®-lined caps. This method of packaging maintains low sorbent background and allows for reuse of the sorbent with care in handling.



Specifications for Ultra II

Dimensions:	1.4 in (3.5 cm) dia. x 2.5 in (6.3 cm) x 0.6 in (1.5 cm)
Sorbents:	Tenax® TA, Chromosorb® 106, Anasorb® GCB1, or Carbopack X *Sorbent is sold separately and supplied in glass vials with Teflon®-lined lids. Select the sorbent appropriate for the target compound.*
Analysis:	Thermal desorption using a 0.25-in OD (0.194-in ID) x 3.5-in L thermal desorption tube (Perkin Elmer) and gas chromatography (GC)
Shelf-life:	Sorbent must be used or repurged 30 days from date of manufacture. Store at <39.2 F (4 C).
Sampling rates:	Go to www.skcinc.com and click on "Sampling Guides." Select "Passive (Diffusive) Sampling Guide."

Preparation and Sampling

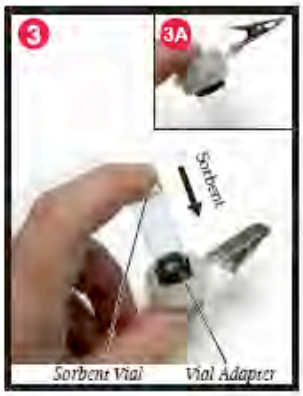
1. Open resealable pouch and remove sampler.



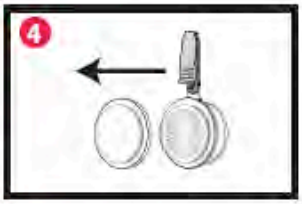
2. Write start time and sample ID number on pouch label.



3. In a clean, organic solvent-free environment, remove plug from vial adapter on back of sampler housing (side without holes). Remove lid from sorbent vial. Hold housing vial adapter down over the open end of the vial. Screw open end of vial into the adapter (*see inset 3A*). Rotate assembly until sorbent is draining from vial to sampler. Tap vial lightly before removing from adapter. Replace plug on adapter.



4. Remove cover from face of sampler housing (side with holes) immediately before sampling. Store cover for reuse. Clip sampler in the area to be sampled. Ensure diffusion holes are not covered.



5. After desired sampling period, unclip sampler and seal with cover.



6. Write stop time on pouch label.



7 In a clean, organic solvent-free environment, carefully remove plug from vial adapter on back of sampler housing. Screw open end of sorbent vial into adapter (*see inset 7A*). Rotate assembly until sorbent is draining from sampler to vial. Tap sampler lightly. Ensure all sorbent is recovered in the vial. Screw lid onto vial.



8 Mark sample vial as appropriate and insert into the pouch. Carefully package sample vial and a blank sorbent vial. Send to a laboratory for analysis.



Factors for Determining Application and Storage

Prior to purchasing Ultra II Samplers, evaluate specific compounds of interest and expected levels. A factor that should be considered is the sorbent. Polymetric sorbents such as Tenax TA can increase in background during storage. Refrigerated storage can reduce, but not eliminate off-gassing.

Storage

Before Sampling: Up to 30 days at <39.2 F (4 C) in a clean, organic solvent-free environment.

After Sampling: 21 days at <39.2 F (4 C) in a clean, organic solvent-free environment.

Analysis

1. Remove lid from vial, pour sorbent from vial into a 0.25-in OD (0.194-in ID) x 3.5-in L thermal desorption tube, and thermally desorb the sample. The Transfer Funnel accessory can facilitate the pouring process (*see Ordering*).
2. Analyze samples using a gas chromatograph (GC) with the detector specified in the method for the target compound.

The thermal desorption process automatically purges the sorbent so that it is ready for reuse. If desired, employ additional in-house purging procedures.

Validation‡

Ultra I Passive Samplers were evaluated by the U.S. Military[1, 2], OSHA Technical Center (Salt Lake)[3], Swedish researchers[4], and SKC R&D Laboratories[5, 6]. Samplers with specific sorbents were found to be suitable for 8-hr workshift sampling, 24-hr indoor air studies targeting medium-to-high boiling point compounds, and for 24-hr or 7-day sampling of benzene and 1,3-butadiene*.

Ultra Passive Samplers use the same sorbents and analysis as specified in the active method EPA TO-17. Ultra samplers provide comparable low limits of detection in the low ppb to ppt concentration range for some chemicals while offering the benefits of economy and convenience.[7]

† *Uptake rates for 1,3-butadiene were found to decline over a one-week period.*

‡ *Ultra I Samplers were used in these studies. However, Ultra II Samplers utilize the same housing and sorbents. The difference is sorbent storage. Ultra II sorbent is stored in glass vials, instead of the housing, before and after sampling to ensure low sorbent background.*

References

1. *Hendricks, W.D., et. al., Feasibility of Diffusive Sampling to Monitor U.S. Military Personnel for Exposure to Toxic Chemical Substances, OSHA, SLTC, Salt Lake City, UT, 2002.*
2. *Hendricks, W., The Marines Project: A Laboratory Study of Diffusive Sampling/Thermal Desorption/Mass Spectrometry Techniques for Monitoring Personal Exposure to Toxic Industrial Chemicals, Industrial Hygiene Division, OSHA, SLTC, Salt Lake City, UT, Apr. 2002.*
3. *Hendricks, W., Performance of SKC Ultra Passive Samplers Containing Carboxen 1016, Carbotrap Z, or Chromosorb 106 When Challenged With a Mixture Containing Twenty of OSHA SLTC's Top Solvent Analytes, Methods Development Team, Industrial Hygiene Chemistry Division, OSHA, SLTC, Salt Lake City, UT, Feb. 2003, www.osha.gov (search on "Ultra")*
4. *Strandberg, B., et. al., "Evaluation of Two Types of Diffusive Samplers and Adsorbents for Measuring 1,3-butadiene and Benzene in Air," Atm. Environ., Vol. 39, July 2005, pp. 4104-4110.*
5. *Coyne, L., et. al., Using Diffusive Samplers for Monitoring for Ppb Levels of Volatile Organic Compounds in Indoor Air, presented at AirMon 02, Lillehammer, Norway, Feb. 2002.*
6. *Coyne, L., et. al., Using Diffusive Samplers for Monitoring for Ppb Levels of Volatile Organic Compounds in Air, presented at AIHce 2002, San Diego, CA, June 2002.*
7. *SKC Update to EPA Method TO-17 available at www.skcinc.com.*

Ordering

Description	Catalog No.
Ultra II Sampler, empty housing only, packaged in reusable pouch, *requires sorbent in vial listed below*	**590-259**
Sorbent in Vial with Teflon-lined Cap *Select the sorbent appropriate for the target compound*	**Catalog No.**
Tenax TA Sorbent, 265 mg	**590-260***
Chromosorb 106 Sorbent, 285 mg	**590-261*** ∞
Anasorb GCB1 Sorbent#, 370 mg	**590-262***
Carbopack X Sorbent, 500 mg	**590-265***

* *Use within 30 days or repurge to ensure low background; storage at <39.2 F (4 C) recommended.*

\# *Comparable to Carbopack B*

∞*See Reference 3 for additional information on Chromosorb 106 sampling rates.*

Analysis Accessories	Catalog No.
Transfer Funnel, aluminum, facilitates transfer of sorbent from vial to 0.25-in OD thermal desorption tubes	**590-264**
Thermal Desorption Tube, Perkin Elmer, includes screens and end caps	**P226530**

Notice: This operating instruction may not address all safety concerns (if any) associated with this product and its use. The user is responsible for determining and following the appropriate safety and health practices and regulatory limitations (if any) before using the product. The information contained in this document should not be construed as legal advice, opinion, or as a final authority on legal or regulatory procedures.

Form # 40061 Rev 0710

Section 2. Canister Sampling

This section provides a description of air sampling canisters, practical considerations for sampling, and step-by-step instructions for collecting a grab and integrated sample. Photographs illustrate the correct way to assemble the various sampling components. Tables provide detailed information on many operational factors that ultimately influence the quality of the data obtained from a canister sample.

2.1 Introduction to Canisters

An air sampling canister is a container for collecting a whole air sample for ambient and indoor air applications. The canister is best suited for projects involving analysis of compounds in the ppbv range. However, canisters can be used for other applications such as landfill and soil gas involving analysis of compounds in the ppmv range.



A canister can be spherical or cylindrical and is constructed of stainless steel. The canister is prepared for sampling by evacuating the contents to a vacuum of approximately 29.9 inches of Mercury (in. Hg). Opening the stainless steel bellows valve allows the air sample to enter the canister. When the target volume of sample is collected, the valve is closed and the canister is returned to the laboratory.

Canisters can range in volume from less than 1 liter (L) to greater than 6 L. At Air Toxics Ltd., 6 L canisters are used for ambient air samples and for taking integrated samples. 1 L canisters are normally used for taking high concentration (i.e., greater than 5 ppbv) grab samples, although exceptions to these guidelines are common. Variations of air sampling canisters include glass bulbs, sample cylinders (or "sample bombs"), and Summa canisters. Glass bulbs are rarely used in field applications due to lack of ruggedness. Sample cylinders are DOT-approved, high pressure, thick-walled, stainless steel cylinders with a valve at each end (see Section 4.4). The remainder of this section focuses on Summa canisters.



2.1.1 Summa Canister

A Summa canister is a stainless steel container that has had the internal surfaces specially passivated using a "Summa" process. This process combines an electropolishing step with a chemical deactivation step to produce a surface that is nearly chemically inert. A Summa surface has the appearance of a mirror: bright, shiny, and smooth. The degree of chemical inertness of a whole air sample container is crucial to minimizing reactions with the sample and maximizing recovery of target compounds from the container. Air Toxics Ltd. maintains a large inventory of Summa canisters in 6 and 1 L volumes.

2.1.2 Canister Cleaning and Hold Time



Canister sampling differs considerably from collecting a water sample in a VOA vial or a soil sample in an amber jar in that the container (valued at over $450) is cleaned and reused. A canister will hold a high vacuum (i.e., greater than 25 in. Hg) for more than 30 days. Air Toxics Ltd., however, requires that our canisters be returned within 30 days.

☞ Media hold time for a canister is 30 days

Air Toxics Ltd. provides two types of canister cleaning certification, 10% and 100%, depending upon the requirements of the project. The 10% certification process is appropriate for routine ambient air applications and high concentration applications such as soil vapor and landfill gas monitoring. The 10% certification process begins by cleaning canisters using a combination of dilution, heat, and high vacuum. After completing the cleaning steps, 10% of the canisters are certified each day. Canisters are certified for approximately 60 VOCs using GC/MS by Modified EPA Method TO-15. The 10% certification process requires that target compound concentrations be below 0.2 ppbv. Alternatively, the 100% certification (i.e., individual certification) process is appropriate for ambient and indoor air applications driven by risk assessment or litigation that require pptv (parts per trillion by volume) sensitivity. Similar to the 10% certification, the 100% certification also begins with the canister cleaning process. The difference with the 100% certification is that canisters are individually certified for a client-specific list of target compounds using GC/MS by TO-15. The 100% certified canisters are shipped with analytical documentation demonstrating that they are free of the target compounds down to the project reporting limits.

☞ Specify whether your project requires 10% or 100% canister cleaning certification

Although 14 days is the most commonly cited hold time for a canister sample, the hold time is compound specific. For example, non-polar compounds such as chloroform, benzene, and vinyl chloride are stable in a canister for at least 30 days. In fact, EPA Method TO-15 states: "Fortunately, under conditions of normal usage for sampling ambient air, most VOCs can be recovered from canisters near their original concentrations for after storage times of up to thirty days". However, recovery of polar compounds such as methanol and acetone begin to drop significantly after 14 days. Analysis of these samples should be performed within 14 days.

☞ Sample hold time to analysis for a canister is 14-30 days for VOCs

2.2 Associated Canister Hardware

Associated hardware used with the canister includes the valve, brass cap, particulate filter, and vacuum gauge.

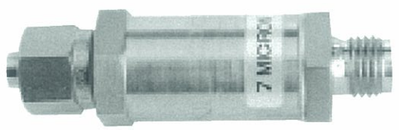
2.2.1 Valve

An industry standard, 1/4 in. stainless steel bellows valve (manufactured by Nupro) is mounted at the top of the canister. The valve allows vacuum to be maintained in the canister prior to sampling and seals off the canister once the sample has been collected. No more than a half turn by hand is required to open the valve. Do not over-tighten the valve after sampling or it may become damaged. A damaged valve can leak and possibly compromise the sample. Some canisters have a metal cage near the top to protect the valve.

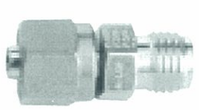
2.2.2 Brass Cap

Each canister comes with a brass cap (i.e., Swagelok 1/4 in. plug) secured to the inlet of the valve assembly. The cap serves two purposes. First, it ensures that there is no loss of vacuum due to a leaky valve or valve that is accidentally opened during handling. Second, it prevents dust and other particulate matter from fouling the valve. The cap is removed prior to sampling and replaced following sample collection.

☞ **Always replace the brass cap following canister sampling**



7 Micron



5 Micron

2.2.3 Particulate Filter

Each canister comes with a particulate filter provided separately in the packing box. The filter prevents particulate matter from fouling the valve (or flow controller) and entering the canister. Particulate filters should be cleaned between uses. Air Toxics Ltd. provides two types of particulate filters: 7 micron and 5 micron. The longer, 7 micron particulate filter is normally used with 6 L canisters and whenever an integrated sample is being collected. This device filters particulate matter greater than 7 microns in diameter and does not significantly restrict the flow rate in to the canister. Typical fill times for canisters are shown in the following table. The shorter, 5 micron particulate filter is often used to slow down grab sampling with 1 L canisters and mini-cans. This device is a fritted stainless steel disk that has been pressed into a conventional Swagelok adapter. This device filters particulate matter greater than 5 microns in diameter and has a relatively high pressure drop across the fritted disk. It restricts the flow into the canister and fill times are increased.

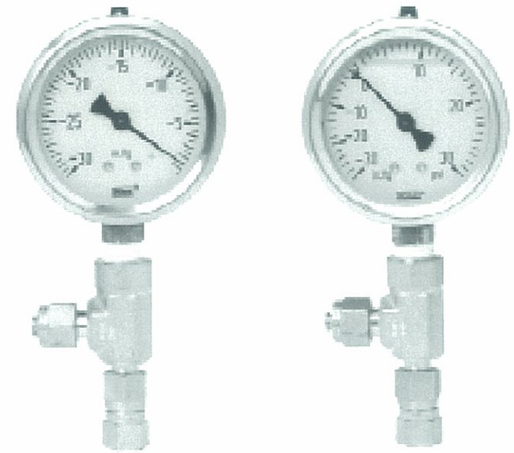
☞ **Always use the particulate filter for canister sampling**

Table 2.2.3 Fill Times for Canisters

CANISTER VOLUME	7 micron filter	5 micron filter
6 L	16 sec	23 min
1 L	3 sec	4 min
400 mL (mini-can)	1-2 sec	1 min 20 sec

2.2.4 Vacuum Gauge

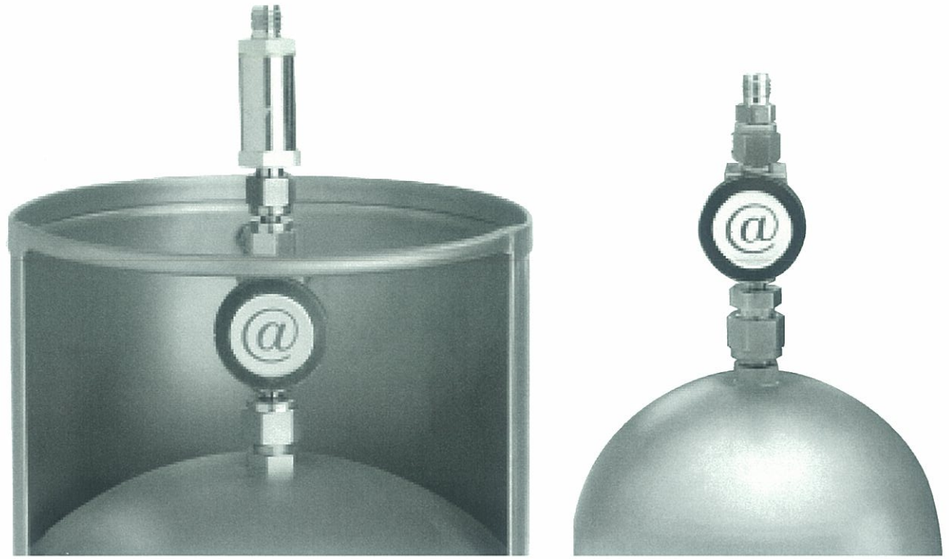
A vacuum gauge can be used to measure the initial vacuum of the canister before sampling and the final vacuum upon completion. A gauge can also be used to monitor the fill rate of the canister when collecting an integrated sample. Gauges are generally not used during the brief interval for grab sampling. Gauges are used only to provide a relative measure of "change". The accuracy of gauges provided by Air Toxics Ltd. is such that gauge-to-gauge comparisons have no merit. Individuals engaged in frequent air sampling or air projects driven by risk assessment or litigation are highly encouraged to purchase and maintain their own gauge. Upon request, Air Toxics Ltd. provides two types of gauges: vacuum gauges reading 0 to 30 in. Hg and vacuum-pressure gauges reading 30 in. Hg to 30 psig (pounds per square inch gage).



☞ **Air Toxics Ltd. provides gauges only if requested**

2.3 Grab Sampling with Canisters

There are two basic modes of canister sampling: grab and integrated. A grab sample is taken over a short interval (i.e., 1-5 minutes) while an integrated sample is taken over an extended period (e.g., 0.5-2 hours for a 1 L canister and 0.5-24 hours for a 6 L canister). In both modes the canister vacuum is used to draw sample into the canister. This is commonly referred to as passive sampling. Active sampling utilizes a pump to fill the canister. The most common hardware configuration used to take a grab sample are illustrated in the following figure. A particulate filter is used to prevent particulate matter from fouling the valve and entering the canister.



2.3.1 Considerations for Grab Sampling With Canisters

The following are some considerations for collecting a grab sample in a canister.

- **Avoid Leaks in Sampling Train**: All fittings on the sampling hardware are 1/4 in. Swagelok. A 9/16 in. crescent wrench is used to assemble the hardware. It is not necessary to over tighten the fittings; finger tight plus 1/4 turn with the wrench is adequate. In practice this should be tight enough so that the various pieces of equipment, when assembled, cannot be rotated by hand.

- **Verify Gauge Operation**: If the indicator does not read "zero" upon arrival, the gauge either needs to equilibrated or the gauge may be damaged and unusable. Equilibrate the gauge by "cracking" the rubber plug on top of the gauge. For more details on the equilibration procedure, see instructions included with the gauge or call Client Services at 800-985-5955.

- **Verify Initial Vacuum of Canister**: Prior to shipment, each canister is checked for mechanical integrity. However, it is still important to check the vacuum of the canister prior to use and record the initial vacuum on the chain-of-custody. The initial vacuum of the canister should be greater than 25 in. Hg. If the canister vacuum is less than 25 in. Hg, do not use it. Call Client Services at 800-985-5955 and arrange for a replacement canister. If sampling at altitude, there are special considerations for gauge readings and sampling (see Section 4.2). The procedure to verify the initial vacuum of a canister is simple, but unforgiving.

1. Confirm that valve is closed (knob should already be tightened clockwise)
2. Remove the brass cap
3. Attach gauge
4. Attach brass cap to side of gauge tee fitting
5. Open and close valve quickly (a few seconds)
6. Read vacuum on the gauge
7. Record gauge reading on "Initial Vacuum" column of chain-of-custody
8. Verify that canister valve is closed and remove gauge
9. Replace the brass cap

- **Leave Residual Vacuum**: A grab sample can be collected either by allowing the canister to reach ambient conditions or by leaving some residual vacuum (e.g., 5 in. Hg) in the canister. In either case, the final vacuum should be noted on the "Final Vacuum" column on the chain-of-custody. This will enable the laboratory to compare the final vacuum with the receipt vacuum (i.e., the vacuum measured upon arrival at the laboratory). If the two readings differ significantly, Client Services will contact you for instructions on how to proceed.

2.3.2 Step-by-Step Procedures for Canister Grab Sampling

These procedures are for a typical ambient air sampling application and actual field conditions and procedures may vary.

Before you get to the field:

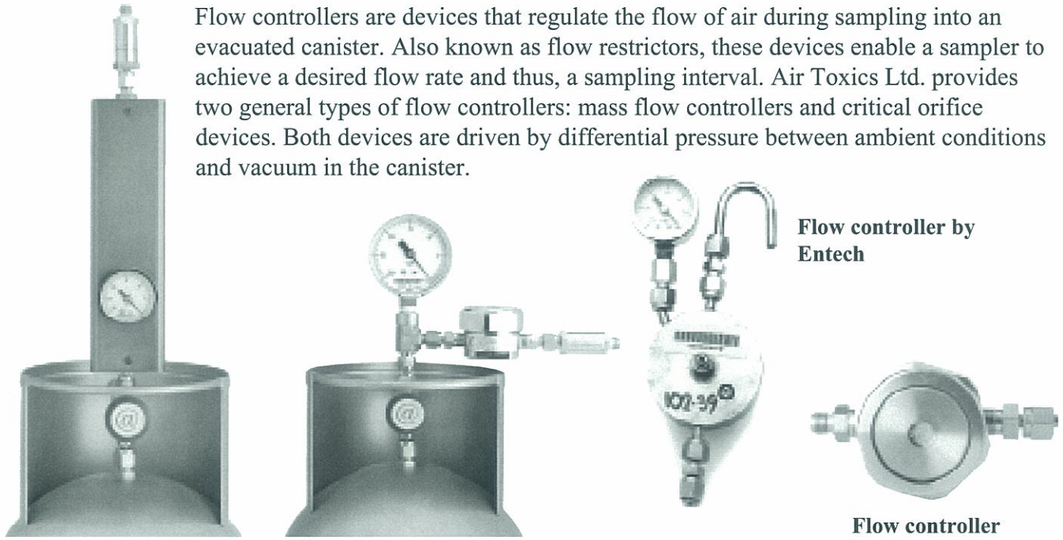
1. Verify contents of the shipped package (e.g., chain-of-custody, canister, particulate filter, and gauge – if requested)
2. Verify that gauge is working properly (see Section 2.3.1)
3. Verify and record initial vacuum of canister (see Section 2.3.1)

When ready to sample:

4. Remove brass cap
5. Attach particulate filter to canister
6. Open valve 1/2 turn (6 L canister normally takes about 16 sec to fill)
7. Close valve by hand tightening knob clockwise
8. Verify and record final vacuum of canister (repeat steps used to verify initial vacuum)
9. Replace brass cap
10. Fill out canister sample tag
11. Return canister in box provided
    - Unreturned canister charge of $450 each
12. Return sample media in packaging provided. Unreturned equipment charges:
    - $45 per particulate filter
    - $45 per gauge
13. Fill out chain-of-custody and relinquish samples properly
14. Place chain-of-custody in box and retain pink copy
15. Tape box shut and affix custody seal (if applicable) across flap
16. Ship accordingly to meet method holding times

2.4 Integrated Sampling with Canisters and Flow Controllers

An air sample collected over more than a few minutes is referred to as an integrated sample and can provide information on compound concentrations in air averaged or composited over time. An 8- or 10-hour integrated sample can be used to determine indoor air quality in the workplace. Similarly, a 24-hour integrated sample can be an economical and practical approach to determine residential exposure to indoor or outdoor air sources. The most common hardware configurations used to take an integrated sample are illustrated below.



Flow controller by Entech

Flow controller by Veriflo

Flow controllers are devices that regulate the flow of air during sampling into an evacuated canister. Also known as flow restrictors, these devices enable a sampler to achieve a desired flow rate and thus, a sampling interval. Air Toxics Ltd. provides two general types of flow controllers: mass flow controllers and critical orifice devices. Both devices are driven by differential pressure between ambient conditions and vacuum in the canister.

2.4.1 Mass Flow Controller

A mass flow controller employs a diaphragm that actively compensates to maintain a constant mass flow rate. As the differential pressure decreases, the flow rate tends to decrease and the diaphragm responds by opening up to allow more air to pass through. Mass flow controllers can be adjustable or fixed and can provide integrated samples with intervals ranging from hours to days. Air Toxics Ltd. provides a fixed mass flow controller that is calibrated at the laboratory for 24-hour sampling. Adjustable mass flow controllers have a knob that can be adjusted in the field to provide integrated samples with intervals ranging from one to 24 hours. The rugged conditions of field sampling are not usually compatible with adjustable mass flow controllers and Air Toxics Ltd. designed a more reliable flow controller based on a critical orifice design.

2.4.2 Critical Orifice Device

Air Toxics Ltd. designed a critical orifice flow restrictor to provide integrated samples with intervals from 0.5 to 8 hours. The device restricts air flow by forcing the sample to enter a capillary column of minute radius. This device is passive compared to an actively compensating diaphragm and the flow rate decreases as the driving force (differential pressure) decreases. For sampling intervals from 0.5 to

8 hours, however, the flow rate is relatively constant. The main advantages of the Air Toxics Ltd. flow restrictors are improved ruggedness and cleanliness. With no moving or adjustable parts, the Air Toxics Ltd. design is unlikely to lose its flow setting. In addition, a vacuum gauge is built in to the device to monitor sampling progress. To ensure there are no contamination issues from previous use, the capillary column is replaced before shipping to the field.



2.4.3 Sampling Interval and Flow Controller Setting

When you request canisters and flow controllers from Air Toxics Ltd., you will be asked for the sampling interval, and the flow controllers will be pre-set prior to shipment according to the table below. The flow controller is set to collect 5 L of sample over the sample interval. Final canister vacuum is targeted at 5 in. Hg. The flow rate is set at standard atmospheric conditions (approximately sea level). If the air sample is a process (pressurized or under vacuum) or is collected at elevation, the canisters will fill faster or slower depending on the sampling conditions. If you specify the pressure of the source at project set-up, we can set the flow controller accordingly. See Section 4 for a discussion of collecting a sample at elevation. The 24-hr flow controllers should not be used for process or source samples.

Table 2.4.3 Flow Rates for Selected Sampling Intervals (mL/min)

Sampling Interval (hrs)	0.5	1	2	4	8	12	24
6 L Canister	167	83.3	41.7	20.8	11.5	7.6	3.5
1 L Canister	26.6	13.3	6.7	-	-	-	-

Note: Target fill volumes for 6 L and 1 L canisters are 5,000 mL and 800 mL, respectively.

$$\text{Flow Rate(mL/min)} = \frac{\text{Target Fill Volume (mL)}}{\text{Sampling Interval (min)}}$$

2.4.4 Final Canister Vacuum and Flow Controller Performance

Ideally the final vacuum of a 6 L canister should be 5 in. Hg or greater. As long as the differential pressure is greater than 4 in. Hg ambient pressure, then the flow through the device will remain approximately constant as the canister fills. If there is insufficient differential pressure, the flow through the controller will decrease as the canister pressure approaches ambient. Because of the normal fluctuations in the flow rate (due to changes in ambient temperature, pressure, and diaphragm instabilities) during sampling, the final vacuum will range between 2 and 10 in. Hg.

- **If the residual canister vacuum is greater than 5 in. Hg** (i.e., more vacuum), the flow rate was low and less than 5 L of sample was collected. When the canister is pressurized to 5 psig prior to analysis, sample dilution will be greater than normal. This will result in elevated reporting limits.

- **If the residual canister vacuum is less than 5 in. Hg** (i.e., less vacuum), the initial flow rate was high. Once the vacuum decreases below 5 in. Hg, the flow rate begins to drop significantly. This scenario indicates that the sample is skewed in favor of the first portion of the sampling interval.

- **If the final vacuum is near ambient** (i.e., less than 1 in. Hg), there is inadequate differential pressure to drive the flow controller. The sampler cannot be certain the desired sampling interval was achieved before the canister arrived at ambient conditions. The sample could have been acquired over a 1-hour interval (which would be the case if the connection between the canister and flow controller leaked or if the flow controller malfunctioned) or a 24-hour interval. Although the actual sampling interval is uncertain, the canister still contains sample from the site.

Table 2.4.4 Relationship Between Final Canister Vacuum, Volume Sampled, and Dilution Factor (6 L Canister)

Final Vacuum (in. Hg)	0	2.5	5	7.5	10	12.5	15	17.5	20
Volume Sampled (L)	6	5.5	5	4.5	4	3.5	3	2.5	2
Dilution Factor*	1.34	1.46	1.61	1.79	2.01	2.30	2.68	3.22	4.02

* Canister pressurized to 5 psig for analysis

$$\text{Final Reporting Limit} = \text{Method Reporting Limit} \times \text{Dilution Factor (Canister Pressurization)} \times \text{Dilution Factor (Sample Concentration)}$$

$$\text{Dilution Factor (Canister Pressurization)} = \frac{\text{Pressurization for Analysis}}{\text{Receipt Vacuum}} = \frac{14.7 \text{ psig} + \text{Press. for Analysis (psig)}}{14.7 \text{ psig} \left[1 - \frac{\text{Rec. Vac. (in. Hg)}}{29.9 \text{ in. Hg}}\right]}$$

2.4.5 Considerations for Integrated Sampling with Canisters

Collecting an integrated air sample is more involved than collecting a grab sample. Sampling considerations include verifying that the media is ready, monitoring the integrated sampling progress, and avoiding contamination.

- **Avoid Leaks in the Sampling Train**: See Section 2.3.1 for instructions on how to securely assemble sampling hardware. A leak in any one of these connections means that some air will be pulled in through the leak and not through the flow controller. A final pressure near ambient is one indication that there may have been a leak.

- **Verify Initial Vacuum of Canister:** See Section 2.3.1 for instructions on verifying initial canister vacuum. If you are using an Air Toxics Ltd. critical orifice flow controller, note that you can use the built-in gauge. It is important to note both the canister and flow controller serial numbers on the chain-of-custody.

- **Monitor Integrated Sampling Progress**: It is a good idea to monitor the progress of the integrated sampling during the sampling interval. The volume of air sampled is a linear function of canister vacuum. For example, halfway (4 hours) into an 8-hour sampling interval, the canister should be half filled (2.5 L) and the gauge should read approximately 17 in. Hg. More vacuum than 17 in. Hg indicates that the canister is filling too slowly; less than 17 in. Hg and the canister is filling too quickly. If the canister is filling too slowly, a valid sample can still be collected (see Section 2.4.4). If the canister is filling too quickly because of a leak or incorrect flow controller setting, corrective action can be taken. Ensuring all connections are tight may eliminate a leak. It is possible to take an intermittent sample. The time interval need not be continuous. Eight 1-hour increments, taken by opening and closing the canister valve, will yield a valid sample.

Table 2.4.5 Gauge Readings for an 8-Hour Sampling Interval

Sampling Interval (hrs)	0	4	8
Canister Vacuum (in. Hg)	29.9	17.4	5
Volume Sampled (L)	0	2.5	5

- **Avoid Contamination**: Flow controllers should be cleaned between uses. This is normally accomplished by returning them to the laboratory. For large air sampling projects, Air Toxics Ltd. has designed a field conditioning program for 24-hour flow controllers involving a purge manifold. This arrangement provides the sampler with scheduling flexibility, inventory control, and convenience in the field. Air Toxics Ltd. will provide the 24-hour flow controllers, a purge manifold, Teflon tubing, rubber ferrules, vacuum pump, and flow meter. The sampler will need to provide the certified nitrogen cylinder and the certified high pressure regulator. Call Client Services at 800-985-5955 if you are interested in the field conditioning program.

- **Keep Sampling Train Out of Direct Sunlight**: The sampling train should be kept out of direct sunlight during sampling. There will be some flow rate drift if the temperature of the controllers is allowed to vary significantly.

2.4.6 Step-by-Step Procedures for Integrated Sampling

These procedures are for a typical ambient air sampling application and actual field conditions and procedures may vary.

Before you get to the field:

1. Verify contents of the shipped package (e.g., chain-of-custody, canister, particulate filter, and flow controller)
2. Verify initial vacuum of canister (see Section 2.3.1)

When ready to sample:

3. Remove brass cap
4. Attach flow controller to canister
5. Attach particulate filter to flow controller
6. Open valve 1/2 turn
7. Monitor integrated sampling progress periodically (see Section 2.4.5)

At end of sampling interval:

8. Verify and record final vacuum of canister (for 24-hr flow controller repeat steps used to verify initial vacuum and for critical orifice device simply read built-in gauge)
9. Close valve by hand tightening knob clockwise
10. Replace brass cap
11. Fill out canister sample tag
12. Return canisters in boxes provided
    - Unreturned canister charge of $450 each
13. Return sample media in packaging provided. Unreturned equipment charges:
    - $45 per particulate filter
    - $50-500 per flow controller
14. Fill out chain-of-custody and relinquish samples properly
15. Place chain-of-custody in box and retain pink copy
16. Tape box shut and affix custody seal (if applicable) across flap
17. Ship accordingly to meet method holding times

Section 3. Tedlar Bag Sampling

This section provides a description of Tedlar bags, practical considerations for sampling, and step-by-step instructions for collecting a grab sample. Photographs illustrate the correct way to assemble the various sampling components.



3.1 Introduction to Tedlar Bags

A Tedlar bag is a container used to collect a whole air sample for landfill gas, soil gas, and stationary source applications. The Tedlar bag is best suited for projects involving analysis of compounds in the ppmv range. However, Tedlar bags can be used for other applications such as ambient air monitoring for atmospheric/fixed gases. They can be used to collect sulfur compounds, but only if the fittings are non-metallic (e.g., polypropylene, Teflon, or Nylon).

A Tedlar bag is made of two plies of Tedlar film sealed together at the edges and features a valve that allows the interior to be filled. Sample collection requires a pressurized sampling port, a low flow rate pump, or a lung sampler. The bag expands as sample enters. When the target volume of sample is collected, the valve is closed and the Tedlar bag is returned to the laboratory. Air Toxics Ltd. maintains a limited inventory of Tedlar bags in 1 L , 3 L, and 5 L volumes.

3.1.1 Tedlar Film

Tedlar is a trade name for polyvinyl fluoride film developed by DuPont Corporation in the 1960's. This patented fluoropolymer has been used in a wide variety of applications including protective surfacing for signs, exterior wall panels, and aircraft interiors. Tedlar film is tough, yet flexible and retains its impressive mechanical properties over a wide range of temperatures (well below freezing to over 200° F). Tedlar exhibits low permeability to gases, good chemical inertness, good weathering resistance, and low off-gassing.

3.1.2 How "Active" is the Surface of a Tedlar Bag?

The surface of a Tedlar bag is a work in progress. The surface of a new bag is essentially free of VOCs at the single digit ppbv level. Compounds detected from analyzing new Tedlar bags include methylene chloride, toluene, acetone, ethanol, and 2-propanol. Note that 2-propanol has been detected in some new bags up to 45 ppbv. Once the Tedlar bag is used, however, the surface has been exposed to moisture and possibly VOCs. It may irreversibly adsorb many VOCs at the low ppbv level. A series of purges with certified gas will not remove the VOCs from the surface. $15 for a new bag is a small price to pay for peace of mind.

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APPENDIX D

Transient Model Derivation for Radial Diffusion to a Passive Soil Vapor Probe

May 2015

APPENDIX D:

Transient Model Derivation for Radial Diffusion to a Passive Soil Vapor Probe

The transient model derivation is provided below. The governing equations are:

Concentration in the gas phase within the void space $c_g(r,t)$;

$$\frac{\partial c_g}{\partial t} - D_{air}\left[\frac{\partial^2 c_g}{\partial r^2} + \frac{1}{r}\frac{\partial c_g}{\partial r}\right] = 0 \qquad 0 \le r < r_2 \tag{8}$$

Concentration in the soil vapor surrounding the void space $c_s(r,t)$;

$$\frac{\partial c_s}{\partial t} - D_{eff}\left[\frac{\partial^2 c_s}{\partial r^2} + \frac{1}{r}\frac{\partial c_s}{\partial r}\right] = 0 \qquad r_2 \le r < r_3 \tag{9}$$

with the following initial and boundary conditions:

$$c_g(r_2,t) = c_s(r_2,t) \tag{10}$$

$$c_g(r,0) = 0 \tag{11}$$

$$c_s(r,0) = c_{s_0} \tag{12}$$

$$\frac{\partial c_g}{\partial r}(r_1,t) = 0 \tag{13}$$

$$\frac{\partial c_s}{\partial r}(r_3,t) = 0 \tag{14}$$

$$D_{air}\frac{\partial c_g}{\partial r}(r_2,t) = D_{eff}\frac{\partial c_s}{\partial r}(r_2,t) \tag{15}$$

Applying the Laplace transform to Equation (8) to transform the time derivative in order to convert the partial differential equation (PDE) into an ordinary differential equation (ODE):

$$L\left[c_g(r,t)\right] = \bar{c}_g(r,p) \tag{16}$$

$$L\left[\frac{\partial c_g}{\partial t}\right] = -c_g(r,0) + p\bar{c}_g(r,p) = p\bar{c}_g(r,p) \tag{17}$$

$$D_{air}\left[\frac{\partial^2 \bar{c_g}}{\partial r^2}+\frac{1}{r}\frac{\partial \bar{c_g}}{\partial r}\right]-p\bar{c}_g=0 \tag{18}$$

where p is the Laplace transform variable and is complex-valued.

Applying the Laplace transform to Equation (9):

$$L[c_s(r,t)]=\bar{c}_s(r,p) \tag{19}$$

$$L\left[\frac{\partial c_s}{\partial t}\right]=-c_s(r,0)+p\bar{c}_s(r,p)=\ -c_{s_0}+p\bar{c}_s(r,p) \tag{20}$$

$$D_{eff}\left[\frac{\partial^2 \bar{c_s}}{\partial r^2}+\frac{1}{r}\frac{\partial \bar{c_s}}{\partial r}\right]-p\bar{c}_s=-c_{s_0} \tag{21}$$

Applying the Laplace transform to initial and boundary Equations (10), (13), (14) and (15),

$$\bar{c}_g(r_2,p)=\bar{c}_s(r_2,p) \tag{22}$$

$$L\left[\frac{\partial c_g}{\partial r}(r_1,t)\right]=\int_0^\infty \frac{\partial c_g}{\partial r}(r_1,t)\,e^{-pt}dt=\frac{\partial}{\partial r}\int_0^\infty c_g(r_1,t)\,e^{-pt}dt \tag{23}$$

$$=\frac{\partial \bar{c}_g}{\partial r}(r_1,p)=0$$

$$L\left[\frac{\partial c_s}{\partial r}(r_3,t)\right]=\frac{\partial \bar{c}_s}{\partial r}(r_3,p)=0 \tag{24}$$

$$D_{air}\frac{\partial \bar{c}_g}{\partial r}(r_2,p)=D_{eff}\frac{\partial \bar{c}_s}{\partial r}(r_2,p) \tag{25}$$

The transformed governing equation (Equation 18) is a linear, second-order homogeneous ODE that has a solution of the general form:

$$\bar{c}_c=AI_0\left(q_g r\right)+BK_0(q_g r) \tag{26}$$

where ${q_g}^2 = \left|-\frac{p}{D_{air}}\right| = \frac{p}{D_{air}}, if\ p > 0$, I_0 is the modified Bessel function I of order zero and K_0 is the modified Bessel function of K of order zero.

Differentiating $\bar{c}_g$ with respect to r, we obtain

$$\frac{\partial \bar{c}_g}{\partial r} = q_g A I_1(q_g r) - q_g B K_1(q_g r) \tag{27}$$

where I_1 is the modified Bessel function I of order one and K_1 is the modified Bessel function of K of order one. Using Equation (23),

$$q_g A I_1(q_g r_1) - q_g B K_1(q_g r_1) = 0 \tag{28}$$

$$A = \frac{B K_1(q_g r_1)}{I_1(q_g r_1)} \tag{29}$$

$$\bar{c}_c = B\left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_0(q_g r) + K_0(q_g r)\right]. \tag{30}$$

The general form solution of Equation (21) is

$$\bar{c}_s = \frac{c_{s_0}}{p} + E I_0(q_s r) + F K_0(q_s r) \tag{31}$$

where ${q_s}^2 = \frac{p}{D_s}$.

Differentiating $\bar{c}_s$ with respect to r, we obtain

$$\frac{\partial \bar{c}_s}{\partial r} = q_s E I_1(q_s r) - q_s F K_1(q_s r) \tag{32}$$

and using Equation (24),

$$q_s E I_1(q_s r_3) - q_s F K_1(q_s r_3) = 0 \tag{33}$$

$$E = \frac{FK_1(q_s r_3)}{I_1(q_s r_3)} \tag{34}$$

$$\bar{c}_s = \frac{c_{s_0}}{p} + F\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_0(q_s r) + K_0(q_s r)\right]. \tag{35}$$

In order to solve the constant F based on Equation (25), differentiate $\bar{c}_s$ with respect to r again

$$\frac{\partial \bar{c}_s}{\partial r} = Fq_s \frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_1(q_s r) - Fq_s K_1(q_s r) \tag{36}$$

and do the same to Equation (30),

$$\frac{\partial \bar{c}_g}{\partial r} = Bq_g \frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_1(q_g r) - Bq_g K_1(q_g r). \tag{37}$$

Substituting Equation (25) with the two equations above,

$$FD_s q_s\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_1(q_s r_2) - K_1(q_s r_2)\right] = BD_{air} q_g\left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_1(q_g r_2) - K_1(q_g r_2)\right] \tag{38}$$

$$F = B \underbrace{\frac{D_{air} q_g}{D_{eff} q_s}}_{\varphi_3} \underbrace{\frac{\left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_1(q_g r_2) - K_1(q_g r_2)\right]}{\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_1(q_s r_2) - K_1(q_s r_2)\right]}}_{\varphi_1 \,/\, \varphi_2}$$

$$F = B\frac{\varphi_1 \varphi_3}{\varphi_2}$$

$$\therefore \quad \bar{c}_s = \frac{c_{s_0}}{p} + B\frac{\varphi_1 \varphi_3}{\varphi_2}\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_0(q_s r) + K_0(q_s r)\right]. \tag{39}$$

In order to determine the constant B in Equation (30) and (39), Equation (22) is applied:

$$B\left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_0(q_g r_2) + K_0(q_g r_2)\right] = \frac{c_{s_0}}{p} + B\frac{\varphi_1\varphi_3}{\varphi_2}\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_0(q_s r_2) + K_0(q_s r_2)\right]$$

$$B = \frac{c_{s_0}}{p}\{\underbrace{\left[\frac{K_1(q_c r_1)}{I_1(q_c r_1)} I_0(g r_2) + K_0(q_g r_2)\right]}_{\varphi_4} - \frac{\varphi_1\varphi_3}{\varphi_2}\underbrace{\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_0(q_s r_2) + K_0(q_s r_2)\right]}_{\varphi_5}\}^{-1}$$

$$B = \frac{c_{s_0}}{p}\frac{1}{\varphi_4 - \frac{\varphi_1\varphi_3\varphi_5}{\varphi_2}} = \frac{c_{s_0}}{p}\frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5}. \tag{40}$$

Finally, arranging the constant B into the governing equations, we obtain

$$\bar{c}_g = \frac{c_{s_0}}{p}\frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5}\left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_0(q_g r) + K_0(q_g r)\right] \tag{41}$$

for $0 \le r < r_2$

$$\bar{c}_s = \frac{c_{s_0}}{p} + \kappa\frac{c_{s_0}}{p}\frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5}\frac{\varphi_1\varphi_3}{\varphi_2}\left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_0(q_s r) + K_0(q_s r)\right] \tag{42}$$

for $r_2 \le r < r_3$

To find the total mass $M(t)$ per unit area in the thin film when $r = r_2$ as a function of time, we have:

$$M(t) = D_c\int_0^t \left.\frac{\partial c_g}{\partial r}\right|_{r=r_2} \partial\tau \tag{43}$$

Therefore,

$$\bar{M}(p) = \frac{D_{air}}{p}\left.\frac{\partial \bar{c}_g}{\partial r}\right|_{r=r_2} \tag{44}$$

$$\text{or} \quad \bar{M}(p) = \frac{D_{eff}}{p} \frac{\partial \bar{c}_s}{\partial r}\Big|_{r=r_2} \tag{45}$$

Differentiating Equation (41) with respect to r,

$$\frac{\partial \bar{c}_g}{\partial r} = \frac{c_{s_0}}{p} \frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5} \left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} q_g I_1(q_g r) - q_g K_1(q_g r) \right] \tag{46}$$

And then rearranging the mass function, we obtain,

$$\begin{aligned} \bar{M}(p) &= \frac{D_{air} c_{s_0}}{p^2} q_g \frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5} \left[\frac{K_1(q_g r_1)}{I_1(q_g r_1)} I_1(q_g r_2) - K_1(q_g r_2) \right] \\ &= \frac{D_{air} c_{s_0}}{p^2} q_g \frac{\varphi_2\varphi_1}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5}. \end{aligned} \tag{47}$$

Equation (47) allows the calculation of the mass in the void space based on the mass flux across the borehole wall from the void side.

Again, differentiating Equation (42) with respect to r,

$$\frac{\partial \bar{c}_s}{\partial r} = \frac{c_{s_0}}{p} \frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5} \frac{\varphi_1\varphi_3}{\varphi_2} \left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} q_s I_1(q_s r) - q_s K_1(q_s r) \right]$$

$$\begin{aligned} \bar{M}(p) &= \frac{D_s c_{s_0}}{p^2} q_s \frac{\varphi_2}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5} \frac{\varphi_1\varphi_3}{\varphi_2} \left[\frac{K_1(q_s r_3)}{I_1(q_s r_3)} I_1(q_s r_2) - K_1(q_s r_2) \right] \\ &= \frac{D_s c_{s_0}}{p^2} q_s \frac{\varphi_2\varphi_1\varphi_3}{\varphi_2\varphi_4 - \varphi_1\varphi_3\varphi_5}. \end{aligned} \tag{48}$$

Equation (48) allows the calculation of the mass in the void space based on the mass flux across the borehole wall from the soil side.

The inverse Laplace transforms of Equation (41), (42), (47) and (48) are computed numerically using the algorithm developed by DeHoog et al.[29].

Bessel functions

The modified Bessel functions I_α and K_α used for Equations (41), (42), (47) and (48) are defined by

$$I_\alpha(x) = i^{-\alpha} J_\alpha(ix) = \sum_{m=0}^{\infty} \frac{1}{m!\,\Gamma(m+\alpha+1)} \left(\frac{x}{2}\right)^{2m+\alpha} \tag{49}$$

$$K_\alpha(x) = \frac{\pi}{2} \frac{I_{-\alpha}(x) - I_\alpha(x)}{\sin(\alpha\pi)} = \frac{\pi}{2} i^{\alpha+1} H_\alpha^{(1)}(ix) = \frac{\pi}{2} (-i)^{\alpha+1} H_\alpha^{(2)}(-ix) \tag{50}$$

The axis of symmetry at $r = r_1$ was assigned a very small radius (10^{-6} cm). The radius of the borehole or void space is assigned to be r_2. Nominal 1-inch (2.54 cm) and 4-inch (10.2 cm) diameter holes were considered because these are common for hand tools used in passive sampler deployment. The radial distance at which concentrations remain essentially unaffected throughout the passive sampling duration (r_3) was assigned to be 1 m. A smaller value for r_3 would result in a higher diffusive delivery rate of vapors from the soil to the void space. The sensitivity of this value was evaluated using the steady-state model, described below. Where needed for calculating the volume of the void space, the vertical height of the void space was assumed to be 10 cm.

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APPENDIX E

Results of Center-Point (a.k.a. ANOVA) Low Concentration Laboratory Tests

May 2015

Table E1: Temperature and Relative Humidity measured during initial Center-Point (ANOVA) Chamber Tests

ANOVA Round #1

		Chamber 1		Chamber 2	
Date	Time	Temp. °C	RH%	Temp. °C	RH%
12/18/09	952	21.3	53.3	--	--
12/18/09	1005	21.3	58.5	21.3	54.4
12/18/09	1021	--	--	20.8	58.8
12/18/09	1031	--	--	20.8	59.2
12/18/09	1107	--	--	20.8	59.9
12/18/09	1121	--	--	20.6	62.0
12/18/09	1209	--	--	20.6	59.7
12/18/09	1344	--	--	21.0	57.4
12/18/09	1407	--	--	21.3	57.5
12/18/09	1533	--	--	21.4	57.9
12/18/09	1546	--	--	21.3	58.4
12/18/09	1607	21.8	57.1	--	--
12/18/09	1629	--	--	21.2	59.1
12/18/09	1812	--	--	20.9	58.5
12/18/09	1916	--	--	20.8	57.9
12/18/09	2014	--	--	21.0	57.4
12/18/09	2020	21.0	57.6	--	--
12/19/09	826	21.6	58.2	--	--
12/19/09	1031	21.8	58.0	--	--
12/19/09	1247	21.6	58.3	21.6	58.1
12/19/09	1452	--	--	21.1	59.2
12/19/09	1657	21.3	58.8	20.9	59.4
12/20/09	810	21.8	58.4	21.4	59.6
12/20/09	1022	21.8	58.7	21.5	59.6
12/20/09	1230	21.9	58.9	21.8	59.5
12/20/09	1451	21.8	59.3	21.6	60.1
12/20/09	1654	21.5	59.4	21.4	59.7
12/20/09	1857	21.8	58.8	21.6	59.4
12/21/09	716	21.5	59.7	21.6	60.1
12/21/09	921	21.4	60.6	21.2	60.9
12/21/09	1029	21.6	59.9	21.4	60.0
12/21/09	1135	21.6	60.9	21.4	61.2
12/21/09	1230	21.9	60.4	21.7	60.7
12/21/09	1403	21.8	61.6	21.6	61.7
12/21/09	1456	22.0	60.3	21.9	60.2
12/21/09	1606	21.6	60.9	21.5	61.1
12/21/09	1726	21.7	60.7	21.5	60.9
12/21/09	1927	21.4	61.5	21.2	60.5
12/22/09	712	21.3	63.8	21.4	61.3
12/22/09	815	21.6	64.9	21.5	62.3
12/22/09	838	21.7	58.6	21.7	55.6
12/22/09	933	21.6	57.1	--	--
	Mean	21.6	59.4	21.3	59.4
	Std. Dev.	0.23	2.18	0.34	1.69
	%RSD	1.08	3.67	1.62	2.85

Both Chambers

Zero Air Flow Rate: 10.00 L·min^{-1}

Standard Flow Rate: 50.0 mL·min^{-1}

ANOVA Round #2

		Chamber 1		Chamber 2	
Date	Time	Temp. °C	RH%	Temp. °C	RH%
12/27/09	1403	21.8	59.1	--	--
12/27/09	1421	--	--	21.9	59.1
12/27/09	1457	22.0	60.0	21.6	60.7
12/27/09	1673	21.6	60.8	21.7	60.1
12/27/09	1656	21.4	61.9	21.2	61.5
12/27/09	1800	21.9	59.9	21.7	59.6
12/27/09	1910	22.0	59.6	21.6	60.6
12/27/09	2003	22.0	60.7	21.9	60.0
12/28/09	739	21.7	61.3	21.7	60.9
12/28/09	840	21.7	61.6	21.6	60.4
12/28/09	939	21.7	61.6	21.6	60.9
12/28/09	1037	21.4	61.6	21.5	60.0
12/28/09	1315	21.3	61.8	21.1	61.1
12/28/09	1433	21.4	61.1	21.3	60.3
12/28/09	1710	21.4	60.7	20.9	61.5
12/28/09	1846	21.6	61.0	21.8	60.0
12/29/09	747	21.6	61.8	21.4	62.3
12/29/09	845	22.0	61.7	22.0	61.4
12/29/09	949	21.6	62.5	21.5	62.7
12/29/09	1101	21.2	62.3	21.3	60.4
12/29/09	1202	--	--	20.8	61.9
12/29/09	1451	21.2	61.1	21.4	60.8
12/29/09	1642	20.9	63.2	20.7	63.1
12/29/09	1837	21.3	57.4	20.9	57.9
12/29/09	2220	21.7	55.7	--	--
12/30/09	814	22.0	49.9	21.8	50.1
12/30/09	921	21.7	50.6	21.7	50.6
12/30/09	1031	21.7	51.2	21.5	51.6
12/30/09	1140	21.7	62.1	21.3	62.6
12/30/09	1226	21.7	63.5	21.7	62.3
12/30/09	1247	21.7	61.6	21.3	62.0
12/30/09	1346	21.7	61.1	21.7	61.3
12/30/09	1429	21.9	66.6	21.5	67.1
12/30/09	1454	21.9	66.2	--	--
12/30/09	1533	22.0	65.8	21.4	65.1
12/30/09	1640	21.8	65.0	--	--
12/30/09	1715	--	--	21.0	64.3
12/30/09	1824	21.6	64.8	21.0	57.7
12/30/09	1844	--	--	21.1	57.8
12/30/09	1904	21.5	63.7	21.0	60.1
12/30/09	1927	21.7	59.5	21.3	56.1
12/31/09	2232	--	--	21.6	59.1
12/31/09	850	21.7	58.5	21.6	59.6
12/31/09	943	22.1	54.5	--	--
12/31/09	1012	21.7	58.6	21.5	58.1
12/31/09	1059	21.6	59.3	21.6	59.4
12/31/09	1118	21.4	60.5	21.2	60.5
12/31/09	1147	21.6	55.9	--	--
12/31/09	1248	21.8	53.3	21.6	52.7
12/31/09	1315	21.8	57.4	21.6	60.5
12/31/09	1353	22.0	64.8	21.7	65.4
	Mean	21.7	60.3	21.4	60.0
	Std. Dev.	0.3	3.8	0.3	3.5
	%RSD	1.2	6.4	1.5	5.8

Both Chambers

Zero Air Flow Rate: 10.00 L·min^{-1}

Chamber 1

Standard Flow Rate: 50.0 mL·min^{-1}

Chamber 2

Standard Flow Rate: 49.1 mL·min^{-1}

ANOVA Round #3

		Chamber 1		Chamber 2	
Date	Time	Temp. °C	RH%	Temp. °C	RH%
1/3/10	1437	21.9	56.8	21.4	57.5
1/3/10	1555	21.6	55.5	21.5	55.8
1/3/10	1626	21.7	55.4	21.6	55.3
1/3/10	1751	21.8	54.6	21.6	54.8
1/3/10	1823	21.8	56.5	21.8	57.0
1/3/10	1936	21.9	59.7	21.8	59.4
1/3/10	2033	21.9	60.6	22.0	60.6
1/4/10	1137	20.8	54.0	20.6	54.5
1/4/10	1247	21.0	58.6	20.9	59.0
1/4/10	1352	21.1	62.0	21.0	61.8
1/4/10	1425	21.6	60.8	21.2	61.8
1/4/10	1649	21.8	60.7	21.6	--
1/4/10	1738	21.4	59.5	21.2	60.9
1/4/10	1845	21.4	56.7	21.0	57.9
1/4/10	2326	--	--	21.6	62.3
1/5/10	1004	21.4	63.7	21.1	64.4
1/5/10	1047	21.5	62.2	21.5	62.1
1/5/10	1147	20.7	64.8	20.6	65.0
1/5/10	1225	20.9	63.7	20.8	63.6
1/5/10	1337	20.8	63.6	20.3	64.9
1/5/10	1438	20.9	63.0	21.0	63.0
1/5/10	1523	20.7	64.2	20.3	65.0
1/5/10	1649	21.0	63.1	21.0	63.3
1/5/10	1805	20.8	63.6	20.8	63.9
1/5/10	2255	21.5	62.9	--	--
1/6/10	1116	20.9	64.4	21.2	63.5
1/6/10	1244	21.1	63.5	20.9	63.6
1/6/10	1318	21.2	63.3	21.3	62.9
1/6/10	1428	21.1	63.2	20.6	65.3
1/6/10	1527	20.9	64.2	21.0	64.1
1/6/10	1606	21.0	64.1	20.5	65.6
1/6/10	1725	21.2	63.3	21.1	63.4
1/6/10	1806	21.0	64.0	20.9	64.1
1/6/10	2312	21.6	62.8	--	--
1/7/10	814	21.1	63.3	21.1	63.4
1/7/10	927	21.1	62.7	21.0	62.9
1/7/10	956	21.4	61.4	20.9	63.1
1/7/10	1056	21.0	63.6	20.9	63.8
1/7/10	1210	21.4	61.9	21.1	62.8
1/7/10	1326	21.0	63.5	20.9	63.6
	Mean	21.3	61.4	21.1	61.8
	Std. Dev.	0.4	3.1	0.4	3.2
	%RSD	1.7	5.1	1.9	5.1

Both Chambers

Zero Air Flow Rate: 10.00 L·min^{-1}

Chamber 1

Standard Flow Rate: 50.0 mL·min^{-1}

Chamber 2

Standard Flow Rate: 49.1 mL·min^{-1}

TABLE E2 - ACTIVE CHAMBER CONCENTRATIONS FOR CENTER-POINT (ANOVA) TESTS
ESTCP Passive Samplers

Center-Point (ANOVA) Test #1

Chamber #	Date	Time	Analyte (ppbv)									
			111-TCA	CT	Hexane	Benzene	12-DCA	TCE	PCE	124-TMB	Naphthalene	2-MEK
1	18-Dec-09	16:05	36	36	43	38	37	37	35	34	3.0	37
1	19-Dec-09	8:40	36	36	46	40	38	38	37	33	3.1	38
1	19-Dec-09	12:54	35	35	44	38	36	38	36	33	3.0	35
1	20-Dec-09	8:20	33	35	42	37	36	35	34	29	2.6	36
1	20-Dec-09	12:44	35	35	43	37	36	36	35	32	3.0	36
1	21-Dec-09	7:24	34	35	42	37	36	35	34	30	2.8	36
1	21-Dec-09	14:02	34	35	44	38	37	37	35	30	2.8	34
1	22-Dec-09	7:21	35	36	44	38	37	37	35	32	3.0	34
		Average	34.8	35.4	43.5	37.9	36.6	36.6	35.1	31.6	2.9	35.8
		Standard Deviation	1.0	0.5	1.3	1.0	0.7	1.2	1.0	1.8	0.2	1.4
		Coefficient of Variation	0.030	0.015	0.030	0.026	0.020	0.032	0.028	0.056	0.056	0.039
2	18-Dec-09	13:50	33	34	43	36	35	35	34	30	3.0	35
2	18-Dec-09	18:18	28	31	41	35	33	34	34	30	2.8	37
2	19-Dec-09	10:40	35	37	44	39	37	38	36	34	3.1	36
2	19-Dec-09	15:03	34	36	43	37	36	36	34	30	2.7	35
2	20-Dec-09	10:31	35	36	44	38	37	38	37	34	3.1	35
2	20-Dec-09	14:57	35	36	44	38	37	37	35	31	2.9	34
2	21-Dec-09	10:32	36	37	44	39	38	37	36	32	2.9	38
2	21-Dec-09	17:30	34	35	43	38	37	36	35	31	2.8	35
		Average	33.8	35.3	43.3	37.5	36.3	36.4	35.1	31.5	2.9	35.6
		Standard Deviation	2.5	2.0	1.0	1.4	1.6	1.4	1.1	1.7	0.1	1.3
		Coefficient of Variation	0.074	0.056	0.024	0.038	0.044	0.039	0.032	0.054	0.050	0.037

TABLE E2 - ACTIVE CHAMBER CONCENTRATIONS FOR CENTER-POINT (ANOVA) TESTS
ESTCP Passive Samplers

Center-Point (ANOVA) Test #2

Chamber #	Date	Time	Analyte (ppbv)									
			111-TCA	CT	Hexane	Benzene	12-DCA	TCE	PCE	124-TMB	Naphthalene	2-MEK
1	27-Dec-09	14:45	37	40	56	43	38	41	40	40	3.5	35
1	28-Dec-09	7:50	36	38	51	40	35	37	38	36	3.2	32
1	28-Dec-09	14:28	34	36	52	40	35	38	38	36	3.2	34
1	29-Dec-09	8:01	36	38	51	40	35	38	37	36	3.3	34
1	29-Dec-09	14:35	31	33	52	39	35	39	38	36	3.2	38
1	30-Dec-09	8:27	38	40	52	41	37	38	38	38	3.4	33
1	30-Dec-09	13:51	38	39	51	40	36	37	37	34	3.0	33
1	31-Dec-09	11:01	38	39	52	40	36	37	37	34	3.0	34
		Average	36.0	37.9	52.1	40.4	35.9	38.1	37.9	36.3	3.2	34.1
		Standard Deviation	2.4	2.4	1.6	1.2	1.1	1.4	1.0	2.0	0.2	1.8
		Coefficient of Variation	0.068	0.062	0.032	0.029	0.031	0.036	0.026	0.055	0.054	0.053
2	27-Dec-09	18:05	37	39	54	42	37	40	38	38	3.4	34
2	28-Dec-09	11:31	34	36	50	39	34	36	36	33	2.9	33
2	28-Dec-09	16:31	35	37	50	39	35	38	37	34	3.0	32
2	29-Dec-09	11:01	37	38	52	40	36	38	38	38	3.4	35
2	29-Dec-09	16:38	36	37	50	39	34	36	34	34	3.0	32
2	30-Dec-09	10:55	36	38	50	40	35	36	36	33	2.9	31
2	30-Dec-09	16:08	38	38	53	41	37	39	39	36	3.3	35
2	31-Dec-09	8:58	38	39	52	40	36	38	37	34	3.1	34
		Average	36.4	37.8	51.4	40.0	35.5	37.6	36.9	35.0	3.1	33.3
		Standard Deviation	1.4	1.0	1.6	1.1	1.2	1.5	1.6	2.1	0.2	1.5
		Coefficient of Variation	0.039	0.027	0.031	0.027	0.034	0.040	0.042	0.059	0.068	0.045

TABLE E2 - ACTIVE CHAMBER CONCENTRATIONS FOR CENTER-POINT (ANOVA) TESTS
ESTCP Passive Samplers

Center-Point (ANOVA) Test #3

Chamber #	Date	Time	Analyte (ppbv)									
			111-TCA	CT	Hexane	Benzene	12-DCA	TCE	PCE	124-TMB	Naphthalene	2-MEK
1	3-Jan-10	14:35	35	36	56	44	37	40	37	34	3.1	36
1	4-Jan-10	11:50	34	36	52	41	35	36	34	32	2.9	33
1	4-Jan-10	16:35	35	35	53	41	35	36	34	30	2.8	34
1	5-Jan-10	12:30	37	37	55	43	37	37	36	33	3.0	32
1	6-Jan-10	11:20	34	34	52	41	36	36	34	31	2.8	34
1	6-Jan-10	15:27	40	42	56	44	39	38	37	32	3.0	37
1	7-Jan-10	10:26	36	39	54	42	36	38	37	33	3.0	39
		Average	35.9	37.0	54.0	42.3	36.4	37.3	35.6	32.1	2.9	35.0
		Standard Deviation	2.1	2.7	1.7	1.4	1.4	1.5	1.5	1.3	0.1	2.4
		Coefficient of Variation	0.059	0.073	0.032	0.033	0.038	0.040	0.043	0.042	0.039	0.070
2	3-Jan-10	16:41	36	37	55	43	36	38	36	32	3.0	35
2	4-Jan-10	13:54	34	36	53	42	35	37	35	33	3.1	33
2	5-Jan-10	10:26	36	36	53	42	36	36	35	34	3.1	32
2	5-Jan-10	14:40	34	34	53	41	36	37	36	33	3.0	32
2	6-Jan-10	13:22	37	38	54	43	37	38	37	34	3.1	34
2	7-Jan-10	8:21	36	36	55	43	38	38	36	33	3.0	36
		Average	35.5	36.2	53.8	42.3	36.3	37.3	35.8	33.2	3.1	33.7
		Standard Deviation	1.2	1.3	1.0	0.8	1.0	0.8	0.8	0.8	0.1	1.6
		Coefficient of Variation	0.034	0.037	0.018	0.019	0.028	0.022	0.021	0.023	0.018	0.049

APPENDIX TABLE E3A
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
WMS SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
1	PS-D11	2-butanone (MEK)	50	1060	5760	1.25	72.12	147	49.4
	Chamber 1	n-hexane	50	1600	5760	1.31	86.18	212	59.5
		1,2-dichloroethane	50	2640	5760	2.58	98.96	178	43.4
		1,1,1-trichloroethane	50	2040	5760	1.27	133.41	279	50.6
		Benzene	50	1870	5760	2.15	78.12	151	46.7
		Carbon Tetrachloride	50	2740	5760	1.50	143.82	317	53.3
		Trichlorothene	50	4390	5760	3.28	131.39	232	42.8
		Tetrachloroethene	50	6500	5760	5.35	165.83	211	30.8
		1,2,4-Trimethylbenzene	50	8140	5760	12.5	120.19	113	22.7
		Naphthalene	50	1400	5760	25.6	128.17	9.49	1.8
	PS-D12	2-butanone (MEK)	50	1100	5760	1.25	72.12	153	51.2
	Chamber 2	n-hexane	50	1620	5760	1.31	86.18	215	60.2
		1,2-dichloroethane	50	2680	5760	2.58	98.96	180	44.0
		1,1,1-trichloroethane	50	2070	5760	1.27	133.41	283	51.2
		Benzene	50	1960	5760	2.15	78.12	158	48.9
		Carbon Tetrachloride	50	2770	5760	1.50	143.82	321	53.9
		Trichlorothene	50	4620	5760	3.28	131.39	245	45.0
		Tetrachloroethene	50	6990	5760	5.35	165.83	227	33.0
		1,2,4-Trimethylbenzene	50	9290	5760	12.5	120.19	129	25.9
		Naphthalene	50	1470	5760	25.6	128.17	9.97	1.9
	PS-D13	2-butanone (MEK)	50	1130	5760	1.25	72.12	157	52.6
	Chamber 1	n-hexane	50	1730	5760	1.31	86.18	229	64.3
		1,2-dichloroethane	50	2740	5760	2.58	98.96	184	45.1
		1,1,1-trichloroethane	50	2140	5760	1.27	133.41	293	53.0
		Benzene	50	2040	5760	2.15	78.12	165	51.0
		Carbon Tetrachloride	50	2850	5760	1.50	143.82	330	55.5
		Trichlorothene	50	4750	5760	3.28	131.39	251	46.3
		Tetrachloroethene	50	7170	5760	5.35	165.83	233	33.9
		1,2,4-Trimethylbenzene	50	8490	5760	12.5	120.19	118	23.7
		Naphthalene	50	1420	5760	25.6	128.17	9.63	1.8
	PS-D14	2-butanone (MEK)	50	1070	5760	1.25	72.12	149	49.8
	Chamber 2	n-hexane	50	1630	5760	1.31	86.18	216	60.6
		1,2-dichloroethane	50	2600	5760	2.58	98.96	175	42.7
		1,1,1-trichloroethane	50	2020	5760	1.27	133.41	276	50.0
		Benzene	50	1940	5760	2.15	78.12	157	48.4
		Carbon Tetrachloride	50	2710	5760	1.50	143.82	314	52.7
		Trichlorothene	50	4590	5760	3.28	131.39	243	44.7
		Tetrachloroethene	50	7130	5760	5.35	165.83	231	33.7
		1,2,4-Trimethylbenzene	50	8700	5760	12.5	120.19	121	24.3
		Naphthalene	50	1690	5760	25.6	128.17	11.46	2.2
	PS-D15	2-butanone (MEK)	50	1130	5760	1.25	72.12	157	52.6
	Chamber 1	n-hexane	50	1720	5760	1.31	86.18	228	64.0
		1,2-dichloroethane	50	2670	5760	2.58	98.96	180	43.9
		1,1,1-trichloroethane	50	2120	5760	1.27	133.41	290	52.5
		Benzene	50	2000	5760	2.15	78.12	161	50.0
		Carbon Tetrachloride	50	2810	5760	1.50	143.82	325	54.7
		Trichlorothene	50	4630	5760	3.28	131.39	245	45.1
		Tetrachloroethene	50	6960	5760	5.35	165.83	226	32.9
		1,2,4-Trimethylbenzene	50	8440	5760	12.5	120.19	117	23.6
		Naphthalene	50	1530	5760	25.6	128.17	10.38	2.0
	PS-D16	2-butanone (MEK)	50	1120	5760	1.25	72.12	156	52.1
	Chamber 2	n-hexane	50	1620	5760	1.31	86.18	215	60.2
		1,2-dichloroethane	50	2670	5760	2.58	98.96	180	43.9
		1,1,1-trichloroethane	50	2050	5760	1.27	133.41	280	50.7
		Benzene	50	1980	5760	2.15	78.12	160	49.4
		Carbon Tetrachloride	50	2750	5760	1.50	143.82	318	53.5
		Trichlorothene	50	4680	5760	3.28	131.39	248	45.5
		Tetrachloroethene	50	7580	5760	5.35	165.83	246	35.8
		1,2,4-Trimethylbenzene	50	9200	5760	12.5	120.19	128	25.7
		Naphthalene	50	1570	5760	25.6	128.17	10.65	2.0

APPENDIX TABLE E3A
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
WMS SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
2	PS-D01	2-butanone (MEK)	50	1160	5760	1.25	72.12	161	54.0
		n-hexane	50	1050	5760	1.31	86.18	139	39.0
		1,2-dichloroethane	50	2420	5760	2.58	98.96	163	39.8
		1,1,1-trichloroethane	50	1860	5760	1.27	133.41	254	46.0
		Benzene	50	1850	5760	2.15	78.12	149	46.2
		Carbon Tetrachloride	50	2490	5760	1.50	143.82	288	48.4
		Trichlorothene	50	3880	5760	3.28	131.39	205	37.8
		Tetrachloroethene	50	7510	5760	5.35	165.83	244	35.5
		1,2,4-Trimethylbenzene	50	8850	5760	12.5	120.19	123	24.7
		Naphthalene	50	945	5760	25.6	128.17	6.41	1.2
	PS-D02	2-butanone (MEK)	50	1190	5760	1.25	72.12	165	55.3
		n-hexane	50	1000	5760	1.31	86.18	133	37.1
		1,2-dichloroethane	50	2440	5760	2.58	98.96	164	40.1
		1,1,1-trichloroethane	50	1880	5760	1.27	133.41	257	46.5
		Benzene	50	1860	5760	2.15	78.12	150	46.4
		Carbon Tetrachloride	50	2510	5760	1.50	143.82	291	48.8
		Trichlorothene	50	3920	5760	3.28	131.39	207	38.1
		Tetrachloroethene	50	8950	5760	5.35	165.83	290	42.3
		1,2,4-Trimethylbenzene	50	10900	5760	12.5	120.19	151	30.4
		Naphthalene	50	1150	5760	25.6	128.17	7.80	1.5
	PS-D03	2-butanone (MEK)	50	1170	5760	1.25	72.12	163	54.4
		n-hexane	50	1040	5760	1.31	86.18	138	38.6
		1,2-dichloroethane	50	2430	5760	2.58	98.96	164	39.9
		1,1,1-trichloroethane	50	1860	5760	1.27	133.41	254	46.0
		Benzene	50	1850	5760	2.15	78.12	149	46.2
		Carbon Tetrachloride	50	2480	5760	1.50	143.82	287	48.2
		Trichlorothene	50	3890	5760	3.28	131.39	206	37.9
		Tetrachloroethene	50	7740	5760	5.35	165.83	251	36.6
		1,2,4-Trimethylbenzene	50	9070	5760	12.5	120.19	126	25.3
		Naphthalene	50	979	5760	25.6	128.17	6.64	1.3
	PS-D04	2-butanone (MEK)	50	1160	5760	1.25	72.12	161	53.9
		n-hexane	50	996	5760	1.31	86.18	132	37.0
		1,2-dichloroethane	50	2400	5760	2.58	98.96	161	39.4
		1,1,1-trichloroethane	50	1840	5760	1.27	133.41	252	45.5
		Benzene	50	1820	5760	2.15	78.12	147	45.4
		Carbon Tetrachloride	50	2440	5760	1.50	143.82	282	47.4
		Trichlorothene	50	3810	5760	3.28	131.39	202	37.1
		Tetrachloroethene	50	7370	5760	5.35	165.83	239	34.8
		1,2,4-Trimethylbenzene	50	8960	5760	12.5	120.19	124	25.0
		Naphthalene	50	929	5760	25.6	128.17	6.30	1.2
	PS-D05	2-butanone (MEK)	50	1190	5760	1.25	72.12	165	55.4
		n-hexane	50	1060	5760	1.31	86.18	140	39.4
		1,2-dichloroethane	50	2490	5760	2.58	98.96	168	40.9
		1,1,1-trichloroethane	50	1920	5760	1.27	133.41	262	47.5
		Benzene	50	1880	5760	2.15	78.12	152	46.9
		Carbon Tetrachloride	50	2540	5760	1.50	143.82	294	49.4
		Trichlorothene	50	3920	5760	3.28	131.39	207	38.2
		Tetrachloroethene	50	7610	5760	5.35	165.83	247	36.0
		1,2,4-Trimethylbenzene	50	8710	5760	12.5	120.19	121	24.3
		Naphthalene	50	887	5760	25.6	128.17	6.02	1.1
	PS-D06	2-butanone (MEK)	50	1320	5760	1.25	72.12	183	61.4
		n-hexane	50	1130	5760	1.31	86.18	150	42.0
		1,2-dichloroethane	50	2660	5760	2.58	98.96	179	43.7
		1,1,1-trichloroethane	50	2090	5760	1.27	133.41	286	51.7
		Benzene	50	2050	5760	2.15	78.12	166	51.2
		Carbon Tetrachloride	50	2760	5760	1.50	143.82	319	53.6
		Trichlorothene	50	4210	5760	3.28	131.39	223	40.9
		Tetrachloroethene	50	8070	5760	5.35	165.83	262	38.1
		1,2,4-Trimethylbenzene	50	8900	5760	12.5	120.19	124	24.8
		Naphthalene	50	925	5760	25.6	128.17	6.27	1.2

APPENDIX TABLE E3A
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
WMS SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
3	PS-C41	2-butanone (MEK)	50	1160	5760	1.25	72.12	161	54.0
		n-hexane	50	961	5760	1.31	86.18	127	35.8
		1,2-dichloroethane	50	2350	5760	2.58	98.96	158	38.7
		1,1,1-trichloroethane	50	1780	5760	1.27	133.41	243	44.1
		Benzene	50	1750	5760	2.15	78.12	141	43.8
		Carbon Tetrachloride	50	2400	5760	1.50	143.82	278	46.7
		Trichlorothene	50	3680	5760	3.28	131.39	195	35.9
		Tetrachloroethene	50	7310	5760	5.35	165.83	237	34.6
		1,2,4-Trimethylbenzene	50	8170	5760	12.5	120.19	113	22.8
		Naphthalene	50	870	5760	25.6	128.17	5.90	1.1
	PS-C42	2-butanone (MEK)	50	1150	5760	1.25	72.12	160	53.5
		n-hexane	50	1060	5760	1.31	86.18	140	39.4
		1,2-dichloroethane	50	2420	5760	2.58	98.96	163	39.8
		1,1,1-trichloroethane	50	1860	5760	1.27	133.41	254	46.1
		Benzene	50	1830	5760	2.15	78.12	148	45.7
		Carbon Tetrachloride	50	2500	5760	1.50	143.82	289	48.6
		Trichlorothene	50	3860	5760	3.28	131.39	204	37.6
		Tetrachloroethene	50	7870	5760	5.35	165.83	255	37.2
		1,2,4-Trimethylbenzene	50	9080	5760	12.5	120.19	126	25.4
		Naphthalene	50	895	5760	25.6	128.17	6.07	1.1
	PS-C43	2-butanone (MEK)	50	1200	5760	1.25	72.12	167	55.9
		n-hexane	50	1020	5760	1.31	86.18	135	37.9
		1,2-dichloroethane	50	2510	5760	2.58	98.96	169	41.3
		1,1,1-trichloroethane	50	1920	5760	1.27	133.41	262	47.6
		Benzene	50	1910	5760	2.15	78.12	154	47.8
		Carbon Tetrachloride	50	2580	5760	1.50	143.82	299	50.2
		Trichlorothene	50	4080	5760	3.28	131.39	216	39.8
		Tetrachloroethene	50	8150	5760	5.35	165.83	264	38.6
		1,2,4-Trimethylbenzene	50	9640	5760	12.5	120.19	134	26.9
		Naphthalene	50	996	5760	25.6	128.17	6.75	1.3
	PS-C44	2-butanone (MEK)	50	1240	5760	1.25	72.12	172	57.7
		n-hexane	50	1130	5760	1.31	86.18	150	42.0
		1,2-dichloroethane	50	2600	5760	2.58	98.96	175	42.7
		1,1,1-trichloroethane	50	2030	5760	1.27	133.41	278	50.3
		Benzene	50	2020	5760	2.15	78.12	163	50.5
		Carbon Tetrachloride	50	2740	5760	1.50	143.82	317	53.3
		Trichlorothene	50	4230	5760	3.28	131.39	224	41.2
		Tetrachloroethene	50	8320	5760	5.35	165.83	270	39.3
		1,2,4-Trimethylbenzene	50	9740	5760	12.5	120.19	135	27.2
		Naphthalene	50	950	5760	25.6	128.17	6.44	1.2
	PS-C45	2-butanone (MEK)	50	1230	5760	1.25	72.12	171	57.3
		n-hexane	50	1060	5760	1.31	86.18	140	39.4
		1,2-dichloroethane	50	2520	5760	2.58	98.96	170	41.5
		1,1,1-trichloroethane	50	1950	5760	1.27	133.41	267	48.3
		Benzene	50	1950	5760	2.15	78.12	157	48.8
		Carbon Tetrachloride	50	2610	5760	1.50	143.82	302	50.8
		Trichlorothene	50	4100	5760	3.28	131.39	217	40.0
		Tetrachloroethene	50	7730	5760	5.35	165.83	251	36.6
		1,2,4-Trimethylbenzene	50	8900	5760	12.5	120.19	124	24.9
		Naphthalene	50	962	5760	25.6	128.17	6.52	1.2
	PS-C48	2-butanone (MEK)	50	1170	5760	1.25	72.12	163	54.5
		n-hexane	50	1010	5760	1.31	86.18	134	37.5
		1,2-dichloroethane	50	2430	5760	2.58	98.96	164	39.9
		1,1,1-trichloroethane	50	1870	5760	1.27	133.41	256	46.3
		Benzene	50	1890	5760	2.15	78.12	153	47.2
		Carbon Tetrachloride	50	2520	5760	1.50	143.82	292	49.0
		Trichlorothene	50	3990	5760	3.28	131.39	211	38.8
		Tetrachloroethene	50	7160	5760	5.35	165.83	232	33.9
		1,2,4-Trimethylbenzene	50	8320	5760	12.5	120.19	116	23.2
		Naphthalene	50	862	5760	25.6	128.17	5.85	1.1

APPENDIX TABLE E3A
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
WMS SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								($\mu g/m^3$)	(ppbv)
--	PS-D08	2-butanone (MEK)	50		5760	1.25	72.12	0	0.0
		n-hexane	50	140	5760	1.31	86.18	19	5.3
	Trip	1,2-dichloroethane	50		5760	2.58	98.96	0	0.0
	blank	1,1,1-trichloroethane	50		5760	1.27	133.41	0	0.0
		Benzene	50		5760	2.15	78.12	0	0.0
		Carbon Tetrachloride	50		5760	1.50	143.82	0	0.0
		Trichlorothene	50		5760	3.28	131.39	0	0.0
		Tetrachloroethene	50		5760	5.35	165.83	0	0.0
		1,2,4-Trimethylbenzene	50		5760	12.5	120.19	0	0.0
		Naphthalene	50		5760	25.6	128.17	0.00	0.00

Notes:

ng - nanograms
min - minutes
mL/min - millilitres per minute
g/mol - grams per mole
$\mu g/m^3$ - micrograms per cubic metre
ppbv - parts per billion

APPENDIX TABLE E3B
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
ATD TENAX SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler ID	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
1	Chamber 1 TenaxTA (1)	1,1,1-trichloroethane	20	310	5760	0.5	133.41	108	19.5
		Carbon Tetrachloride	20	370	5760	0.5	143.82	128	21.6
		n-hexane	50	250	5760	0.5	86.18	87	24.4
		Benzene	20	240	5760	0.35	78.12	119	36.9
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.1
		Trichlorothene	20	350	5760	0.41	131.39	148	27.3
		Tetrachloroethene	20	490	5760	0.5	165.83	170	24.8
		1,2,4-Trimethylbenzene	50	370	5760	0.62	120.19	104	20.8
		Naphthalene	20	42	5760	0.5	128.17	14.58	2.8
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.5
	Chamber 1 TenaxTA (2)	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.2
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.9
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.1
		Trichlorothene	20	360	5760	0.41	131.39	152	28.1
		Tetrachloroethene	20	510	5760	0.5	165.83	177	25.8
		1,2,4-Trimethylbenzene	50	400	5760	0.62	120.19	112	22.5
		Naphthalene	20	47	5760	0.5	128.17	16.32	3.1
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.5
	Chamber 1 TenaxTA (3)	1,1,1-trichloroethane	20	310	5760	0.5	133.41	108	19.5
		Carbon Tetrachloride	20	370	5760	0.5	143.82	128	21.6
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.9
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.1
		Trichlorothene	20	360	5760	0.41	131.39	152	28.1
		Tetrachloroethene	20	520	5760	0.5	165.83	181	26.3
		1,2,4-Trimethylbenzene	50	410	5760	0.62	120.19	115	23.1
		Naphthalene	20	46	5760	0.5	128.17	15.97	3.0
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.5
	Chamber 2 TenaxTA (1)	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.2
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.8
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	360	5760	0.41	131.39	152	28.0
		Tetrachloroethene	20	530	5760	0.5	165.83	184	26.8
		1,2,4-Trimethylbenzene	50	420	5760	0.62	120.19	118	23.6
		Naphthalene	20	50	5760	0.5	128.17	17.36	3.3
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4
	Chamber 2 TenaxTA (2)	1,1,1-trichloroethane	20	330	5760	0.5	133.41	115	20.8
		Carbon Tetrachloride	20	390	5760	0.5	143.82	135	22.7
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	250	5760	0.35	78.12	124	38.4
		1,2-dichloroethane	20	270	5760	0.5	98.96	94	22.9
		Trichlorothene	20	380	5760	0.41	131.39	161	29.6
		Tetrachloroethene	20	540	5760	0.5	165.83	188	27.3
		1,2,4-Trimethylbenzene	50	440	5760	0.62	120.19	123	24.8
		Naphthalene	20	50	5760	0.5	128.17	17.36	3.3
		2-butanone (MEK)	20	220	5760	0.5	72.12	76	25.6
	Chamber 2 TenaxTA (3)	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.2
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.8
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	360	5760	0.41	131.39	152	28.0
		Tetrachloroethene	20	510	5760	0.5	165.83	177	25.8
		1,2,4-Trimethylbenzene	50	400	5760	0.62	120.19	112	22.5
		Naphthalene	20	45	5760	0.5	128.17	15.63	2.9
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4

APPENDIX TABLE E3B
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
ATD TENAX SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler ID	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
2	Chamber 1 TenaxTA	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.2
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.9
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.1
		Trichlorothene	20	360	5760	0.41	131.39	152	28.1
		Tetrachloroethene	20	500	5760	0.5	165.83	174	25.3
		1,2,4-Trimethylbenzene	50	370	5760	0.62	120.19	104	20.9
		Naphthalene	20	42	5760	0.5	128.17	14.58	2.8
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.5
	Chamber 1 TenaxTA	1,1,1-trichloroethane	20	310	5760	0.5	133.41	108	19.5
		Carbon Tetrachloride	20	360	5760	0.5	143.82	125	21.0
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.9
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	360	5760	0.41	131.39	152	28.1
		Tetrachloroethene	20	510	5760	0.5	165.83	177	25.8
		1,2,4-Trimethylbenzene	50	410	5760	0.62	120.19	115	23.1
		Naphthalene	20	47	5760	0.5	128.17	16.32	3.1
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.5
	Chamber 1 TenaxTA	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.2
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.9
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.1
		Trichlorothene	20	360	5760	0.41	131.39	152	28.1
		Tetrachloroethene	20	510	5760	0.5	165.83	177	25.8
		1,2,4-Trimethylbenzene	50	420	5760	0.62	120.19	118	23.7
		Naphthalene	20	48	5760	0.5	128.17	16.67	3.1
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.5
	Chamber 2 TenaxTA	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.2
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.8
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	370	5760	0.41	131.39	157	28.8
		Tetrachloroethene	20	520	5760	0.5	165.83	181	26.3
		1,2,4-Trimethylbenzene	50	420	5760	0.62	120.19	118	23.6
		Naphthalene	20	48	5760	0.5	128.17	16.67	3.1
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4
	Chamber 2 TenaxTA	1,1,1-trichloroethane	20	340	5760	0.5	133.41	118	21.4
		Carbon Tetrachloride	20	400	5760	0.5	143.82	139	23.3
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	250	5760	0.35	78.12	124	38.4
		1,2-dichloroethane	20	270	5760	0.5	98.96	94	22.9
		Trichlorothene	20	370	5760	0.41	131.39	157	28.8
		Tetrachloroethene	20	520	5760	0.5	165.83	181	26.3
		1,2,4-Trimethylbenzene	50	400	5760	0.62	120.19	112	22.5
		Naphthalene	20	47	5760	0.5	128.17	16.32	3.1
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4
	Chamber 2 TenaxTA	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	390	5760	0.5	143.82	135	22.8
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.8
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	360	5760	0.41	131.39	152	28.0
		Tetrachloroethene	20	530	5760	0.5	165.83	184	26.8
		1,2,4-Trimethylbenzene	50	400	5760	0.62	120.19	112	22.5
		Naphthalene	20	46	5760	0.5	128.17	15.97	3.0
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4

APPENDIX TABLE E3B
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
ATD TENAX SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler ID	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
3	Chamber 1 TenaxTA	1,1,1-trichloroethane	20	330	5760	0.5	133.41	115	20.8
		Carbon Tetrachloride	20	400	5760	0.5	143.82	139	23.3
		n-hexane	50	250	5760	0.5	86.18	87	24.3
		Benzene	20	230	5760	0.35	78.12	114	35.3
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	340	5760	0.41	131.39	144	26.5
		Tetrachloroethene	20	490	5760	0.5	165.83	170	24.8
		1,2,4-Trimethylbenzene	50	400	5760	0.62	120.19	112	22.5
		Naphthalene	20	48	5760	0.5	128.17	16.67	3.1
		2-butanone (MEK)	20	200	5760	0.5	72.12	69	23.3
	Chamber 1 TenaxTA	1,1,1-trichloroethane	20	310	5760	0.5	133.41	108	19.5
		Carbon Tetrachloride	20	360	5760	0.5	143.82	125	21.0
		n-hexane	50	250	5760	0.5	86.18	87	24.3
		Benzene	20	230	5760	0.35	78.12	114	35.3
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	350	5760	0.41	131.39	148	27.3
		Tetrachloroethene	20	490	5760	0.5	165.83	170	24.8
		1,2,4-Trimethylbenzene	50	390	5760	0.62	120.19	109	22.0
		Naphthalene	20	46	5760	0.5	128.17	15.97	3.0
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4
	Chamber 1 TenaxTA	1,1,1-trichloroethane	20	330	5760	0.5	133.41	115	20.8
		Carbon Tetrachloride	20	400	5760	0.5	143.82	139	23.3
		n-hexane	50	250	5760	0.5	86.18	87	24.3
		Benzene	20	230	5760	0.35	78.12	114	35.3
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	360	5760	0.41	131.39	152	28.0
		Tetrachloroethene	20	510	5760	0.5	165.83	177	25.8
		1,2,4-Trimethylbenzene	50	420	5760	0.62	120.19	118	23.6
		Naphthalene	20	50	5760	0.5	128.17	17.36	3.3
		2-butanone (MEK)	20	200	5760	0.5	72.12	69	23.3
	Chamber 2 TenaxTA	1,1,1-trichloroethane	20	310	5760	0.5	133.41	108	19.5
		Carbon Tetrachloride	20	380	5760	0.5	143.82	132	22.1
		n-hexane	50	250	5760	0.5	86.18	87	24.3
		Benzene	20	230	5760	0.35	78.12	114	35.3
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	340	5760	0.41	131.39	144	26.5
		Tetrachloroethene	20	480	5760	0.5	165.83	167	24.3
		1,2,4-Trimethylbenzene	50	360	5760	0.62	120.19	101	20.2
		Naphthalene	20	42	5760	0.5	128.17	14.58	2.7
		2-butanone (MEK)	20	200	5760	0.5	72.12	69	23.2
	Chamber 2 TenaxTA	1,1,1-trichloroethane	20	320	5760	0.5	133.41	111	20.1
		Carbon Tetrachloride	20	390	5760	0.5	143.82	135	22.7
		n-hexane	50	250	5760	0.5	86.18	87	24.3
		Benzene	20	230	5760	0.35	78.12	114	35.3
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	350	5760	0.41	131.39	148	27.2
		Tetrachloroethene	20	510	5760	0.5	165.83	177	25.8
		1,2,4-Trimethylbenzene	50	400	5760	0.62	120.19	112	22.5
		Naphthalene	20	47	5760	0.5	128.17	16.32	3.1
		2-butanone (MEK)	20	200	5760	0.5	72.12	69	23.2
	Chamber 2 TenaxTA	1,1,1-trichloroethane	20	340	5760	0.5	133.41	118	21.4
		Carbon Tetrachloride	20	400	5760	0.5	143.82	139	23.3
		n-hexane	50	260	5760	0.5	86.18	90	25.3
		Benzene	20	240	5760	0.35	78.12	119	36.8
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	370	5760	0.41	131.39	157	28.8
		Tetrachloroethene	20	540	5760	0.5	165.83	188	27.3
		1,2,4-Trimethylbenzene	50	410	5760	0.62	120.19	115	23.1
		Naphthalene	20	49	5760	0.5	128.17	17.01	3.2
		2-butanone (MEK)	20	210	5760	0.5	72.12	73	24.4

Notes:

ng - nanograms
min - minutes
mL/min - millilitres per minute
g/mol - grams per mole
µg/m^3 - micrograms per cubic metre
ppbv - parts per billion

APPENDIX TABLE E3C
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
ATD CARBOPACK SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler ID	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
1	Chamber 1 CarboPack B (1)	1,1,1-trichloroethane	20	400	5760	0.5	133.41	139	25.2
		Carbon Tetrachloride	20	480	5760	0.5	143.82	167	28.0
		n-hexane	20	690	5760	0.5	86.18	240	67.2
		Benzene	20	430	5760	0.35	78.12	213	66.0
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	540	5760	0.41	131.39	229	42.1
		Tetrachloroethene	20	730	5760	0.5	165.83	253	37.0
		1,2,4-Trimethylbenzene	20	480	5760	0.62	120.19	134	27.0
		Naphthalene	20	52	5760	0.5	128.17	18.1	3.4
		2-butanone (MEK)	20	72	5760	0.5	72.12	25.0	8.4
	Chamber 1 CarboPack B (2)	1,1,1-trichloroethane	20	390	5760	0.5	133.41	135	24.5
		Carbon Tetrachloride	20	490	5760	0.5	143.82	170	28.6
		n-hexane	20	700	5760	0.5	86.18	243	68.2
		Benzene	20	430	5760	0.35	78.12	213	66.0
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.1
		Trichlorothene	20	560	5760	0.41	131.39	237	43.6
		Tetrachloroethene	20	740	5760	0.5	165.83	257	37.5
		1,2,4-Trimethylbenzene	20	470	5760	0.62	120.19	132	26.5
		Naphthalene	20	52	5760	0.5	128.17	18.1	3.4
		2-butanone (MEK)	20	55	5760	0.5	72.12	19.1	6.4
	Chamber 1 CarboPack B (3)	1,1,1-trichloroethane	20	420	5760	0.5	133.41	146	26.4
		Carbon Tetrachloride	20	520	5760	0.5	143.82	181	30.4
		n-hexane	20	700	5760	0.5	86.18	243	68.2
		Benzene	20	440	5760	0.35	78.12	218	67.6
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	560	5760	0.41	131.39	237	43.6
		Tetrachloroethene	20	740	5760	0.5	165.83	257	37.5
		1,2,4-Trimethylbenzene	20	460	5760	0.62	120.19	129	25.9
		Naphthalene	20	52	5760	0.5	128.17	18.1	3.4
		2-butanone (MEK)	20	62	5760	0.5	72.12	21.5	7.2
	Chamber 2 CarboPack B (1)	1,1,1-trichloroethane	20	360	5760	0.5	133.41	125	22.6
		Carbon Tetrachloride	20	500	5760	0.5	143.82	174	29.2
		n-hexane	20	700	5760	0.5	86.18	243	68.1
		Benzene	20	420	5760	0.35	78.12	208	64.4
		1,2-dichloroethane	20	240	5760	0.5	98.96	83	20.3
		Trichlorothene	20	510	5760	0.41	131.39	216	39.7
		Tetrachloroethene	20	700	5760	0.5	165.83	243	35.4
		1,2,4-Trimethylbenzene	20	430	5760	0.62	120.19	120	24.2
		Naphthalene	20	47	5760	0.5	128.17	16.3	3.1
		2-butanone (MEK)	20	27	5760	0.5	72.12	9.4	3.1
	Chamber 2 CarboPack B (2)	1,1,1-trichloroethane	20	400	5760	0.5	133.41	139	25.2
		Carbon Tetrachloride	20	490	5760	0.5	143.82	170	28.6
		n-hexane	20	720	5760	0.5	86.18	250	70.1
		Benzene	20	420	5760	0.35	78.12	208	64.4
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	530	5760	0.41	131.39	224	41.3
		Tetrachloroethene	20	720	5760	0.5	165.83	250	36.4
		1,2,4-Trimethylbenzene	20	490	5760	0.62	120.19	137	27.6
		Naphthalene	20	51	5760	0.5	128.17	17.7	3.3
		2-butanone (MEK)	20	80	5760	0.5	72.12	27.8	9.3
	Chamber 2 CarboPack B (3)	1,1,1-trichloroethane	20	390	5760	0.5	133.41	135	24.5
		Carbon Tetrachloride	20	510	5760	0.5	143.82	177	29.7
		n-hexane	20	680	5760	0.5	86.18	236	66.2
		Benzene	20	420	5760	0.35	78.12	208	64.4
		1,2-dichloroethane	20	240	5760	0.5	98.96	83	20.3
		Trichlorothene	20	530	5760	0.41	131.39	224	41.3
		Tetrachloroethene	20	700	5760	0.5	165.83	243	35.4
		1,2,4-Trimethylbenzene	20	430	5760	0.62	120.19	120	24.2
		Naphthalene	20	44	5760	0.5	128.17	15.3	2.9
		2-butanone (MEK)	20	55	5760	0.5	72.12	19.1	6.4

APPENDIX TABLE E3C
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
ATD CARBOPACK SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler ID	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
2	Chamber 1 CarboPack B	1,1,1-trichloroethane	20	380	5760	0.5	133.41	132	23.9
		Carbon Tetrachloride	20	520	5760	0.5	143.82	181	30.4
		n-hexane	20	710	5760	0.5	86.18	247	69.2
		Benzene	20	430	5760	0.35	78.12	213	66.1
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	550	5760	0.41	131.39	233	42.9
		Tetrachloroethene	20	730	5760	0.5	165.83	253	37.0
		1,2,4-Trimethylbenzene	20	470	5760	0.62	120.19	132	26.5
		Naphthalene	20	46	5760	0.5	128.17	16.0	3.0
		2-butanone (MEK)	20	35	5760	0.5	72.12	12.2	4.1
	Chamber 1 CarboPack B	1,1,1-trichloroethane	20	390	5760	0.5	133.41	135	24.6
		Carbon Tetrachloride	20	530	5760	0.5	143.82	184	31.0
		n-hexane	20	720	5760	0.5	86.18	250	70.2
		Benzene	20	440	5760	0.35	78.12	218	67.6
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	540	5760	0.41	131.39	229	42.1
		Tetrachloroethene	20	740	5760	0.5	165.83	257	37.5
		1,2,4-Trimethylbenzene	20	470	5760	0.62	120.19	132	26.5
		Naphthalene	20	45	5760	0.5	128.17	15.6	2.9
		2-butanone (MEK)	20	37	5760	0.5	72.12	12.8	4.3
	Chamber 1 CarboPack B	1,1,1-trichloroethane	20	350	5760	0.5	133.41	122	22.0
		Carbon Tetrachloride	20	450	5760	0.5	143.82	156	26.3
		n-hexane	20	670	5760	0.5	86.18	233	65.3
		Benzene	20	410	5760	0.35	78.12	203	63.0
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	510	5760	0.41	131.39	216	39.8
		Tetrachloroethene	20	350	5760	0.5	165.83	122	17.7
		1,2,4-Trimethylbenzene	20	390	5760	0.62	120.19	109	22.0
		Naphthalene	20	36	5760	0.5	128.17	12.5	2.4
		2-butanone (MEK)	20	86	5760	0.5	72.12	29.9	10.0
	Chamber 2 CarboPack B	1,1,1-trichloroethane	20	440	5760	0.5	133.41	153	27.7
		Carbon Tetrachloride	20	550	5760	0.5	143.82	191	32.1
		n-hexane	20	720	5760	0.5	86.18	250	70.1
		Benzene	20	420	5760	0.35	78.12	208	64.5
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	510	5760	0.41	131.39	216	39.7
		Tetrachloroethene	20	710	5760	0.5	165.83	247	35.9
		1,2,4-Trimethylbenzene	20	450	5760	0.62	120.19	126	25.3
		Naphthalene	20	48	5760	0.5	128.17	16.7	3.1
		2-butanone (MEK)	20	70	5760	0.5	72.12	24.3	8.1
	Chamber 2 CarboPack B	1,1,1-trichloroethane	20	410	5760	0.5	133.41	142	25.8
		Carbon Tetrachloride	20	490	5760	0.5	143.82	170	28.6
		n-hexane	20	710	5760	0.5	86.18	247	69.1
		Benzene	20	430	5760	0.35	78.12	213	66.0
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	550	5760	0.41	131.39	233	42.8
		Tetrachloroethene	20	730	5760	0.5	165.83	253	36.9
		1,2,4-Trimethylbenzene	20	490	5760	0.62	120.19	137	27.6
		Naphthalene	20	50	5760	0.5	128.17	17.4	3.3
		2-butanone (MEK)	20	86	5760	0.5	72.12	29.9	10.0
	Chamber 2 CarboPack B	1,1,1-trichloroethane	20	380	5760	0.5	133.41	132	23.9
		Carbon Tetrachloride	20	480	5760	0.5	143.82	167	28.0
		n-hexane	20	680	5760	0.5	86.18	236	66.2
		Benzene	20	420	5760	0.35	78.12	208	64.5
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	520	5760	0.41	131.39	220	40.5
		Tetrachloroethene	20	690	5760	0.5	165.83	240	34.9
		1,2,4-Trimethylbenzene	20	440	5760	0.62	120.19	123	24.8
		Naphthalene	20	49	5760	0.5	128.17	17.0	3.2
		2-butanone (MEK)	20	64	5760	0.5	72.12	22.2	7.4

APPENDIX TABLE E3C
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
ATD CARBOPACK SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler ID	Analyte	Reporting limit (ng)	Mass on sampler (ng)	Exposure time (min)	Uptake rate (mL/min)	Molecular Weight (g/mol)	Concentration	
								(µg/m^3)	(ppbv)
3	Chamber 1 CarboPack B	1,1,1-trichloroethane	20	430	5760	0.5	133.41	149	27.0
		Carbon Tetrachloride	20	540	5760	0.5	143.82	188	31.5
		n-hexane	20	720	5760	0.5	86.18	250	70.1
		Benzene	20	440	5760	0.35	78.12	218	67.5
		1,2-dichloroethane	20	290	5760	0.5	98.96	101	24.6
		Trichlorothene	20	580	5760	0.41	131.39	246	45.2
		Tetrachloroethene	20	750	5760	0.5	165.83	260	37.9
		1,2,4-Trimethylbenzene	20	500	5760	0.62	120.19	140	28.1
		Naphthalene	20	52	5760	0.5	128.17	18.1	3.4
		2-butanone (MEK)	20	130	5760	0.5	72.12	45.1	15.1
	Chamber 1 CarboPack B	1,1,1-trichloroethane	20	460	5760	0.5	133.41	160	28.9
		Carbon Tetrachloride	20	560	5760	0.5	143.82	194	32.7
		n-hexane	20	710	5760	0.5	86.18	247	69.1
		Benzene	20	430	5760	0.35	78.12	213	66.0
		1,2-dichloroethane	20	270	5760	0.5	98.96	94	22.9
		Trichlorothene	20	540	5760	0.41	131.39	229	42.0
		Tetrachloroethene	20	720	5760	0.5	165.83	250	36.4
		1,2,4-Trimethylbenzene	20	440	5760	0.62	120.19	123	24.8
		Naphthalene	20	45	5760	0.5	128.17	15.6	2.9
		2-butanone (MEK)	20	72	5760	0.5	72.12	25.0	8.4
	Chamber 1 CarboPack B	1,1,1-trichloroethane	20	450	5760	0.5	133.41	156	28.3
		Carbon Tetrachloride	20	550	5760	0.5	143.82	191	32.1
		n-hexane	20	710	5760	0.5	86.18	247	69.1
		Benzene	20	430	5760	0.35	78.12	213	66.0
		1,2-dichloroethane	20	280	5760	0.5	98.96	97	23.7
		Trichlorothene	20	540	5760	0.41	131.39	229	42.0
		Tetrachloroethene	20	720	5760	0.5	165.83	250	36.4
		1,2,4-Trimethylbenzene	20	460	5760	0.62	120.19	129	25.9
		Naphthalene	20	47	5760	0.5	128.17	16.3	3.1
		2-butanone (MEK)	20	79	5760	0.5	72.12	27.4	9.2
	Chamber 2 CarboPack B	1,1,1-trichloroethane	20	360	5760	0.5	133.41	125	22.6
		Carbon Tetrachloride	20	470	5760	0.5	143.82	163	27.4
		n-hexane	20	690	5760	0.5	86.18	240	67.1
		Benzene	20	420	5760	0.35	78.12	208	64.4
		1,2-dichloroethane	20	250	5760	0.5	98.96	87	21.2
		Trichlorothene	20	540	5760	0.41	131.39	229	42.0
		Tetrachloroethene	20	700	5760	0.5	165.83	243	35.4
		1,2,4-Trimethylbenzene	20	450	5760	0.62	120.19	126	25.3
		Naphthalene	20	49	5760	0.5	128.17	17.0	3.2
		2-butanone (MEK)	20	34	5760	0.5	72.12	11.8	4.0
	Chamber 2 CarboPack B	1,1,1-trichloroethane	20	400	5760	0.5	133.41	139	25.1
		Carbon Tetrachloride	20	520	5760	0.5	143.82	181	30.3
		n-hexane	20	660	5760	0.5	86.18	229	64.2
		Benzene	20	400	5760	0.35	78.12	198	61.3
		1,2-dichloroethane	20	260	5760	0.5	98.96	90	22.0
		Trichlorothene	20	520	5760	0.41	131.39	220	40.5
		Tetrachloroethene	20	670	5760	0.5	165.83	233	33.9
		1,2,4-Trimethylbenzene	20	420	5760	0.62	120.19	118	23.6
		Naphthalene	20	43	5760	0.5	128.17	14.9	2.8
		2-butanone (MEK)	20	58	5760	0.5	72.12	20.1	6.7
	Chamber 2 CarboPack B	1,1,1-trichloroethane	20	390	5760	0.5	133.41	135	24.5
		Carbon Tetrachloride	20	510	5760	0.5	143.82	177	29.7
		n-hexane	20	710	5760	0.5	86.18	247	69.1
		Benzene	20	420	5760	0.35	78.12	208	64.4
		1,2-dichloroethane	20	280	5760	0.5	98.96	97	23.7
		Trichlorothene	20	540	5760	0.41	131.39	229	42.0
		Tetrachloroethene	20	730	5760	0.5	165.83	253	36.9
		1,2,4-Trimethylbenzene	20	480	5760	0.62	120.19	134	27.0
		Naphthalene	20	53	5760	0.5	128.17	18.4	3.5
		2-butanone (MEK)	20	110	5760	0.5	72.12	38.2	12.8

Notes:

ng - nanograms
min - minutes
mL/min - millilitres per minute
g/mol - grams per mole
µg/m^3 - micrograms per cubic metre
ppbv - parts per billion

APPENDIX TABLE E3D
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
SKC SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Mass on sampler (ng)	Exposure Time (min)	Uptake Rate (mL/min)	Molecular Weight (g/mol)	Concentration	
							($\mu g/m^3$)	(ppbv)
1	ANOVA #2	2-butanone (MEK)	6523.2	5760	17	72.12	67	22.3
	Chamber 1	n-Hexane	12901.7	5760	14	86.18	160	44.9
		1,2-dichloroethane	12718.8	5760	13	98.96	170	41.5
		1,1,1-trichloroethane	18290.8	5760	13	133.41	244	44.3
		Benzene	12251.9	5760	16	78.12	133	41.2
		Carbon Tetrachloride	14405.1	5760	13	143.82	192	32.3
		Trichlorothene	17214.5	5760	15	131.39	199	36.7
		Tetrachloroethene	21513.7	5760	13	165.83	287	41.9
		1,2,4-Trimethylbenzene	13379.4	5760	13	120.19	179	36.0
		Naphthalene	442.0	5760	13	128.17	5.9	1.1
	ANOVA #4	2-butanone (MEK)	7135.0	5760	17	72.12	73	24.4
	Chamber 1	n-Hexane	12880.5	5760	14	86.18	160	44.8
		1,2-dichloroethane	13106.3	5760	13	98.96	175	42.8
		1,1,1-trichloroethane	18371.5	5760	13	133.41	245	44.5
		Benzene	12136.8	5760	16	78.12	132	40.8
		Carbon Tetrachloride	14189.5	5760	13	143.82	189	31.9
		Trichlorothene	17404.5	5760	15	131.39	201	37.1
		Tetrachloroethene	21239.5	5760	13	165.83	284	41.4
		1,2,4-Trimethylbenzene	13110.1	5760	13	120.19	175	35.2
		Naphthalene	478.5	5760	13	128.17	6.4	1.2
	ANOVA #6	2-butanone (MEK)	6798.0	5760	17	72.12	69	23.3
	Chamber 1	n-Hexane	12806.9	5760	14	86.18	159	44.6
		1,2-dichloroethane	12746.2	5760	13	98.96	170	41.6
		1,1,1-trichloroethane	18403.8	5760	13	133.41	246	44.6
		Benzene	12240.7	5760	16	78.12	133	41.1
		Carbon Tetrachloride	14535.2	5760	13	143.82	194	32.6
		Trichlorothene	17729.3	5760	15	131.39	205	37.8
		Tetrachloroethene	21301.7	5760	13	165.83	284	41.5
		1,2,4-Trimethylbenzene	12979.4	5760	13	120.19	173	34.9
		Naphthalene	464.7	5760	13	128.17	6.2	1.2
	ANOVA #3	2-butanone (MEK)	6692.9	5760	17	72.12	68	22.9
	Chamber 2	n-Hexane	13260.6	5760	14	86.18	164	46.1
		1,2-dichloroethane	13195.2	5760	13	98.96	176	43.0
		1,1,1-trichloroethane	19006.2	5760	13	133.41	254	46.0
		Benzene	12401.0	5760	16	78.12	135	41.6
		Carbon Tetrachloride	14553.9	5760	13	143.82	194	32.7
		Trichlorothene	17903.8	5760	15	131.39	207	38.1
		Tetrachloroethene	20901.4	5760	13	165.83	279	40.7
		1,2,4-Trimethylbenzene	13053.1	5760	13	120.19	174	35.0
		Naphthalene	455.2	5760	13	128.17	6.1	1.1
	ANOVA #5	2-butanone (MEK)	6507.1	5760	17	72.12	66	22.3
	Chamber 2	n-Hexane	12793.8	5760	14	86.18	159	44.5
		1,2-dichloroethane	12479.3	5760	13	98.96	167	40.7
		1,1,1-trichloroethane	17847.8	5760	13	133.41	238	43.2
		Benzene	12140.2	5760	16	78.12	132	40.7
		Carbon Tetrachloride	13546.1	5760	13	143.82	181	30.4
		Trichlorothene	17349.9	5760	15	131.39	201	36.9
		Tetrachloroethene	20946.3	5760	13	165.83	280	40.8
		1,2,4-Trimethylbenzene	12439.7	5760	13	120.19	166	33.4
		Naphthalene	414.3	5760	13	128.17	5.5	1.0
	ANOVA #7	2-butanone (MEK)	7331.6	5760	17	72.12	75	25.1
	Chamber 2	n-Hexane	13013.3	5760	14	86.18	161	45.2
		1,2-dichloroethane	13145.6	5760	13	98.96	176	42.9
		1,1,1-trichloroethane	18262.4	5760	13	133.41	244	44.2
		Benzene	12110.6	5760	16	78.12	131	40.6
		Carbon Tetrachloride	14970.0	5760	13	143.82	200	33.6
		Trichlorothene	17421.2	5760	15	131.39	202	37.1
		Tetrachloroethene	22906.8	5760	13	165.83	306	44.6
		1,2,4-Trimethylbenzene	13605.5	5760	13	120.19	182	36.5
		Naphthalene	396.6	5760	13	128.17	5.3	1.0

APPENDIX TABLE E3D
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
SKC SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Mass on sampler (ng)	Exposure Time (min)	Uptake Rate (mL/min)	Molecular Weight (g/mol)	Concentration	
							($\mu g/m^3$)	(ppbv)
2	ANOVA #12	2-butanone (MEK)	7951.6	5760	17	72.12	81	27.2
	Chamber 1	n-Hexane	13674.2	5760	14	86.18	170	47.6
		1,2-dichloroethane	15117.2	5760	13	98.96	202	49.4
		1,1,1-trichloroethane	19564.3	5760	13	133.41	261	47.4
		Benzene	12336.1	5760	16	78.12	134	41.5
		Carbon Tetrachloride	17142.0	5760	13	143.82	229	38.5
		Trichlorothene	17416.8	5760	15	131.39	202	37.1
		Tetrachloroethene	21003.6	5760	13	165.83	280	40.9
		1,2,4-Trimethylbenzene	12166.1	5760	13	120.19	162	32.7
		Naphthalene	321.5	5760	13	128.17	4.3	0.8
	ANOVA #14	2-butanone (MEK)	7191.7	5760	17	72.12	73	24.6
	Chamber 1	n-Hexane	12115.6	5760	14	86.18	150	42.2
		1,2-dichloroethane	13780.5	5760	13	98.96	184	45.0
		1,1,1-trichloroethane	18540.7	5760	13	133.41	248	44.9
		Benzene	11259.2	5760	16	78.12	122	37.8
		Carbon Tetrachloride	15549.4	5760	13	143.82	208	34.9
		Trichlorothene	15963.2	5760	15	131.39	185	34.0
		Tetrachloroethene	18304.2	5760	13	165.83	244	35.7
		1,2,4-Trimethylbenzene	10739.5	5760	13	120.19	143	28.9
		Naphthalene	352.6	5760	13	128.17	4.7	0.9
	ANOVA #16	2-butanone (MEK)	7723.9	5760	17	72.12	79	26.5
	Chamber 1	n-Hexane	12827.9	5760	14	86.18	159	44.7
		1,2-dichloroethane	14627.3	5760	13	98.96	195	47.8
		1,1,1-trichloroethane	19312.1	5760	13	133.41	258	46.8
		Benzene	11842.6	5760	16	78.12	129	39.8
		Carbon Tetrachloride	15507.5	5760	13	143.82	207	34.8
		Trichlorothene	16855.1	5760	15	131.39	195	35.9
		Tetrachloroethene	20267.0	5760	13	165.83	271	39.5
		1,2,4-Trimethylbenzene	12706.9	5760	13	120.19	170	34.2
		Naphthalene	554.7	5760	13	128.17	7.4	1.4
	ANOVA #13	2-butanone (MEK)	7743.7	5760	17	72.12	79	26.5
	Chamber 2	n-Hexane	12512.6	5760	14	86.18	155	43.5
		1,2-dichloroethane	14500.2	5760	13	98.96	194	47.3
		1,1,1-trichloroethane	19640.0	5760	13	133.41	262	47.5
		Benzene	11722.0	5760	16	78.12	127	39.3
		Carbon Tetrachloride	16194.3	5760	13	143.82	216	36.3
		Trichlorothene	16471.7	5760	15	131.39	191	35.1
		Tetrachloroethene	19590.8	5760	13	165.83	262	38.1
		1,2,4-Trimethylbenzene	11805.1	5760	13	120.19	158	31.7
		Naphthalene	436.3	5760	13	128.17	5.8	1.1
	ANOVA #15	2-butanone (MEK)	7727.5	5760	17	72.12	79	26.4
	Chamber 2	n-Hexane	13036.5	5760	14	86.18	162	45.3
		1,2-dichloroethane	15060.5	5760	13	98.96	201	49.1
		1,1,1-trichloroethane	20289.2	5760	13	133.41	271	49.1
		Benzene	12182.6	5760	16	78.12	132	40.9
		Carbon Tetrachloride	16490.3	5760	13	143.82	220	37.0
		Trichlorothene	17483.6	5760	15	131.39	202	37.2
		Tetrachloroethene	20552.6	5760	13	165.83	274	40.0
		1,2,4-Trimethylbenzene	12070.6	5760	13	120.19	161	32.4
		Naphthalene	357.3	5760	13	128.17	4.8	0.9
	ANOVA #17	2-butanone (MEK)	7774.1	5760	17	72.12	79	26.6
	Chamber 2	n-Hexane	13239.3	5760	14	86.18	164	46.0
		1,2-dichloroethane	15043.1	5760	13	98.96	201	49.1
		1,1,1-trichloroethane	20759.8	5760	13	133.41	277	50.2
		Benzene	12455.9	5760	16	78.12	135	41.8
		Carbon Tetrachloride	17242.0	5760	13	143.82	230	38.7
		Trichlorothene	17723.9	5760	15	131.39	205	37.7
		Tetrachloroethene	20242.0	5760	13	165.83	270	39.4
		1,2,4-Trimethylbenzene	12019.7	5760	13	120.19	161	32.3
		Naphthalene	354.6	5760	13	128.17	4.7	0.9

APPENDIX TABLE E3D
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
SKC SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Mass on sampler (ng)	Exposure Time (min)	Uptake Rate (mL/min)	Molecular Weight (g/mol)	Concentration	
							(µg/m^3)	(ppbv)
3	ANOVA #22	2-butanone (MEK)	6972.3	5760	17	72.12	71	23.9
	Chamber 1	n-Hexane	13234.3	5760	14	86.18	164	46.0
		1,2-dichloroethane	14553.9	5760	13	98.96	194	47.5
		1,1,1-trichloroethane	20418.7	5760	13	133.41	273	49.4
		Benzene	12268.7	5760	16	78.12	133	41.2
		Carbon Tetrachloride	16512.5	5760	13	143.82	221	37.0
		Trichlorothene	17557.8	5760	15	131.39	203	37.4
		Tetrachloroethene	20517.8	5760	13	165.83	274	39.9
		1,2,4-Trimethylbenzene	11756.6	5760	13	120.19	157	31.6
		Naphthalene	349.5	5760	13	128.17	4.7	0.9
	ANOVA #24	2-butanone (MEK)	7538.9	5760	17	72.12	77	25.8
	Chamber 1	n-Hexane	13312.1	5760	14	86.18	165	46.3
		1,2-dichloroethane	14278.6	5760	13	98.96	191	46.6
		1,1,1-trichloroethane	19440.3	5760	13	133.41	260	47.0
		Benzene	11764.1	5760	16	78.12	128	39.5
		Carbon Tetrachloride	16193.8	5760	13	143.82	216	36.3
		Trichlorothene	16695.9	5760	15	131.39	193	35.5
		Tetrachloroethene	20851.3	5760	13	165.83	278	40.6
		1,2,4-Trimethylbenzene	12099.9	5760	13	120.19	162	32.5
		Naphthalene	375.5	5760	13	128.17	5.0	0.9
	ANOVA #26	2-butanone (MEK)	6022.1	5760	17	72.12	62	20.6
	Chamber 1	n-Hexane	13339.2	5760	14	86.18	165	46.4
		1,2-dichloroethane	14217.4	5760	13	98.96	190	46.4
		1,1,1-trichloroethane	19280.2	5760	13	133.41	257	46.6
		Benzene	11994.2	5760	16	78.12	130	40.2
		Carbon Tetrachloride	15892.5	5760	13	143.82	212	35.7
		Trichlorothene	16734.1	5760	15	131.39	194	35.6
		Tetrachloroethene	20043.9	5760	13	165.83	268	39.0
		1,2,4-Trimethylbenzene	11550.6	5760	13	120.19	154	31.0
		Naphthalene	307.0	5760	13	128.17	4.1	0.8
	ANOVA #21	2-butanone (MEK)	7307.1	5760	17	72.12	75	25.0
	Chamber 2	n-Hexane	13242.8	5760	14	86.18	164	46.0
		1,2-dichloroethane	14614.8	5760	13	98.96	195	47.6
		1,1,1-trichloroethane	20277.8	5760	13	133.41	271	49.0
		Benzene	12191.1	5760	16	78.12	132	40.9
		Carbon Tetrachloride	16163.7	5760	13	143.82	216	36.2
		Trichlorothene	17254.8	5760	15	131.39	200	36.7
		Tetrachloroethene	20903.0	5760	13	165.83	279	40.6
		1,2,4-Trimethylbenzene	12179.0	5760	13	120.19	163	32.7
		Naphthalene	353.8	5760	13	128.17	4.7	0.9
	ANOVA #23	2-butanone (MEK)	7269.6	5760	17	72.12	74	24.9
	Chamber 2	n-Hexane	13176.6	5760	14	86.18	163	45.8
		1,2-dichloroethane	14077.9	5760	13	98.96	188	45.9
		1,1,1-trichloroethane	19689.2	5760	13	133.41	263	47.6
		Benzene	12213.7	5760	16	78.12	133	41.0
		Carbon Tetrachloride	16472.7	5760	13	143.82	220	36.9
		Trichlorothene	17402.2	5760	15	131.39	201	37.0
		Tetrachloroethene	20795.6	5760	13	165.83	278	40.4
		1,2,4-Trimethylbenzene	11754.1	5760	13	120.19	157	31.5
		Naphthalene	336.4	5760	13	128.17	4.5	0.8
	ANOVA #25	2-butanone (MEK)	6225.0	5760	17	72.12	64	21.3
	Chamber 2	n-Hexane	12978.5	5760	14	86.18	161	45.1
		1,2-dichloroethane	14188.2	5760	13	98.96	189	46.2
		1,1,1-trichloroethane	19292.1	5760	13	133.41	258	46.6
		Benzene	11848.3	5760	16	78.12	129	39.7
		Carbon Tetrachloride	14351.7	5760	13	143.82	192	32.2
		Trichlorothene	16527.7	5760	15	131.39	191	35.2
		Tetrachloroethene	20177.0	5760	13	165.83	269	39.2
		1,2,4-Trimethylbenzene	11833.8	5760	13	120.19	158	31.7
		Naphthalene	355.7	5760	13	128.17	4.7	0.9

Notes:

ng - nanograms
min - minutes
mL/min - millilitres per minute
g/mol - grams per mole
µg/m^3 - micrograms per cubic metre
ppbv - parts per billion

APPENDIX TABLE E3E
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
RADIELLO SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Concentration ($\mu g/m^3$)	Concentration (ppbv)
1	ANOVA 31 Chamber 1	Methylethylketone	25.71	18.95
		n-Hexane	63.61	46.95
		1,2-Dichloroethane	60.05	33.09
		1,1,1-Trichloroethane	72.89	37.00
		Benzene	61.21	41.13
		Carbon tetrachloride	77.83	31.70
		Trichloroethylene	87.28	40.42
		Tetrachloroethylene	102.29	43.90
		1,2,4-Trimethylbenzene	74.97	52.38
		Naphtalene	8.78	11.50
	ANOVA 32 Chamber 1	Methylethylketone	23.09	17.02
		n-Hexane	59.77	44.12
		1,2-Dichloroethane	56.39	31.07
		1,1,1-Trichloroethane	69.51	35.28
		Benzene	56.83	38.18
		Carbon tetrachloride	73.66	30.01
		Trichloroethylene	80.65	37.35
		Tetrachloroethylene	95.73	41.09
		1,2,4-Trimethylbenzene	70.06	48.95
		Naphtalene	7.95	10.41
	ANOVA 33 Chamber 1	Methylethylketone	24.84	18.31
		n-Hexane	63.71	47.03
		1,2-Dichloroethane	61.30	33.78
		1,1,1-Trichloroethane	74.77	37.95
		Benzene	61.76	41.49
		Carbon tetrachloride	79.15	32.24
		Trichloroethylene	87.56	40.55
		Tetrachloroethylene	103.01	44.21
		1,2,4-Trimethylbenzene	74.39	51.98
		Naphtalene	8.07	10.58
	ANOVA 34 Chamber 2	Methylethylketone	24.31	17.90
		n-Hexane	61.26	45.17
		1,2-Dichloroethane	58.81	32.37
		1,1,1-Trichloroethane	72.18	36.60
		Benzene	59.18	39.72
		Carbon tetrachloride	77.77	31.65
		Trichloroethylene	83.51	38.63
		Tetrachloroethylene	99.09	42.49
		1,2,4-Trimethylbenzene	71.11	49.63
		Naphtalene	7.61	9.96
	ANOVA 35 Chamber 2	Methylethylketone	27.82	20.49
		n-Hexane	64.56	47.61
		1,2-Dichloroethane	62.32	34.30
		1,1,1-Trichloroethane	77.03	39.06
		Benzene	63.48	42.61
		Carbon tetrachloride	83.05	33.80
		Trichloroethylene	88.81	41.08
		Tetrachloroethylene	105.60	45.28
		1,2,4-Trimethylbenzene	75.07	52.40
		Naphtalene	7.88	10.32
	ANOVA 36 Chamber 2	Methylethylketone	24.44	17.99
		n-Hexane	62.90	46.39
		1,2-Dichloroethane	61.52	33.86
		1,1,1-Trichloroethane	75.82	38.45
		Benzene	61.48	41.27
		Carbon tetrachloride	81.74	33.26
		Trichloroethylene	86.82	40.16
		Tetrachloroethylene	103.06	44.19
		1,2,4-Trimethylbenzene	73.27	51.14
		Naphtalene	7.54	9.87

APPENDIX TABLE E3E
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
RADIELLO SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Concentration ($\mu g/m^3$)	Concentration (ppbv)
2	ANOVA 2 Chamber 1	Methylethylketone	20.34	15.00
		n-Hexane	63.67	47.02
		1,2-Dichloroethane	62.89	34.67
		1,1,1-Trichloroethane	77.72	39.47
		Benzene	62.49	42.00
		Carbon tetrachloride	84.07	34.26
		Trichloroethylene	88.96	41.21
		Tetrachloroethylene	105.66	45.37
		1,2,4-Trimethylbenzene	74.91	52.36
		Naphtalene	8.20	10.75
	ANOVA 2 Chamber 1	Methylethylketone	19.30	14.23
		n-Hexane	59.69	44.08
		1,2-Dichloroethane	59.21	32.64
		1,1,1-Trichloroethane	72.82	36.98
		Benzene	58.51	39.33
		Carbon tetrachloride	78.86	32.14
		Trichloroethylene	81.90	37.94
		Tetrachloroethylene	98.02	42.09
		1,2,4-Trimethylbenzene	69.55	48.61
		Naphtalene	6.83	8.95
	ANOVA 2 Chamber 1	Methylethylketone	21.48	15.84
		n-Hexane	64.21	47.42
		1,2-Dichloroethane	63.32	34.90
		1,1,1-Trichloroethane	78.13	39.67
		Benzene	62.49	42.00
		Carbon tetrachloride	84.81	34.56
		Trichloroethylene	88.29	40.90
		Tetrachloroethylene	104.80	45.00
		1,2,4-Trimethylbenzene	73.87	51.63
		Naphtalene	8.07	10.58
	ANOVA 2 Chamber 2	Methylethylketone	19.88	14.65
		n-Hexane	61.31	45.23
		1,2-Dichloroethane	61.69	33.97
		1,1,1-Trichloroethane	75.82	38.46
		Benzene	59.90	40.22
		Carbon tetrachloride	83.06	33.81
		Trichloroethylene	85.68	39.65
		Tetrachloroethylene	100.69	43.19
		1,2,4-Trimethylbenzene	71.20	49.71
		Naphtalene	6.84	8.96
	ANOVA 2 Chamber 2	Methylethylketone	22.09	16.27
		n-Hexane	64.55	47.62
		1,2-Dichloroethane	66.01	36.35
		1,1,1-Trichloroethane	81.31	41.24
		Benzene	64.52	43.32
		Carbon tetrachloride	89.22	36.32
		Trichloroethylene	91.30	42.25
		Tetrachloroethylene	108.03	46.34
		1,2,4-Trimethylbenzene	75.32	52.59
		Naphtalene	7.50	9.82
	ANOVA 2 Chamber 2	Methylethylketone	20.77	15.30
		n-Hexane	62.31	45.96
		1,2-Dichloroethane	63.49	34.96
		1,1,1-Trichloroethane	80.07	40.62
		Benzene	62.28	41.82
		Carbon tetrachloride	86.63	35.26
		Trichloroethylene	87.07	40.30
		Tetrachloroethylene	105.13	45.09
		1,2,4-Trimethylbenzene	72.45	50.58
		Naphtalene	6.95	9.10

APPENDIX TABLE E3E
ANALYTICAL RESULTS OF CENTER-POINT (ANOVA) TESTING
RADIELLO SAMPLERS
ESTCP Passive Samplers

ANOVA Test	Sampler	Analyte	Concentration ($\mu g/m^3$)	Concentration (ppbv)
3	ANOVA 3 Chamber 1	Methylethylketone	26.41	19.46
		n-Hexane	65.31	48.18
		1,2-Dichloroethane	66.30	36.51
		1,1,1-Trichloroethane	83.14	42.17
		Benzene	64.97	43.62
		Carbon tetrachloride	89.74	36.53
		Trichloroethylene	91.82	42.49
		Tetrachloroethylene	110.04	47.20
		1,2,4-Trimethylbenzene	75.03	52.39
		Naphtalene	7.82	10.24
	ANOVA 3 Chamber 1	Methylethylketone	26.88	19.80
		n-Hexane	64.51	47.59
		1,2-Dichloroethane	66.39	36.56
		1,1,1-Trichloroethane	81.86	41.53
		Benzene	64.33	43.19
		Carbon tetrachloride	89.98	36.63
		Trichloroethylene	91.48	42.33
		Tetrachloroethylene	108.59	46.57
		1,2,4-Trimethylbenzene	74.11	51.74
		Naphtalene	7.21	9.44
	ANOVA 3 Chamber 1	Methylethylketone	25.65	18.89
		n-Hexane	60.30	44.48
		1,2-Dichloroethane	61.77	34.01
		1,1,1-Trichloroethane	76.52	38.82
		Benzene	59.48	39.94
		Carbon tetrachloride	83.86	34.14
		Trichloroethylene	83.74	38.76
		Tetrachloroethylene	98.61	42.29
		1,2,4-Trimethylbenzene	68.18	47.60
		Naphtalene	6.59	8.62
	ANOVA 3 Chamber 2	Methylethylketone	26.49	19.51
		n-Hexane	62.52	46.10
		1,2-Dichloroethane	64.69	35.61
		1,1,1-Trichloroethane	80.36	40.75
		Benzene	61.98	41.60
		Carbon tetrachloride	88.65	36.07
		Trichloroethylene	88.17	40.79
		Tetrachloroethylene	104.65	44.87
		1,2,4-Trimethylbenzene	71.76	50.08
		Naphtalene	6.85	8.97
	ANOVA 3 Chamber 2	Methylethylketone	27.41	20.19
		n-Hexane	64.63	47.66
		1,2-Dichloroethane	65.99	36.32
		1,1,1-Trichloroethane	83.39	42.29
		Benzene	63.86	42.87
		Carbon tetrachloride	91.43	37.20
		Trichloroethylene	90.45	41.84
		Tetrachloroethylene	107.43	46.06
		1,2,4-Trimethylbenzene	72.76	50.78
		Naphtalene	6.44	8.42
	ANOVA 3 Chamber 2	Methylethylketone	25.76	18.97
		n-Hexane	63.33	46.70
		1,2-Dichloroethane	66.91	36.83
		1,1,1-Trichloroethane	83.38	42.28
		Benzene	63.47	42.60
		Carbon tetrachloride	91.79	37.35
		Trichloroethylene	90.47	41.85
		Tetrachloroethylene	108.00	46.31
		1,2,4-Trimethylbenzene	72.39	50.53
		Naphtalene	6.99	9.15

Notes:

ng - nanograms
min - minutes
mL/min - millilitres per minute
g/mol - grams per mole
$\mu g/m^3$ - micrograms per cubic metre
ppbv - parts per billion

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APPENDIX F

Results of Fractional Factorial Low Concentration Laboratory Tests

May 2015

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		1									
Exposure Time (min):		1,440 (1 day)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	15	6.9	180	82	580	106	17	50	935	13
n-Hexane	1	290	111	220	84	1100	161	31	89	6573	90
1,2-Dichloroethane	1	180	60	210	70	1600	104	33	72	6304	81
1,1,1-Trichloroethane	1	190	47	270	67	1300	127	41	83	8108	77
Benzene	1	240	145	190	115	1200	118	32	84	6120	81
Carbon tetrachloride	1	270	62	300	69	1700	130	46	79	5549	49
Trichloroethene	1	330	83	290	73	2600	100	44	81	8294	70
Tetrachloroethene	1	460	112	370	90	4600	86	54	91	10087	77
1,2,4-Trimethylbenzene	1	260	58	250	55	5300	58	31	86	5517	58
Naphthalene	1	23	5.9	31	8.0	120	0.60	1.9	10	18	0.18
Methylethylketone	2	1.8	0.8	180	82	600	110	18	53	1248	17
n-Hexane	2	290	111	220	84	1200	176	31	91	7826	107
1,2-Dichloroethane	2	170	57	220	73	1700	110	35	76	7329	94
1,1,1-Trichloroethane	2	200	50	280	69	1300	127	43	85	8517	81
Benzene	2	240	145	200	121	1200	118	32	86	6779	90
Carbon tetrachloride	2	220	51	320	73	1800	138	48	82	5503	49
Trichloroethene	2	330	83	300	75	2700	103	46	84	8965	75
Tetrachloroethene	2	460	112	390	95	4600	86	56	94	10749	82
1,2,4-Trimethylbenzene	2	250	55	260	58	5100	56	29	81	5938	63
Naphthalene	2	21	5.4	32	8.2	120	0.60	1.5	7.8	20	0.20
Methylethylketone	3	40	18	240	110	670	123	7.1	21	1095	15
n-Hexane	3	300	115	310	119	1300	190	29	85	6760	93
1,2-Dichloroethane	3	180	60	290	97	1900	123	32	69	6427	83
1,1,1-Trichloroethane	3	210	52	320	79	1500	146	40	79	8041	77
Benzene	3	250	151	210	127	1500	148	30	79	6223	82
Carbon tetrachloride	3	290	67	320	73	2100	161	46	80	5132	45
Trichloroethene	3	340	85	270	68	3100	119	42	76	8103	68
Tetrachloroethene	3	450	109	370	90	5400	101	51	86	9865	76
1,2,4-Trimethylbenzene	3	250	55	290	64	6400	70	27	73	5237	55
Naphthalene	3	23	5.9	32	8.2	160	0.81	1.3	6.9	17	0.17

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		2									
Exposure Time (min):		1,452 (1 day)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	ND	ND	3.4	1.5	ND	ND	ND	ND	2.4	0.032
n-Hexane	1	7.5	2.9	2.8	1.1	240	35	0.41	1.2	34	0.47
1,2-Dichloroethane	1	1.5	0.50	2.2	0.73	ND	ND	ND	ND	1.5	0.019
1,1,1-Trichloroethane	1	3.1	0.76	2.5	0.61	ND	ND	0.18	0.36	9.7	0.09
Benzene	1	5.2	3.1	3.6	2.2	55	5.4	0.35	0.92	68	0.89
Carbon tetrachloride	1	4.9	1.1	3.0	0.68	ND	ND	0.20	0.34	3.3	0.029
Trichloroethene	1	2.9	0.72	2.8	0.70	ND	ND	ND	ND	1.3	0.011
Tetrachloroethene	1	3.5	0.84	3.2	0.77	ND	ND	ND	ND	75	0.57
1,2,4-Trimethylbenzene	1	3.4	0.75	2.9	0.64	ND	ND	0.22	0.60	6.9	0.072
Naphthalene	1	3.5	0.90	9.4	2.4	ND	ND	ND	ND	4.6	0.045
Methylethylketone	2	ND	ND	3.6	1.6	ND	ND	ND	ND	0.80	0.011
n-Hexane	2	5.2	2.0	2.8	1.1	160	23	0.43	1.2	24	0.33
1,2-Dichloroethane	2	1.6	0.53	2.2	0.73	ND	ND	ND	ND	2.0	0.025
1,1,1-Trichloroethane	2	3.2	0.79	2.5	0.61	ND	ND	0.17	0.34	6.0	0.057
Benzene	2	4.2	2.5	3.4	2.0	68	6.6	0.31	0.81	59	0.77
Carbon tetrachloride	2	5.3	1.2	2.9	0.66	ND	ND	0.21	0.36	2.2	0.019
Trichloroethene	2	3.0	0.75	2.7	0.67	ND	ND	ND	ND	1.0	0.0083
Tetrachloroethene	2	3.6	0.87	3.4	0.82	ND	ND	ND	ND	68	0.52
1,2,4-Trimethylbenzene	2	3.0	0.66	2.8	0.62	ND	ND	0.20	0.55	2.6	0.027
Naphthalene	2	3.3	0.84	3.5	0.90	ND	ND	ND	ND	4.2	0.041
Methylethylketone	3	NA	NA	3.2	1.5	ND	ND	ND	ND	4.0	0.053
n-Hexane	3	NA	NA	5.4	2.1	190	28	0.38	1.1	30	0.41
1,2-Dichloroethane	3	NA	NA	2.2	0.73	ND	ND	ND	ND	2.0	0.025
1,1,1-Trichloroethane	3	NA	NA	2.5	0.61	ND	ND	0.18	0.36	5.6	0.053
Benzene	3	NA	NA	3.0	1.8	ND	ND	0.37	1.0	54	0.71
Carbon tetrachloride	3	NA	NA	2.9	0.66	ND	ND	0.19	0.32	2.2	0.02
Trichloroethene	3	NA	NA	2.7	0.67	ND	ND	ND	ND	1.1	0.0091
Tetrachloroethene	3	NA	NA	3.3	0.80	ND	ND	0.19	0.32	53	0.41
1,2,4-Trimethylbenzene	3	NA	NA	3.3	0.73	ND	ND	0.26	0.71	5.4	0.057
Naphthalene	3	NA	NA	2.4	0.61	ND	ND	ND	ND	6.1	0.060

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		3									
Exposure Time (min):		1,441 (1 day)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	15	7.1	150	71	400	76	24	72	4876	68
n-Hexane	1	300	120	200	80	810	123	31	93	6982	99
1,2-Dichloroethane	1	160	56	150	52	1100	74	39	87	7290	97
1,1,1-Trichloroethane	1	180	46	230	59	870	88	47	97	7445	74
Benzene	1	260	163	170	107	870	89	33	90	7249	100
Carbon tetrachloride	1	280	67	250	60	1200	96	50	89	10371	95
Trichloroethene	1	350	92	220	58	1900	76	49	93	10044	88
Tetrachloroethene	1	470	119	280	71	3800	74	56	99	11340	90
1,2,4-Trimethylbenzene	1	260	60	210	48	6000	69	34	96	4104	45
Naphthalene	1	21	5.6	27	7.2	200	1.0	3.3	17	12	0.12
Methylethylketone	2	40	19	130	62	450	86	24	73	2731	38
n-Hexane	2	290	116	170	68	900	137	33	98	7310	104
1,2-Dichloroethane	2	150	52	170	59	1300	87	41	92	7217	96
1,1,1-Trichloroethane	2	210	54	230	59	1000	101	50	103	9172	91
Benzene	2	250	157	160	101	950	97	34	94	7052	97
Carbon tetrachloride	2	280	67	260	62	1300	104	51	91	4486	41
Trichloroethene	2	350	92	240	63	2100	84	51	97	9499	83
Tetrachloroethene	2	450	114	340	86	4000	77	58	101	11281	90
1,2,4-Trimethylbenzene	2	260	60	250	58	6000	69	34	98	6586	72
Naphthalene	2	22	5.9	31	8.3	180	0.94	3.0	16	20	0
Methylethylketone	3	170	81	140	67	330	63	25	76	2804	39
n-Hexane	3	300	120	170	68	680	103	33	98	7316	104
1,2-Dichloroethane	3	170	59	170	59	970	65	40	90	7275	97
1,1,1-Trichloroethane	3	260	67	240	62	760	77	50	103	8967	89
Benzene	3	250	157	160	101	740	76	34	94	6914	95
Carbon tetrachloride	3	300	72	260	62	1000	80	54	96	4069	37
Trichloroethene	3	350	92	240	63	1600	64	50	95	9217	80
Tetrachloroethene	3	460	116	350	88	3200	62	58	101	10852	86
1,2,4-Trimethylbenzene	3	280	65	260	60	5200	59	35	99	6119	67
Naphthalene	3	23	6.2	41	11	160	0.84	3.1	17	13	0.14

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		4									
Exposure Time (min):		10,099 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	ND	ND	2.7	1.3	ND	ND	ND	ND	6.3	0.088
n-Hexane	1	4.5	1.8	3.1	1.2	170	26	0.41	1.2	83	1.2
1,2-Dichloroethane	1	2.0	0.69	2.0	0.69	ND	ND	ND	ND	19	0.25
1,1,1-Trichloroethane	1	2.7	0.70	2.5	0.64	ND	ND	0.25	0.52	11	0.11
Benzene	1	4.4	2.8	2.9	1.8	67	6.9	0.42	1.2	261	3.6
Carbon tetrachloride	1	3.8	0.91	3.0	0.72	ND	ND	0.27	0.48	3.7	0.034
Trichloroethene	1	3.1	0.81	2.5	0.65	ND	ND	ND	ND	5.0	0.044
Tetrachloroethene	1	3.3	0.83	3.7	0.93	ND	ND	ND	ND	90	0.71
1,2,4-Trimethylbenzene	1	2.6	0.60	3.2	0.74	ND	ND	0.30	0.86	49	0.54
Naphthalene	1	2.6	0.70	8.9	2.4	ND	ND	0.83	4.4	10	0.11
Methylethylketone	2	ND	ND	2.4	1.1	ND	ND	ND	ND	1.0	0.014
n-Hexane	2	7.5	3.0	2.7	1.1	210	32	0.46	1.4	82	1.2
1,2-Dichloroethane	2	1.9	0.66	2.0	0.69	ND	ND	ND	ND	19	0.25
1,1,1-Trichloroethane	2	2.9	0.75	2.4	0.62	ND	ND	0.22	0.46	12	0.12
Benzene	2	5.3	3.3	2.4	1.5	63	6.4	0.40	1.1	70	1.0
Carbon tetrachloride	2	4.1	1.0	3.1	0.74	ND	ND	0.22	0.39	3.7	0.034
Trichloroethene	2	3.4	0.89	2.4	0.63	ND	ND	ND	ND	5.0	0.044
Tetrachloroethene	2	3.6	0.91	3.6	0.91	ND	ND	ND	ND	84	0.67
1,2,4-Trimethylbenzene	2	2.8	0.65	2.9	0.67	ND	ND	0.30	0.86	34	0.37
Naphthalene	2	2.4	0.64	3.1	0.83	ND	ND	0.77	4.1	8.8	0.091
Methylethylketone	3	ND	ND	2.8	1.3	ND	ND	ND	ND	7.4	0.10
n-Hexane	3	4.8	1.9	3.1	1.2	210	32	0.49	1.5	95	1.4
1,2-Dichloroethane	3	1.7	0.59	2.1	0.73	ND	ND	ND	ND	31	0.42
1,1,1-Trichloroethane	3	2.7	0.70	2.5	0.64	ND	ND	0.26	0.5	3.4	0.034
Benzene	3	5.4	3.4	2.5	1.6	69	7.1	0.35	1.0	219	3.0
Carbon tetrachloride	3	3.7	0.88	3.2	0.76	ND	ND	0.21	0.37	12	0.11
Trichloroethene	3	3.4	0.89	2.5	0.65	ND	ND	ND	ND	77	0.67
Tetrachloroethene	3	3.6	0.91	3.7	0.93	ND	ND	ND	ND	100	0.80
1,2,4-Trimethylbenzene	3	3.6	0.83	3.2	0.74	ND	ND	0.35	1.0	28	0.31
Naphthalene	3	2.9	0.78	3.0	0.80	ND	ND	0.84	4.5	9.4	0.10

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		5									
Exposure Time (min):		10,099 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	150	10	520	35	1400	38	6.3	2.7	12586	25
n-Hexane	1	2200	125	720	41	3700	80	191	82	38744	78
1,2-Dichloroethane	1	810	40	770	38	6700	64	110	35	9456	18
1,1,1-Trichloroethane	1	1100	40	1000	37	5200	75	131	38	34053	48
Benzene	1	1600	143	740	66	5100	74	202	79	32054	63
Carbon tetrachloride	1	1600	54	1200	41	7800	88	162	41	47044	61
Trichloroethene	1	2100	78	1200	45	10000	57	270	73	53233	66
Tetrachloroethene	1	3000	108	1900	68	24000	66	396	99	89700	101
1,2,4-Trimethylbenzene	1	2100	69	1700	56	31000	50	264	107	49962	78
Naphthalene	1	240	9.1	190	7.2	840	0.62	27	20	2741	4.0
Methylethylketone	2	470	32	540	37	1200	32	6.5	2.8	8769	17
n-Hexane	2	2300	130	750	42	3000	65	188	80	44367	90
1,2-Dichloroethane	2	850	42	830	41	5600	53	113	36	8571	16
1,1,1-Trichloroethane	2	1300	48	1200	44	4300	62	133	39	38429	54
Benzene	2	1600	143	1200	107	4300	62	198	77	35805	70
Carbon tetrachloride	2	1600	54	1300	44	6500	73	164	41	44323	58
Trichloroethene	2	2100	78	1300	48	9300	53	264	71	53725	66
Tetrachloroethene	2	3100	111	2000	72	23000	63	386	96	90777	103
1,2,4-Trimethylbenzene	2	2200	72	1900	62	31000	50	256	104	76888	120
Naphthalene	2	240	9.1	210	8.0	890	0.66	25	19	4116	6.0
Methylethylketone	3	190	13	550	37	1400	38	3.1	1.3	8304	17
n-Hexane	3	2200	125	760	43	3800	82	192	82	45570	92
1,2-Dichloroethane	3	790	39	860	42	7100	68	111	35	6597	13
1,1,1-Trichloroethane	3	1200	44	1200	44	5500	79	131	39	33428	47
Benzene	3	1700	152	1200	107	5400	78	202	79	34470	67
Carbon tetrachloride	3	1600	54	1400	47	8300	94	163	41	42157	55
Trichloroethene	3	2100	78	1300	48	11000	62	269	72	51765	64
Tetrachloroethene	3	3200	115	2100	75	25000	69	398	99	94735	107
1,2,4-Trimethylbenzene	3	2300	75	2000	65	34000	55	265	108	83208	130
Naphthalene	3	240	9.1	220	8.4	950	0.71	27	20	4689	6.9

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		6									
Exposure Time (min):		10,087 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	ND	ND	6.7	0.45	33	0.89	ND	ND	122	0.24
n-Hexane	1	27	1.5	11	0.62	150	3.2	2.1	0.88	168	0.34
1,2-Dichloroethane	1	1.5	0.074	10	0.49	52	0.50	1.7	0.53	172	0.33
1,1,1-Trichloroethane	1	6.3	0.23	14	0.51	43	0.62	2.2	0.63	234	0.33
Benzene	1	20	1.8	10	0.87	40	0.58	2.0	0.76	707	1.4
Carbon tetrachloride	1	6.7	0.23	15	0.51	61	0.69	3.0	0.75	144	0.19
Trichloroethene	1	12	0.45	12	0.45	83	0.47	2.7	0.72	237	0.29
Tetrachloroethene	1	31	1.1	21	0.75	160	0.44	3.5	0.87	969	1.1
1,2,4-Trimethylbenzene	1	18	0.59	20	0.65	180	0.29	2.3	0.94	77	0.12
Naphthalene	1	20	0.76	23	0.88	51	0.038	2.3	1.7	161	0.24
Methylethylketone	2	2.0	0.14	7.4	0.50	78	2.1	ND	ND	86	0.17
n-Hexane	2	30	1.7	12	0.68	250	5.4	2.0	0.87	439	0.89
1,2-Dichloroethane	2	4.5	0.22	10	0.49	53	0.51	1.7	0.55	256	0.49
1,1,1-Trichloroethane	2	10	0.37	14	0.51	43	0.62	2.6	0.77	327	0.46
Benzene	2	21	1.9	12	1.1	43	0.62	2.1	0.80	540	1.1
Carbon tetrachloride	2	13	0.44	15	0.51	61	0.69	2.9	0.74	215	0.28
Trichloroethene	2	21	0.78	12	0.45	81	0.46	2.8	0.74	257	0.32
Tetrachloroethene	2	32	1.1	21	0.75	160	0.44	3.6	0.90	1249	1.4
1,2,4-Trimethylbenzene	2	20	0.65	19	0.62	170	0.28	2.3	0.93	185	0.29
Naphthalene	2	24	0.91	22	0.84	47	0.035	2.2	1.7	242	0.35
Methylethylketone	3	ND	ND	5.8	0.39	ND	ND	ND	ND	80	0.16
n-Hexane	3	25	1.4	12	0.68	140	3.0	2.0	0.87	158	0.32
1,2-Dichloroethane	3	1.4	0.069	10	0.49	57	0.54	1.9	0.60	149	0.28
1,1,1-Trichloroethane	3	5.9	0.22	15	0.55	45	0.65	2.1	0.60	156	0.22
Benzene	3	18	1.6	10	0.87	43	0.62	2.1	0.80	405	0.79
Carbon tetrachloride	3	6.2	0.21	15	0.51	63	0.71	2.4	0.60	104	0.14
Trichloroethene	3	11	0.41	13	0.48	86	0.49	2.3	0.63	146	0.18
Tetrachloroethene	3	31	1.1	21	0.75	160	0.44	3.5	0.87	1211	1.4
1,2,4-Trimethylbenzene	3	18	0.59	19	0.62	160	0.26	2.3	0.94	20	0.030
Naphthalene	3	21	0.80	21	0.80	48	0.036	2.2	1.7	125	0.18

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		7									
Exposure Time (min):		10,086 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		SKC Ultra	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	110	7.2	710	46	4200	110	203	84	33574	65
n-Hexane	1	2000	109	990	54	5900	123	219	91	44397	87
1,2-Dichloroethane	1	1100	52	1100	52	9900	91	276	85	33068	61
1,1,1-Trichloroethane	1	1600	57	1400	49	8100	113	331	94	57932	79
Benzene	1	1700	147	1400	121	7800	110	230	87	40711	77
Carbon tetrachloride	1	1900	62	1700	56	11000	120	359	88	66334	84
Trichloroethene	1	2300	83	1600	57	16000	88	343	89	62266	74
Tetrachloroethene	1	3000	104	2300	80	28000	74	391	94	88754	97
1,2,4-Trimethylbenzene	1	2100	66	1900	60	27000	42	238	93	78352	118
Naphthalene	1	220	8.1	210	7.7	830	0.60	20	14	4007	5.7
Methylethylketone	2	420	27	710	46	4000	105	190	79	34627	67
n-Hexane	2	2000	109	980	54	5500	115	210	87	46855	92
1,2-Dichloroethane	2	1100	52	1100	52	9400	87	265	82	34538	63
1,1,1-Trichloroethane	2	1600	57	1400	49	7500	104	318	91	61983	84
Benzene	2	1700	147	1300	112	7400	104	220	83	43009	81
Carbon tetrachloride	2	2000	66	1600	52	10000	109	347	85	69715	88
Trichloroethene	2	2300	83	1600	57	15000	82	328	85	66252	79
Tetrachloroethene	2	2900	101	2400	83	28000	74	375	90	90766	99
1,2,4-Trimethylbenzene	2	2000	63	2000	63	27000	42	230	90	78853	119
Naphthalene	2	210	7.7	210	7.7	870	0.63	20	15	4217	6.0
Methylethylketone	3	510	33	710	46	4300	112	187	78	31558	61
n-Hexane	3	2100	115	990	54	6000	125	219	91	45590	89
1,2-Dichloroethane	3	1100	52	1000	48	10000	92	274	85	33220	61
1,1,1-Trichloroethane	3	1600	57	1400	49	8200	114	330	94	60301	82
Benzene	3	1700	147	1500	129	7700	108	229	86	41728	79
Carbon tetrachloride	3	2000	66	1600	52	11000	120	364	89	64209	81
Trichloroethene	3	2300	83	1600	57	16000	88	342	89	63951	77
Tetrachloroethene	3	3000	104	2300	80	30000	80	391	94	87016	95
1,2,4-Trimethylbenzene	3	2100	66	1900	60	28000	44	241	95	75820	114
Naphthalene	3	220	8.1	210	7.7	870	0.63	21	16	4036	5.7

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		8									
Exposure Time (min):		10,083 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	6.2	0.41	8.6	0.56	28	0.73	1.2	0.51	135	0.26
n-Hexane	1	27	1.5	15	0.82	190	4.0	2.2	0.90	662	1.3
1,2-Dichloroethane	1	12	0.57	12	0.57	62	0.57	2.3	0.71	576	1.1
1,1,1-Trichloroethane	1	19	0.67	17	0.60	58	0.81	3.0	0.86	62	0.084
Benzene	1	22	1.9	11	0.95	52	0.73	2.0	0.77	500	0.94
Carbon tetrachloride	1	25	0.82	18	0.59	75	0.82	3.0	0.72	328	0.41
Trichloroethene	1	24	0.86	15	0.54	100	0.55	2.7	0.71	541	0.65
Tetrachloroethene	1	29	1.0	23	0.80	170	0.45	3.4	0.82	987	1.1
1,2,4-Trimethylbenzene	1	19	0.60	18	0.57	140	0.22	2.1	0.84	153	0.23
Naphthalene	1	20	0.74	19	0.70	32	0.023	1.5	1.1	267	0.38
Methylethylketone	2	3.8	0.25	7.6	0.50	24	0.63	1.2	0.51	176	0.34
n-Hexane	2	25	1.4	14	0.77	200	4.2	2.1	0.87	515	1.0
1,2-Dichloroethane	2	10	0.48	12	0.57	69	0.64	2.6	0.80	489	0.90
1,1,1-Trichloroethane	2	17	0.60	16	0.57	57	0.79	3.0	0.85	474	0.64
Benzene	2	21	1.8	11	0.95	53	0.74	1.9	0.73	493	0.93
Carbon tetrachloride	2	23	0.75	18	0.59	80	0.87	3.1	0.76	252	0.32
Trichloroethene	2	23	0.83	15	0.54	100	0.5	2.6	0.68	506	0.61
Tetrachloroethene	2	30	1.0	22	0.76	180	0.48	3.2	0.78	928	1.0
1,2,4-Trimethylbenzene	2	18	0.57	18	0.57	150	0.24	2.1	0.82	662	1.0
Naphthalene	2	22	0.81	19	0.70	30	0.022	1.8	1.3	325	0.46
Methylethylketone	3	1.7	0.11	7.8	0.51	24	0.63	1.1	0.47	202	0.39
n-Hexane	3	26	1.4	14	0.77	180	3.8	2.1	0.89	566	1.1
1,2-Dichloroethane	3	8.6	0.41	12	0.57	72	0.67	2.2	0.69	494	0.91
1,1,1-Trichloroethane	3	15	0.53	17	0.60	58	0.81	2.9	0.81	517	0.70
Benzene	3	19	1.6	12	1.0	51	0.72	1.9	0.72	440	0.83
Carbon tetrachloride	3	22	0.72	18	0.59	83	0.91	3.1	0.76	246	0.31
Trichloroethene	3	23	0.83	15	0.54	100	0.55	2.7	0.69	516	0.62
Tetrachloroethene	3	30	1.0	23	0.80	180	0.48	3.4	0.81	967	1.1
1,2,4-Trimethylbenzene	3	19	0.60	18	0.57	150	0.24	2.1	0.84	669	1.0
Naphthalene	3	20	0.74	19	0.70	37	0.027	1.5	1.1	156	0.22

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		9									
Exposure Time (min):		5,758 (4 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	50	5.8	200	23	700	33	10	7	8116	28
n-Hexane	1	530	52	270	26	1300	48	59	44	11360	39
1,2-Dichloroethane	1	310	26	300	25	2300	38	63	35	10601	35
1,1,1-Trichloroethane	1	500	31	380	24	1800	45	82	42	15687	38
Benzene	1	490	75	280	43	1600	40	60	41	10323	35
Carbon tetrachloride	1	600	35	450	26	2400	47	98	40	15866	36
Trichloroethene	1	650	42	420	27	3800	37	85	40	14722	31
Tetrachloroethene	1	830	51	650	40	7100	34	102	44	21034	41
1,2,4-Trimethylbenzene	1	550	31	530	30	8300	23	66	46	16414	44
Naphthalene	1	52	3.4	60	3.9	190	0.24	4.3	5.71	1334	3.4
Methylethylketone	2	22	2.6	200	23	700	33	10	7	9449	32
n-Hexane	2	520	51	280	27	1200	45	61	45	11328	39
1,2-Dichloroethane	2	320	27	300	25	2200	36	65	36	11336	37
1,1,1-Trichloroethane	2	510	32	390	25	1700	42	84	43	15457	37
Benzene	2	490	75	290	44	1600	40	61	42	10366	35
Carbon tetrachloride	2	590	34	450	26	2400	47	96	39	15978	36
Trichloroethene	2	650	42	430	27	3700	36	88	41	14887	32
Tetrachloroethene	2	840	52	660	41	7200	34	105	45	20851	41
1,2,4-Trimethylbenzene	2	550	31	530	30	8900	25	67	47	14800	40
Naphthalene	2	51	3.3	51	3.3	190	0.24	4.8	6.32	1144	2.9
Methylethylketone	3	60	7.0	200	23	800	37	8	6	6185	21
n-Hexane	3	530	52	280	27	1400	52	61	45	11003	38
1,2-Dichloroethane	3	320	27	300	25	2600	43	66	36	10746	35
1,1,1-Trichloroethane	3	500	31	390	25	2000	50	85	43	15007	36
Benzene	3	500	77	290	44	1900	47	62	42	10121	34
Carbon tetrachloride	3	620	36	450	26	2800	54	95	39	10761	24
Trichloroethene	3	650	42	430	27	4200	41	88	41	14373	31
Tetrachloroethene	3	880	54	670	41	7900	37	106	45	19820	39
1,2,4-Trimethylbenzene	3	580	33	540	30	8900	25	68	47	14259	38
Naphthalene	3	54	3.5	52	3.4	190	0.24	4.9	6.41	1033	2.6

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		10									
Exposure Time (min):		5,761 (4 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	74	8.6	200	23	870	40	12	9.2	9643	33
n-Hexane	1	540	53	280	27	1500	56	61	45	11672	41
1,2-Dichloroethane	1	320	27	300	25	2300	38	67	37	11212	37
1,1,1-Trichloroethane	1	500	31	390	25	1800	45	85	43	16265	39
Benzene	1	500	77	300	46	1700	42	61	41	10946	37
Carbon tetrachloride	1	610	36	460	27	2400	47	96	39	16777	38
Trichloroethene	1	650	41	430	27	3800	37	87	40	15711	33
Tetrachloroethene	1	880	54	680	42	6900	33	105	45	20407	40
1,2,4-Trimethylbenzene	1	580	33	550	31	8100	23	67	47	14676	39
Naphthalene	1	56	3.7	52	3.4	180	0.23	5.2	6.7	1085	2.7
Methylethylketone	2	63	7.3	200	23	760	35	8.8	6.5	9476	32
n-Hexane	2	540	53	280	27	1400	52	59	43	11692	41
1,2-Dichloroethane	2	310	26	300	25	2400	39	63	35	11288	37
1,1,1-Trichloroethane	2	460	29	400	25	1900	47	81	41	15389	37
Benzene	2	500	77	290	44	1800	45	60	40	10851	36
Carbon tetrachloride	2	570	33	460	27	2600	51	96	39	15684	35
Trichloroethene	2	650	41	430	27	3800	37	85	39	15463	33
Tetrachloroethene	2	870	54	670	41	7100	34	102	44	21155	41
1,2,4-Trimethylbenzene	2	570	32	540	30	8100	23	65	46	15369	41
Naphthalene	2	54	3.5	51	3.3	170	0.22	5.3	7.0	1213	3.1
Methylethylketone	3	82	9.5	200	23	730	34	9.4	6.9	9538	33
n-Hexane	3	550	54	280	27	1300	48	61	45	11657	41
1,2-Dichloroethane	3	320	27	300	25	2300	38	65	36	11132	36
1,1,1-Trichloroethane	3	500	31	390	25	1800	45	84	43	15580	38
Benzene	3	510	78	290	44	1700	42	62	41	10633	36
Carbon tetrachloride	3	620	36	460	27	2500	49	96	39	16016	36
Trichloroethene	3	660	42	420	27	3800	37	86	40	15260	32
Tetrachloroethene	3	880	54	680	42	7000	33	106	45	21893	43
1,2,4-Trimethylbenzene	3	580	33	540	30	7800	22	68	47	15345	41
Naphthalene	3	54	3.5	52	3.4	170	0.22	5.5	7.2	1070	2.7

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		11									
Exposure Time (min):		1,446 (1 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	12	5.5	160	73	430	78	25	72	2889	39
n-Hexane	1	360	137	210	80	650	95	27	79	5166	70
1,2-Dichloroethane	1	240	80	230	76	1100	71	34	74	5172	66
1,1,1-Trichloroethane	1	310	76	260	64	900	87	40	81	6386	60
Benzene	1	250	150	180	108	770	75	28	74	4794	63
Carbon tetrachloride	1	380	87	300	69	1200	91	43	70	4543	40
Trichloroethene	1	380	95	280	70	1500	57	40	74	6786	57
Tetrachloroethene	1	460	111	370	89	2300	43	48	81	8004	61
1,2,4-Trimethylbenzene	1	280	62	250	55	1700	19	27	76	1975	21
Naphthalene	1	27	6.9	22	5.6	32	0.16	1.5	7.6	15	0.15
Methylethylketone	2	25	11.4	160	73	450	82	24	71	2849	38
n-Hexane	2	360	137	210	80	710	103	27	80	5128	70
1,2-Dichloroethane	2	220	73	230	76	1100	71	33	73	5242	67
1,1,1-Trichloroethane	2	270	67	260	64	960	93	40	82	6435	61
Benzene	2	260	156	190	114	850	83	28	76	4770	63
Carbon tetrachloride	2	380	87	300	69	1300	99	45	73	4553	40
Trichloroethene	2	380	95	280	70	1600	61	42	77	6771	56
Tetrachloroethene	2	480	116	360	87	2600	48	48	81	7894	60
1,2,4-Trimethylbenzene	2	300	66	250	55	2000	22	28	79	1373	14
Naphthalene	2	25	6.4	24	6.2	39	0.20	1.7	9.0	11	0.11
Methylethylketone	3	15	6.8	160	73	440	80	24	69	3063	41
n-Hexane	3	360	137	200	76	710	103	27	78	5200	71
1,2-Dichloroethane	3	230	76	220	73	1100	71	33	72	5526	71
1,1,1-Trichloroethane	3	290	71	260	64	890	86	40	81	6744	64
Benzene	3	260	156	180	108	790	77	28	74	4881	64
Carbon tetrachloride	3	390	89	290	66	1200	91	45	73	4991	44
Trichloroethene	3	390	98	280	70	1500	57	41	75	6936	58
Tetrachloroethene	3	460	111	350	85	2400	44	47	80	7955	61
1,2,4-Trimethylbenzene	3	290	64	240	53	1800	20	28	77	2135	22
Naphthalene	3	27	6.9	22	5.6	33	0.17	1.3	6.9	14	0.14

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		12									
Exposure Time (min):		1,460 (1 day)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	0.86	0.39	3.3	1.5	14	2.5	ND	ND	8.0	0.11
n-Hexane	1	3.3	1.2	2.8	1.1	12	1.7	0.57	1.7	77	1.0
1,2-Dichloroethane	1	2.0	0.66	2.4	0.79	6.6	0.42	ND	ND	42	0.53
1,1,1-Trichloroethane	1	3.6	0.88	2.7	0.66	4.7	0.45	ND	ND	20	0.19
Benzene	1	2.6	1.5	4.1	2.4	13	1.3	0.44	1.2	89	1.2
Carbon tetrachloride	1	5.2	1.2	3.3	0.75	7.8	0.59	0.20	0.32	12	0.1
Trichloroethene	1	3.7	0.92	3.0	0.74	12	0.45	ND	ND	47	0.39
Tetrachloroethene	1	4.3	1.0	4.1	1.0	27	0.50	ND	ND	126	1.0
1,2,4-Trimethylbenzene	1	2.1	0.46	4.2	0.92	53	0.57	0.35	0.96	1.3	0.54
Naphthalene	1	2.2	0.56	2.9	0.74	ND	ND	ND	ND	19	0.18
Methylethylketone	2	1.0	0.44	2.9	1.3	61	11	ND	ND	5.6	0.07
n-Hexane	2	3.2	1.2	3.3	1.2	68	10	0.54	1.57	81	1.1
1,2-Dichloroethane	2	2.2	0.72	2.5	0.82	7.1	0.45	ND	ND	51	0.64
1,1,1-Trichloroethane	2	3.3	0.81	2.8	0.68	4.0	0.38	0.30	0.60	20	0.19
Benzene	2	2.4	1.4	3.0	1.8	21	2.0	0.41	1.1	120	1.6
Carbon tetrachloride	2	4.9	1.1	3.3	0.75	8.6	0.65	0.40	0.64	14	0.12
Trichloroethene	2	3.6	0.89	3.0	0.74	16	0.60	ND	ND	69	0.57
Tetrachloroethene	2	4.3	1.0	4.2	1.0	36	0.66	ND	ND	129	1.0
1,2,4-Trimethylbenzene	2	2.8	0.61	5.4	1.2	64	0.69	0.33	0.91	0.7	0.53
Naphthalene	2	3.0	0.76	3.2	0.81	ND	ND	ND	ND	20	0.20
Methylethylketone	3	1.7	0.77	2.6	1.2	27	4.9	ND	ND	12	0.16
n-Hexane	3	3.3	1.2	2.9	1.1	26	3.8	0.58	1.7	77	1.0
1,2-Dichloroethane	3	2.2	0.72	2.3	0.76	7.0	0.45	ND	ND	53	0.67
1,1,1-Trichloroethane	3	3.4	0.83	2.8	0.68	4.6	0.44	0.17	0.34	28	0.26
Benzene	3	2.9	1.7	2.9	1.7	13	1.3	0.37	0.98	101	1.3
Carbon tetrachloride	3	5.0	1.1	3.2	0.72	8.3	0.63	0.28	0.45	16	0.14
Trichloroethene	3	3.6	0.89	2.9	0.72	13	0.49	ND	ND	67	0.55
Tetrachloroethene	3	4.3	1.0	4.2	1.0	29	0.53	ND	ND	124	0.94
1,2,4-Trimethylbenzene	3	3.0	0.66	3.4	0.74	53	0.57	0.35	0.96	50	0.52
Naphthalene	3	3.4	0.86	3.0	0.76	ND	ND	ND	ND	22	0.21

Run Number:		13									
Exposure Time (min):		10,100 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	270	17.6	790	52	620	16	38	16	16494	32
n-Hexane	1	2000	109	1000	55	5200	108	165	69	40667	79
1,2-Dichloroethane	1	1100	52	1200	57	7000	65	140	44	19553	36
1,1,1-Trichloroethane	1	1300	46	1400	49	6000	83	166	48	46940	64
Benzene	1	1700	146	920	79	5600	78	175	67	32741	62
Carbon tetrachloride	1	1800	59	1600	52	7600	83	208	48	47819	60
Trichloroethene	1	2300	82	1500	54	10000	55	241	64	48966	58
Tetrachloroethene	1	2900	100	2100	73	16000	42	329	80	60898	66
1,2,4-Trimethylbenzene	1	1900	60	1700	54	16000	25	220	88	35911	54
Naphthalene	1	170	6.2	160	5.9	340	0.24	18	13	3147	4.4
Methylethylketone	2	420	27.4	800	52	640	17	22	9.4	16242	31
n-Hexane	2	2100	115	1000	55	5100	106	161	68	39738	78
1,2-Dichloroethane	2	1100	52	1200	57	6900	64	137	43	18832	34
1,1,1-Trichloroethane	2	1400	49	1400	49	6000	83	164	48	45482	62
Benzene	2	1700	146	920	79	5500	77	170	65	32328	61
Carbon tetrachloride	2	1800	59	1600	52	7600	83	205	48	47325	60
Trichloroethene	2	2300	82	1500	54	10000	55	234	62	48564	58
Tetrachloroethene	2	3000	104	2100	73	16000	42	317	77	56558	62
1,2,4-Trimethylbenzene	2	2000	63	1700	54	17000	27	211	84	35084	53
Naphthalene	2	180	6.6	170	6.2	340	0.24	16	12	3355	4.7
Methylethylketone	3	250	16.3	790	52	610	16	20	8.5	16543	32
n-Hexane	3	2000	109	1000	55	5400	113	164	69	37435	73
1,2-Dichloroethane	3	1100	52	1200	57	7100	65	137	43	19677	36
1,1,1-Trichloroethane	3	1400	49	1400	49	6300	88	163	47	44126	60
Benzene	3	1700	146	910	78	5800	81	174	67	30591	58
Carbon tetrachloride	3	1900	62	1600	52	7800	85	203	47	44885	57
Trichloroethene	3	2300	82	1500	54	11000	60	239	63	46502	56
Tetrachloroethene	3	3000	104	2000	69	16000	42	326	80	54577	60
1,2,4-Trimethylbenzene	3	2000	63	1700	54	16000	25	219	87	34984	53
Naphthalene	3	170	6.2	160	5.9	300	0.22	18	13	3199	4.5

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		14									
Exposure Time (min):		10,125 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	ND	ND	8.4	0.55	24	0.6	1.2	0.48	11	0.020
n-Hexane	1	31	1.7	20	1.1	91	1.9	2.5	1.0	368	0.72
1,2-Dichloroethane	1	10	0.47	11	0.52	99	0.91	2.4	0.75	12	0.022
1,1,1-Trichloroethane	1	18	0.63	16	0.56	74	1.0	2.6	0.76	211	0.29
Benzene	1	22	1.9	12	1.0	78	1.1	2.5	0.93	493	0.93
Carbon tetrachloride	1	18	0.59	17	0.56	110	1.2	3.0	0.69	57	0.072
Trichloroethene	1	27	1.0	16	0.57	160	0.87	3.0	0.79	11	0.013
Tetrachloroethene	1	35	1.2	25	0.86	320	0.85	4.4	1.1	887	1.0
1,2,4-Trimethylbenzene	1	22	0.69	21	0.66	340	0.53	2.6	1.0	173	0.26
Naphthalene	1	21	0.77	18	0.66	64	0.05	2.0	1.5	257	0.36
Methylethylketone	2	ND	ND	8.7	0.57	ND	ND	1.0	0.40	7.1	0.014
n-Hexane	2	34	1.9	14	0.76	87	1.8	2.8	1.2	366	0.71
1,2-Dichloroethane	2	10	0.47	11	0.52	87	0.80	2.0	0.62	18	0.033
1,1,1-Trichloroethane	2	19	0.67	17	0.60	64	0.89	2.9	0.84	254	0.34
Benzene	2	22	1.9	13	1.1	71	1.0	2.6	1.0	513	1.0
Carbon tetrachloride	2	22	0.72	18	0.59	110	1.2	2.3	0.52	75	0.094
Trichloroethene	2	27	1.0	16	0.57	140	0.76	2.6	0.69	14	0.017
Tetrachloroethene	2	35	1.2	25	0.86	290	0.77	4.1	1.0	883	1.0
1,2,4-Trimethylbenzene	2	23	0.73	21	0.66	340	0.53	2.9	1.2	167	0.25
Naphthalene	2	21	0.77	19	0.70	67	0.05	2.2	1.6	256	0.36
Methylethylketone	3	ND	ND	9.4	0.61	ND	ND	1.1	0.46	6.5	0.013
n-Hexane	3	36	2.0	13	0.71	98	2.0	2.5	1.0	352	0.69
1,2-Dichloroethane	3	11	0.52	12	0.57	92	0.85	2.3	0.71	11	0.020
1,1,1-Trichloroethane	3	19	0.67	16	0.56	68	0.94	3.0	0.86	235	0.32
Benzene	3	22	1.9	12	1.0	74	1.0	2.3	0.86	488	0.92
Carbon tetrachloride	3	24	0.78	18	0.59	81	0.88	3.2	0.73	88	0.11
Trichloroethene	3	26	0.93	16	0.57	145	0.79	3.1	0.82	19	0.022
Tetrachloroethene	3	35	1.2	24	0.83	300	0.79	3.8	0.93	859	0.94
1,2,4-Trimethylbenzene	3	22	0.69	20	0.63	340	0.53	2.6	1.0	148	0.22
Naphthalene	3	21	0.77	18	0.66	64	0.05	2.3	1.7	179	0.25

Run Number:		15									
Exposure Time (min):		10,046 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	540	36.7	560	38	2200	60	172	73	16494	32
n-Hexane	1	1800	103	750	43	4300	93	195	82	40667	80
1,2-Dichloroethane	1	960	48	840	42	6100	59	231	73	19553	36
1,1,1-Trichloroethane	1	1300	48	1100	40	5300	77	287	83	46940	64
Benzene	1	1500	135	700	63	5100	75	204	78	32741	62
Carbon tetrachloride	1	1800	61	1200	41	6700	76	329	77	47819	61
Trichloroethene	1	2200	82	1200	45	9200	52	302	80	48966	59
Tetrachloroethene	1	3100	112	1900	69	14000	39	354	87	60898	67
1,2,4-Trimethylbenzene	1	2400	79	1800	59	15000	25	233	93	35911	54
Naphthalene	1	220	8.4	210	8.0	320	0.24	19	14	3147	4.5
Methylethylketone	2	510	34.7	560	38	1700	46	169	71	16242	31
n-Hexane	2	1800	103	740	42	4000	87	199	84	39738	78
1,2-Dichloroethane	2	980	49	830	41	5600	54	235	74	18832	35
1,1,1-Trichloroethane	2	1400	52	1100	40	4900	71	291	85	45482	62
Benzene	2	1500	135	700	63	4700	69	208	80	32328	61
Carbon tetrachloride	2	1800	61	1200	41	6200	71	334	78	47325	60
Trichloroethene	2	2200	82	1200	45	8600	49	307	81	48564	58
Tetrachloroethene	2	3200	115	1900	69	14000	39	362	89	56558	62
1,2,4-Trimethylbenzene	2	2400	79	1800	59	15000	25	237	95	35084	53
Naphthalene	2	230	8.8	200	7.7	320	0.24	19	14	3355	4.8
Methylethylketone	3	380	25.9	590	40	2200	60	167	70	16543	32
n-Hexane	3	1800	103	770	44	4300	93	194	82	37435	73
1,2-Dichloroethane	3	970	48	850	42	6100	59	230	72	19677	36
1,1,1-Trichloroethane	3	1200	44	1000	37	5300	77	286	83	44126	60
Benzene	3	1500	135	690	62	5100	75	203	78	30591	58
Carbon tetrachloride	3	1800	61	1200	41	6600	75	328	77	44885	57
Trichloroethene	3	2200	82	1200	45	9300	53	299	79	46502	56
Tetrachloroethene	3	3100	112	1900	69	15000	41	354	87	54577	60
1,2,4-Trimethylbenzene	3	2300	76	1800	59	16000	26	233	93	34984	53
Naphthalene	3	220	8.4	190	7.3	330	0.25	20	15	3199	4.5

Run Number:		16									
Exposure Time (min):		10,033 (7 days)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	ND	ND	6.4	0.44	ND	ND	2.4	1.0	22	0.043
n-Hexane	1	24	1.4	8.9	0.51	72	1.6	2.8	1.2	820	1.7
1,2-Dichloroethane	1	10	0.50	8.4	0.42	74	0.71	2.7	0.85	562	1.1
1,1,1-Trichloroethane	1	15	0.55	11	0.41	54	0.78	3.7	1.1	419	0.6
Benzene	1	22	2.0	10	0.85	59	0.86	2.7	1.0	748	1.5
Carbon tetrachloride	1	24	0.82	12	0.41	62	0.71	3.7	0.86	163	0.21
Trichloroethene	1	28	1.0	12	0.45	120	0.68	3.6	0.95	362	0.45
Tetrachloroethene	1	39	1.4	20	0.72	250	0.69	4.6	1.1	1396	1.6
1,2,4-Trimethylbenzene	1	25	0.83	20	0.66	300	0.49	3.0	1.2	712	1.1
Naphthalene	1	23	0.88	20	0.77	62	0.046	3.1	2.3	356	0.53
Methylethylketone	2	ND	ND	6.4	0.44	24	0.65	2.4	1.0	26	0.053
n-Hexane	2	23	1.3	8.7	0.50	73	1.6	2.6	1.1	587	1.2
1,2-Dichloroethane	2	10	0.50	8.3	0.41	78	0.75	3.1	1.0	415	0.79
1,1,1-Trichloroethane	2	14	0.52	11	0.41	58	0.84	3.5	1.0	431	0.61
Benzene	2	21	1.9	8.5	0.76	61	0.89	2.5	1.0	523	1.0
Carbon tetrachloride	2	25	0.86	12	0.41	61	0.70	3.5	0.82	126	0.17
Trichloroethene	2	27	1.0	12	0.45	115	0.66	3.7	1.0	305	0.38
Tetrachloroethene	2	38	1.4	21	0.76	230	0.64	4.7	1.2	952	1.1
1,2,4-Trimethylbenzene	2	25	0.83	20	0.66	260	0.43	2.8	1.1	496	0.78
Naphthalene	2	21	0.81	21	0.81	54	0.040	3.4	2.6	275	0.41
Methylethylketone	3	ND	ND	6.1	0.42	26	0.71	2.3	1.0	211	0.42
n-Hexane	3	23	1.3	8.3	0.47	81	1.8	2.7	1.1	614	1.3
1,2-Dichloroethane	3	8	0.39	8.7	0.43	81	0.78	3.1	1.0	548	1.0
1,1,1-Trichloroethane	3	12	0.44	11	0.41	59	0.86	3.9	1.1	663	0.94
Benzene	3	21	1.9	9.0	0.81	65	0.95	2.7	1.0	558	1.1
Carbon tetrachloride	3	22	0.75	13	0.44	100	1.14	3.8	0.88	316	0.42
Trichloroethene	3	28	1.0	12	0.45	130	0.74	4.0	1.1	657	0.82
Tetrachloroethene	3	39	1.4	20	0.72	260	0.72	4.4	1.1	993	1.1
1,2,4-Trimethylbenzene	3	26	0.86	20	0.66	310	0.51	3.0	1.2	464	0.73
Naphthalene	3	23	0.88	21	0.81	62	0.046	2.9	2.2	144	0.21

APPENDIX F: RESULTS OF FRACTIONAL FACTORIAL TESTING

Run Number:		17									
Exposure Time (min):		1,420 (1 day)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	17	8.2	140	68	190	37	10	29	364	5.2
n-Hexane	1	330	134	180	73	540	84	30	91	4790	69
1,2-Dichloroethane	1	200	71	200	71	930	64	31	69	3700	50
1,1,1-Trichloroethane	1	180	47	240	63	750	77	40	82	6208	63
Benzene	1	270	173	160	102	710	74	31	84	4549	64
Carbon tetrachloride	1	310	75	270	66	950	77	46	76	4058	38
Trichloroethene	1	400	107	260	69	1400	57	43	81	5870	52
Tetrachloroethene	1	540	139	360	93	2600	51	54	94	10950	89
1,2,4-Trimethylbenzene	1	360	85	290	68	2800	33	35	98	4995	56
Naphthalene	1	25	6.8	33	9.0	54	0.29	2.8	15	534	5.6
Methylethylketone	2	12	5.8	140	68	250	49	11	34	414	5.9
n-Hexane	2	320	130	180	73	750	116	30	90	4790	69
1,2-Dichloroethane	2	190	67	200	71	1100	75	31	68	3855	52
1,1,1-Trichloroethane	2	190	50	240	63	910	94	38	79	6474	65
Benzene	2	280	179	160	102	870	91	31	84	4695	66
Carbon tetrachloride	2	310	75	290	71	1200	97	49	81	4419	41
Trichloroethene	2	410	109	260	69	1700	69	43	81	6697	59
Tetrachloroethene	2	550	142	390	100	3000	59	54	93	10608	86
1,2,4-Trimethylbenzene	2	370	87	300	70	3000	35	35	99	4943	55
Naphthalene	2	29	7.9	32	8.7	57	0.30	2.6	14	497	5.2
Methylethylketone	3	30	14.6	150	73	191	37	10	29	307	4.4
n-Hexane	3	320	130	180	73	560	87	30	89	4922	71
1,2-Dichloroethane	3	200	71	200	71	960	66	30	66	3535	48
1,1,1-Trichloroethane	3	250	66	240	63	770	80	38	78	6611	67
Benzene	3	270	173	170	109	740	77	30	83	4972	70
Carbon tetrachloride	3	350	85	290	71	1000	81	43	70	4781	45
Trichloroethene	3	400	107	270	72	1500	61	43	80	6676	59
Tetrachloroethene	3	520	134	380	98	2900	57	53	91	11209	91
1,2,4-Trimethylbenzene	3	370	87	300	70	2000	23	34	96	4507	50
Naphthalene	3	29	7.9	31	8.5	60	0.32	3.0	16	542	5.7

Run Number:		18									
Exposure Time (min):		1,437 (1 day)									
		ATD Tube - CB		ATD Tube - TA		WMS		Radiello		WMS	
Analyte	Replicate	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)	Mass (ng)	Concn (ppbv)
Methylethylketone	1	ND	ND	3.2	1.5	ND	ND	ND	ND	10	0.14
n-Hexane	1	3.4	1.4	2.1	0.84	ND	ND	0.53	1.6	11	0.16
1,2-Dichloroethane	1	0.81	0.28	1.8	0.63	3.3	0.22	ND	ND	0.24	0.0032
1,1,1-Trichloroethane	1	1.6	0.42	2.2	0.57	9.3	1.0	ND	ND	11	0.11
Benzene	1	3.5	2.2	2.5	1.58	11	1.1	0.48	1.3	118	1.6
Carbon tetrachloride	1	2.3	0.55	2.6	0.63	15	1.2	0.35	0.57	5.0	0.046
Trichloroethene	1	3.5	0.92	2.5	0.66	10	0.40	ND	ND	4.0	0.035
Tetrachloroethene	1	4.9	1.2	3.8	1.0	25	0.49	ND	ND	91	0.73
1,2,4-Trimethylbenzene	1	3.1	0.72	3.2	0.74	32	0.37	0.37	1.0	7.3	0.081
Naphthalene	1	2.8	0.76	3.6	1.0	3.3	0.017	ND	ND	15	0.15
Methylethylketone	2	ND	ND	2.6	1.2	ND	ND	ND	ND	4.6	0.065
n-Hexane	2	3.9	1.6	2.0	0.80	ND	ND	0.66	1.9	46	0.66
1,2-Dichloroethane	2	1.2	0.42	1.7	0.59	2.2	0.15	ND	ND	1.6	0.021
1,1,1-Trichloroethane	2	1.5	0.39	2.3	0.60	5.9	0.60	0.28	0.57	16	0.16
Benzene	2	3.4	2.2	2.4	1.5	15	1.5	0.33	0.89	90	1.2
Carbon tetrachloride	2	1.8	0.43	2.8	0.67	15	1.2	0.15	0.24	6.5	0.060
Trichloroethene	2	3.8	1.0	2.5	0.66	10	0.40	ND	ND	1.5	0.013
Tetrachloroethene	2	5.5	1.4	3.7	0.94	28	0.55	ND	ND	122	0.98
1,2,4-Trimethylbenzene	2	3.0	0.70	3.2	0.74	39	0.45	0.42	1.2	32	0.36
Naphthalene	2	1.9	0.51	3.5	0.95	4.4	0.023	ND	ND	33	0.34
Methylethylketone	3	ND	ND	2.5	1.2	ND	ND	ND	ND	6.6	0.094
n-Hexane	3	3.9	1.6	2.1	0.84	ND	ND	0.70	2.1	36	0.52
1,2-Dichloroethane	3	1.4	0.49	2.0	0.70	2.3	0.16	0.15	0.00	0.6	0.01
1,1,1-Trichloroethane	3	1.7	0.44	2.4	0.62	6.5	0.66	0.26	0.53	13	0.13
Benzene	3	3.1	2.0	2.7	1.7	15	1.5	0.42	1.1	92	1.3
Carbon tetrachloride	3	1.4	0.34	2.8	0.67	16	1.3	0.32	0.52	5.9	0.055
Trichloroethene	3	3.7	1.0	2.6	0.69	10	0.40	ND	ND	1.6	0.014
Tetrachloroethene	3	5.1	1.3	3.8	1.0	26	0.51	ND	ND	106	0.85
1,2,4-Trimethylbenzene	3	3.3	0.77	3.6	0.84	35	0.40	0.46	1.29	26	0.28
Naphthalene	3	2.4	0.65	6.0	1.6	3.8	0.020	ND	ND	47	0.49

Notes:

NA - Not Analyzed
ng - nanograms
ppbv - parts per billion by volume
Concn - concentration

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September 2, 2011

Ms. Hester Groenevelt, M.Sc.
Geosyntec Consultants, Inc.
130 Research Lane, Suite 2
Guelph, ON N1G 5G3

Re: SKC sampler observations & recommendations—Columbia Analytical

Dear Hester,

Throughout the course of the ESTCP Passive Sampler Project, Columbia Analytical has made several observations and experienced several analytical challenges related to the analysis of the SKC Ultra II sampling devices. The purpose of this memo is to document these issues, as well as provide our recommendations for future work in this area. Our comments are focused on two different sorbents that were used throughout the course of the project for thermal desorption analysis: Carbograph 5 and Carbopack X.

OBSERVATIONS

1. Sampler Design. The SKC Ultra II sampler is designed such that the sorbent material may be stored separately from the housing, with the intent of preserving the cleanliness of the sorbent media. Sorbent material may be thoroughly cleaned and certified by the laboratory, shipped in a small vial, and then poured into the sampler housing immediately before use in the field. This approach, while nice in theory, did not prove to be practical in a real world setting. Conditions in the field are often not conducive for dealing with sampling media that require fine motor skills and careful transfer of sorbent. In Columbia Analytical's opinion, it is not clear whether there would be a significant improvement in data quality when packing the sorbent material into the housing in the field, versus pre-packing the material in the laboratory—during this project we observed issues with field blank contamination under both scenarios. Additionally, with these sorbents, minimizing the transfer of the material is desirable (see sorbent durability below), so pre-packed samplers may be a better choice.

   Once in the laboratory, the SKC Ultra II samplers require transfer of the sorbent material (either from the glass vial, or from the sampler housing) into a thermal desorption tube for analysis. Although the laboratory is a location better suited for performing such tasks, this sorbent material proved to be messy and difficult to transfer (see sorbent durability below). Also, since the sorbent is exposed in the badge style sampler during sampling, it is assumed that the compounds of interest are evenly distributed throughout the sorbent material. This material is then placed in a traditional thermal desorption tube, with a gas flow purging through the tube and sweeping vapors onto the column for analysis. Since Carbograph 5/Carbopack X are strong sorbents, it is possible that all the analytes of interest are not completely desorbed off the back of the tube. The opposite may also be true—for the more volatile compounds, there may be losses off of the material at the front of the tube. Columbia Analytical has not had a chance to investigate this phenomenon further, but this phenomenon (likely in conjunction with several other factors) could contribute to the biases and/or anomalies that were seen with this sampling media.

2. Sorbent Durability/Physical Characteristics. Carbograph 5/Carbopack X were chosen as the sorbent materials for use in the SKC Ultra II samplers. Even with minimal use, these materials transfer fine particles and sooty material to the fingers of the user (sampling technician in the field and/or analytical staff in the laboratory) and/or the analytical instrumentation, potentially resulting in sample loss and a low bias. One solution that Columbia Analytical employed on this project was to sieve the material (removing fine particles) and then check/re-check the sorbent material for cleanliness prior to shipping to the field. Clearly, this additional step adds lead time to a project and increases the cost for the laboratory performing the work.

3. Sorbent Lifespan. A related issue is the overall lifespan of the Carbograph 5/Carbopack X sorbent material. One benefit of typical thermal desorption media is its ability to regenerate and be re-used for a fairly long period of time, thus increasing the cost effectiveness of the technique in the long term. In Columbia Analytical's experience, these sorbents have a much shorter lifespan than other sorbents. After only a few uses, our chemists observed residual background contamination in the sorbent media that could not be removed.

4. Sorbent Background Contamination. Our chemists observed background levels of benzene and MEK in these sorbents and were forced to therefore raise the reporting limit of these compounds. The sorbent media as received from the manufacturer required additional conditioning to meet the objectives of this project (i.e. low reporting limits), and even with additional cleaning, background levels of benzene were still observed (in the range of approximately 20-25 ng). It is possible that for higher concentration applications, or applications where low reporting limits were not needed, that the background levels seen on the media would not pose a concern.

5. Analytical Challenges. Since the passive samplers were being used to sample various concentration sources, and were deployed for various lengths of time, Columbia Analytical had to utilize two different calibration ranges: one low level (approximately 1-500 ng/tube) and one high level (approximately 200-50,000 ng/tube). Optimally, a laboratory would have one calibration curve spanning several orders of magnitude (e.g. 50-50,000 ng/tube), and samples would be deployed long enough such that the reporting limit was sensitive enough (and high enough above background levels) to meet the objectives of the project. Calibrating for a range of volatile organic compounds on a strong sorbent like Carbograph 5/Carbopack X proved difficult overall, as compared with calibration for a short targeted list of compounds with a sorbent matched specifically to the compounds of interest. Unlike canister samples, thermal desorption tube samples cannot easily be screened in the laboratory to determine the optimal split ratio/injection volume. While samples may be split and re-collected using current instrumentation, this clearly adds time and uses additional resources at the laboratory, which would increase the cost for a commercially available analysis.

RECOMMENDATIONS

1. QC of Sorbent Media. Based on the experience in this study, as well as other programs, ***Columbia Analytical recommends checking the cleanliness of all thermally desorbed media prior to use in the field.*** Upon receiving a batch of samplers/sampling media, an initial batch QC check is recommended. Subsequent uses of the material/samplers, Columbia Analytical recommends individual QC of the media prior to use in the field. A thorough documentation of background levels present in the media will be key to the success of sampling programs which use the SKC Ultra II sampler and/or Carbograph 5/Carbopack X sorbents.

2. Trip Blanks. For any project using sorbent materials, especially strong sorbents such as Carbograph 5/Carbopack X, a trip blank will prove to be a critical piece of information. As observed with Trip Blank B24264 for this project, even though the laboratory cleaned and certified the sorbent material prior to shipping to the field (certified with no MEK detected, and only 23ng of benzene), levels of contaminants were seen at significantly higher levels in the field blank (MEK at 220 ng and benzene at 320 ng).

3. Sorbent Selection. For a wide range of compounds, a strong sorbent such as Carbograph 5/Carbopack X may not be the optimal choice. While the strong sorbent was needed to effectively capture compounds such as MEK, Columbia Analytical holds the opinion that the cons of these sorbents (poor durability, short lifespan, background contamination) outweighed the pros for this project.

Please let us know if you have any follow up questions about the information and opinions we have shared in this document. We thank you for teaming with us on this substantial research effort, and we look forward to working with you on the upcoming final sampling event.

Best regards,

Alyson Fortune
Air Quality Scientist
Columbia Analytical Services
afortune@caslab.com

cc. Kelly Horiuchi, Chris Parnell, Michael Tuday

Geosyntec
consultants

APPENDIX G

Results of Indoor and Outdoor Air Monitoring at MCAS Cherry Point

May 2015

TABLE G1
Passive and Active Sample VOC Concentrations at MCAS 137, Cherry Point

Matrix:	Indoor Air											
Sample Location:	Indoor Air Location #1											
Sampler Type:	OVM			Radiello			WMS			SKC		
Sample Location:	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C
Client Sample ID:	137-IA-1A-OVM	137-IA-1B-OVM	137-IA-1C-OVM	137-IA-1A-RAD	137-IA-1B-RAD	137-IA-1C-RAD	137-IA-1A-WMS	137-IA-1B-WMS	137-IA-1C-WMS	137-IA-1A-SKC	137-IA-1B-SKC	137-IA-1C-SKC
Sampler Type/Sorbent:	Regular/charcoal	Regular/charcoal	Regular/charcoal	Yellow body/thermal	Yellow body/thermal	Yellow body/thermal	Regular/Carbopack B	Regular/Carbopack B	Regular/Carbopack B	Regular II/Carbograph 5	Regular II/Carbograph 5	Regular II/Carbograph 5
Deployment Date/Time:	1-6-11 2:17 PM	1-6-11 2:17 PM	1-6-11 2:17 PM	1-6-11 2:29 PM	1-6-11 2:30 PM	1-6-11 2:31 PM	1-6-11 2:39 PM	1-6-11 2:39 PM	1-6-11 2:40 PM	1-6-11 2:35 PM	1-6-11 2:36 PM	1-6-11 2:37 PM
Collection Date/Time:	1-13-11 12:03 PM	1-13-11 12:00 PM	1-13-11 12:00 PM	1-13-11 12:06 PM	1-13-11 12:05 PM	1-13-11 12:05 PM	1-13-11 11:52 AM	1-13-11 11:51 AM	1-13-11 11:53 AM	1-13-11 11:55 AM	1-13-11 11:57 AM	1-13-11 11:58 AM
Exposure Duration (min):	9946	9943	9943	9937	9935	9934	9913	9912	9913	9920	9921	9921
Exposure Duration (days):	6.91	6.90	6.90	6.90	6.90	6.90	6.88	6.88	6.88	6.89	6.89	6.89
Laboratory Sample ID:	1101206C-21A	1101206C-22A	1101206C-23A	1101206A-01A	1101206A-02A	1101206A-03A	1101206D-31A	1101206D-32A	1101206D-33A	1101206B-11A	1101206B-12A	1101206B-13A
Volatile Organic Compounds ($\mu g/m^3$)												
1,1,1-Trichloroethane	**6.4**	**6.4**	**8**	**15 E**	**15 E**	**15 E**	**3.3**	**3.4**	**3.7**	**2.8**	**2.8**	**3.4**
1,1,2-Trichloroethane	0.25 U	0.25 U	0.25 U	0.027 U	0.027 U	0.027 U	0.069 U	0.069 U	0.069 U	0.025 U	0.025 U	0.025 U
1,1-Dichloroethane	**3.6**	**3.7**	**4**	**0.48**	**0.52**	**0.48**	**0.3**	**0.47**	**0.45**	**4.1**	**3.8**	**4.2**
1,1-Dichloroethene	**0.81 J**	**0.82 J**	**0.94 J**	**0.022**	**0.028**	**0.019**	0.25 U	**0.36**	**0.25**	**1.4**	**1.5**	**1.4**
1,2-Dichloroethane	**0.23 J**	**0.23 J**	**0.23 J**	**0.061**	**0.061**	**0.061**	0.078 U	0.078 U	0.078 U	**0.14**	**0.14**	**0.15**
Benzene	**0.75**	**0.8**	**0.77**	**0.83**	**0.91**	**0.87**	**0.52**	**0.54**	**0.6**	**1.3**	**1.2**	**1.3**
cis-1,2-Dichloroethene	**1.1**	**1.1**	**1.1**	**0.063**	**0.063**	**0.06**	**0.1**	**0.14**	**0.15**	**1.6**	**1.6**	**1.7**
Ethyl Benzene	**0.39**	**0.41**	**0.41**	**0.63**	**0.67**	**0.67**	**0.3**	**0.27**	**0.28**	**0.72**	**0.71**	**0.77**
m,p-Xylene	**1.4**	**1.5**	**1.6**	**2.2**	**2.5**	**2.3**	**1.2**	**1.1**	**1.2**	**2.6**	**2.6**	**2.9**
o-Xylene	**0.52**	**0.54**	**0.55**	**0.9**	**0.98**	**0.94**	**0.43**	**0.42**	**0.41**	**1**	**1**	**1.1**
Tetrachloroethene	**0.079**	**0.083**	**0.083**	**0.06**	**0.058**	**0.058**	**0.066**	0.064 U	**0.068**	**0.086**	**0.092**	**0.1**
Toluene	**9.2**	**9.8**	**10**	**9.1 E**	**11 E**	**11 E**	**7.5**	**6.9**	**7.5**	**13 E**	**13 E**	**13 E**
trans-1,2-Dichloroethene	**2.9**	**2.8**	**2.9**	**0.46**	**0.44**	**0.44**	**0.63**	**0.71**	**0.73**	**4.5**	**4.4**	**4.7**
Trichloroethene	**3.3**	**3.2**	**3.7**	**1.4**	**1.5**	**1.5**	**1.8**	**1.8**	**2**	**3.2**	**3.2**	**3.5**

Notes: U = non-detect (associated value is the reporting limit
E = estimated value

TABLE G1
Passive and Active Sample VOC Concentrations at MCAS 137, Cherry Point

Matrix:	Indoor Air												
Sample Location:	Indoor Air Location #1						Indoor Air Location #2						
Sampler Type:	ATD Tube			Summa			OVM			Radiello			WMS
Sample Location:	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A
Client Sample ID:	137-IA-1A-ATD	137-IA-1B-ATD	137-IA-1C-ATD	137-IA-1A-SUM	137-IA-1B-SUM	137-IA-1C-SUM	137-IA-2A-OVM	137-IA-2B-OVM	137-IA-2C-OVM	137-IA-2A-RAD	137-IA-2B-RAD	137-IA-2C-RAD	137-IA-2A-WMS
Sampler Type/Sorbent:	Regular/Carbopack B	Regular/Carbopack B	Regular/Carbopack B	--	--	--	Regular/charcoal	Regular/charcoal	Regular/charcoal	Yellow body/thermal	Yellow body/thermal	Yellow body/thermal	Regular/Carbopack B
Deployment Date/Time:	11-01-06	11-01-06	11-01-06	11-01-06	11-01-06	11-01-06	1-6-11 1:25 PM	1-6-11 1:27 PM	1-6-11 1:29 PM	1-6-11 1:37 PM	1-6-11 1:38 PM	1-6-11 1:41 PM	1-6-11 1:33 PM
Collection Date/Time:	11-01-13	11-01-13	11-01-13	1/13/11	1/13/11	1/13/11	1-13-11 10:53 AM	1-13-11 10:54 AM	1-13-11 10:55 AM	1-13-11 10:51 AM	1-13-11 10:50 AM	1-13-11 10:50 AM	1-13-11 10:45 AM
Exposure Duration (min):	9920	9921	9923				9928	9927	9926	9914	9912	9909	9912
Exposure Duration (days):	6.89	6.89	6.89	--	--	--	6.89	6.89	6.89	6.88	6.88	6.88	6.88
Laboratory Sample ID:	1101206E-41A	1101206E-42A	1101206E-43A	P1100149-001	P1100149-002	P1100149-003	1101206C-24A	1101206C-25A	1101206C-26A	1101206A-04A	1101206A-05A	1101206A-06A	1101206D-34A
Volatile Organic Compounds ($\mu g/m^3$)													
1,1,1-Trichloroethane	**8.3**	**8.1**	**8.1**	**11**	**10**	**11**	0.24 U	0.24 U	0.24 U	0.14 U	0.14 U	0.14 U	0.18 U
1,1,2-Trichloroethane	0.46 U	0.46 U	0.46 U	0.12 U	0.18 U	0.13 U	0.25 U	0.25 U	0.25 U	0.027 U	0.027 U	0.027 U	0.069 U
1,1-Dichloroethane	**2.6**	**2.4**	**2**	**6.2**	**5.8**	**6.1**	0.23 U	0.23 U	0.23 U	0.0087 U	0.0087 U	0.0087 U	0.17 U
1,1-Dichloroethene	**0.9**	**0.94**	**1.2**	**2.4**	**2.1**	**2.2**	**0.45 J**	**0.45 J**	**0.45 J**	0.0026 U	0.0026 U	0.0026 U	0.25 U
1,2-Dichloroethane	0.40 U	0.40 U	0.40 U	**0.21**	**0.21**	**0.19**	**0.23 J**	**0.23 J**	**0.23 J**	**0.012**	**0.013**	**0.014**	0.078 U
Benzene	**1.6**	**1.8**	**1.6**	**0.76**	**0.7**	**0.67**	**0.94**	**0.9**	**0.86**	**0.91**	**0.98**	**0.91**	**0.59**
cis-1,2-Dichloroethene	**1.2**	**1.1**	**1.2**	**1.8**	**1.7**	**1.7**	**0.024**	**0.025**	**0.023**	0.0031 U	0.0031 U	0.0031 U	0.1 U
Ethyl Benzene	**0.84**	**0.84**	**0.97**	0.62 U	0.91 U	0.64 U	**0.45**	**0.53**	**0.5**	**0.78**	**0.79**	**0.75**	**0.34**
m,p-Xylene	**3**	**3**	**3.7**	**1.9**	**1.7**	**1.8**	**1.2**	**1.4**	**1.3**	**2.1**	**2.1**	**2**	**1.1**
o-Xylene	**1.2**	**1.1**	**1.4**	**0.7**	0.91 U	**0.68**	**0.47**	**0.54**	**0.51**	**0.86**	**0.9**	**0.86**	**0.38**
Tetrachloroethene	0.84 U	0.84 U	0.84 U	**0.13**	0.18 U	0.13 U	**0.18**	**0.2**	**0.19**	**0.15**	**0.15**	**0.14**	**0.14**
Toluene	**23**	**22**	**23**	**16**	**15**	**15**	**3.3**	**3.7**	**3.5**	**4.7 E**	**4.7 E**	**4.4 E**	**3.4**
trans-1,2-Dichloroethene	**3.2**	**3.2**	**3.4**	**4.2**	**4.2**	**4.1**	**29**	**32**	**31**	**2.3 E**	**2.5 E**	**2.9 E**	**3.3**
Trichloroethene	**4.4**	**4.4**	**4.6**	**4.9**	**4.8**	**4.7**	**0.025**	**0.024**	**0.026**	**0.0073**	**0.0094**	**0.0088**	0.083 U

Notes: U = non-detect (associated v
E = estimated value

TABLE G1
Passive and Active Sample VOC Concentrations at MCAS 137, Cherry Point

Matrix:	Indoor Air											
Sample Location:	Indoor Air Location #2											
Sampler Type:	WMS		SKC			ATD Tube			Summa			
Sample Location:	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C
Client Sample ID:	137-IA-2B-WMS	137-IA-2C-WMS	137-IA-2A-SKC	137-IA-2B-SKC	137-IA-2C-SKC	137-IA-2A-ATD	137-IA-2B-ATD	137-IA-2C-ATD	137-IA-2A-SUM	137-IA-2B-SUM	137-IA-2C-SUM
Sampler Type/Sorbent:	Regular/Carbopack B	Regular/Carbopack B	Regular II/Carbograph 5	Regular II/Carbograph 5	Regular II/Carbograph 5	Regular/Carbopack B	Regular/Carbopack B	Regular/Carbopack B	--	--	--
Deployment Date/Time:	1-6-11 1:33 PM	1-6-11 1:32 PM	1-6-11 1:48 PM	1-6-11 1:50 PM	1-6-11 1:51 PM	11-01-06	11-01-06	11-01-06	11-01-06	11-01-06	11-01-06
Collection Date/Time:	1-13-11 10:46 AM	1-13-11 10:46 AM	1-13-11 10:53 AM	1-13-11 10:54 AM	1-13-11 10:55 AM	11-01-13	11-01-13	11-01-13	1/13/11	1/13/11	1/13/11
Exposure Duration (min):	9913	9914	9905	9904	9904	9912	9914	9912			
Exposure Duration (days):	6.88	6.88	6.88	6.88	6.88	6.88	6.88	6.88	--	--	--
Laboratory Sample ID:	1101206D-35A	1101206D-36A	1101206B-14A	1101206B-15A	1101206B-16A	1101206E-44A	1101206E-45A	1101206E-46A	P1100149-004	P1100149-005	P1100149-006
Volatile Organic Compounds ($\mu g/m^3$)											
1,1,1-Trichloroethane	0.18 U	0.18 U	0.029 U	0.029 U	0.029 U	0.54 U	0.54 U	0.54 U	0.15 U	0.14 U	0.18 U
1,1,2-Trichloroethane	0.069 U	0.069 U	0.025 U	0.025 U	0.025 U	0.46 U	0.46 U	0.46 U	0.15 U	0.14 U	0.18 U
1,1-Dichloroethane	0.17 U	0.17 U	0.015 U	0.015 U	0.015 U	0.40 U	0.40 U	0.40 U	0.15 U	0.14 U	0.18 U
1,1-Dichloroethene	0.25 U	0.25 U	**0.037**	**0.036**	**0.024**	0.35 U	0.35 U	0.35 U	0.15 U	0.14 U	0.18 U
1,2-Dichloroethane	0.078 U	0.078 U	**0.056**	**0.057**	**0.054**	0.40 U	0.40 U	0.40 U	0.15 U	0.14 U	0.18 U
Benzene	**0.61**	**0.61**	**1.8**	**1.8**	**1.6**	**1.8**	**1.8**	**1.6**	**0.88**	**0.85**	**0.87**
cis-1,2-Dichloroethene	0.1 U	0.1 U	**0.16**	**0.16**	**0.16**	0.43 U	0.43 U	0.43 U	0.15 U	0.14 U	0.18 U
Ethyl Benzene	**0.32**	**0.29**	**0.87**	**0.9**	**0.84**	**0.98**	**1**	**1**	0.76 U	0.70 U	0.92 U
m,p-Xylene	**1**	**0.93**	**2.6**	**2.7**	**2.5**	**2.8**	**2.8**	**2.8**	**1.7**	**1.7**	**1.7**
o-Xylene	**0.36**	**0.34**	**1**	**1.1**	**0.96**	**1.1**	**1.1**	**1.1**	0.76 U	0.70 U	0.92 U
Tetrachloroethene	**0.13**	**0.13**	**0.24**	**0.25**	**0.22**	0.84 U	0.84 U	0.84 U	**0.28**	**0.28**	**0.26**
Toluene	**3.2**	**2.7**	**6.4**	**6.5**	**6.1**	**7.9**	**7.9**	**8.2**	**5.6**	**5.4**	**5.7**
trans-1,2-Dichloroethene	**5.3**	**6.2**	**28 E**	**29 E**	**28 E**	**32**	**29**	**29**	**47**	**49**	**49**
Trichloroethene	0.083 U	0.083 U	**0.035**	**0.031**	**0.026**	0.54 U	0.54 U	0.54 U	0.15 U	0.14 U	0.18 U

Notes: U = non-detect (associated v
E = estimated value

TABLE G1
Passive and Active Sample VOC Concentrations at MCAS 137, Cherry Point

Matrix:	Indoor Air											
Sample Location:	Indoor Air Location #3											
Sampler Type:	OVM			Radiello			WMS			SKC		
Sample Location:	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C
Client Sample ID:	137-IA-3A-OVM	137-IA-3B-OVM	137-IA-3C-OVM	137-IA-3A-RAD	137-IA-3B-RAD	137-IA-3C-RAD	137-IA-3A-WMS	137-IA-3B-WMS	137-IA-3C-WMS	137-IA-3A-SKC	137-IA-3B-SKC	137-IA-3C-SKC
Sampler Type/Sorbent:	Regular/charcoal	Regular/charcoal	Regular/charcoal	Yellow body/thermal	Yellow body/thermal	Yellow body/thermal	Regular/Carbopack B	Regular/Carbopack B	Regular/Carbopack B	Regular II/Carbograph 5	Regular II/Carbograph 5	Regular II/Carbograph 5
Deployment Date/Time:	1-6-11 12:16 PM	1-6-11 12:18 PM	1-6-11 12:20 PM	1-6-11 12:23 PM	1-6-11 12:27 PM	1-6-11 12:28 PM	1-6-11 1:01 PM	1-6-11 12:58 PM	1-6-11 1:02 PM	1-6-11 12:48 PM	1-6-11 12:46 PM	1-6-11 12:49 PM
Collection Date/Time:	1-13-11 11:20 AM	1-13-11 11:23 AM	1-13-11 11:18 AM	1-13-11 11:10 AM	1-13-11 11:11 AM	1-13-11 11:13 AM	1-13-11 11:15 AM	1-13-11 11:14 AM	1-13-11 11:15 AM	1-13-11 11:24 AM	1-13-11 11:25 AM	1-13-11 11:26 AM
Exposure Duration (min):	10024	10025	10018	10007	10004	10005	9974	9976	9973	9996	9999	9997
Exposure Duration (days):	6.96	6.96	6.96	6.95	6.95	6.95	6.93	6.93	6.93	6.94	6.94	6.94
Laboratory Sample ID:	1101206C-27A	1101206C-28A	1101206C-29A	1101206A-07A	1101206A-08A	1101206A-09A	1101206D-37A	1101206D-38A	1101206D-39A	1101206B-17A	1101206B-18A	1101206B-19A
Volatile Organic Compounds												
(µg/m³)	10024	10025										
1,1,1-Trichloroethane	0.24 U	0.24 U	0.24 U	0.13 U	0.13 U	0.13 U	0.18 U	0.18 U	0.18 U	0.029 U	0.029 U	0.029 U
1,1,2-Trichloroethane	0.25 U	0.25 U	0.25 U	0.027 U	0.027 U	0.027 U	0.069 U	0.069 U	0.069 U	0.024 U	0.024 U	0.024 U
1,1-Dichloroethane	0.22 U	0.22 U	0.22 U	0.0086 U	0.0086 U	0.0086 U	0.17 U	0.17 U	0.17 U	0.015 U	0.015 U	0.015 U
1,1-Dichloroethene	**0.45 J**	**0.45 J**	**0.45 J**	0.0025 U	0.0025 U	0.0025 U	0.24 U	0.24 U	0.24 U	0.02 U	**0.022**	**0.024**
1,2-Dichloroethane	**0.22 J**	**0.22 J**	**0.22 J**	**0.016**	**0.02**	**0.018**	0.078 U	0.078 U	0.078 U	**0.054**	**0.058**	**0.053**
Benzene	**1**	**1.1**	**1.2**	**1**	**1**	**1**	**0.61**	**0.66**	**0.66**	**1.6**	**1.6**	**1.5**
cis-1,2-Dichloroethene	**0.027**	0.021 U	**0.024**	0.0031 U	0.0031 U	0.0031 U	0.1 U	0.1 U	0.1 U	**0.14**	**0.14**	**0.13**
Ethyl Benzene	**0.5**	**0.45**	**0.52**	**0.7**	**0.62**	**0.66**	**0.32**	**0.31**	**0.27**	**0.74**	**0.81**	**0.79**
m,p-Xylene	**1.4**	**1.2**	**1.4**	**1.8**	**1.6**	**1.7**	**0.96**	**0.94**	**0.83**	**2.1**	**2.3**	**2.2**
o-Xylene	**0.52**	**0.48**	**0.38**	**0.77**	**0.69**	**0.77**	**0.36**	**0.37**	**0.32**	**0.87**	**0.93**	**0.88**
Tetrachloroethene	**0.2**	**0.16**	**0.19**	**0.13**	**0.11**	**0.12**	**0.12**	**0.13**	**0.11**	**0.18**	**0.2**	**0.18**
Toluene	**4**	**3.7**	**4.2**	**4.7 E**	**4.3 E**	**4.7 E**	**2.5**	**2.6**	**2.4**	**5.9**	**6.4**	**6.1**
trans-1,2-Dichloroethene	**30**	**26**	**35**	**2.4 E**	**3.6 E**	**2.8 E**	**1.7**	**2.5**	**1.9**	**26 E**	**27 E**	**26 E**
Trichloroethene	**0.024**	0.024 U	**0.026**	**0.0067**	**0.0077**	**0.0072**	0.082 U	0.082 U	0.082 U	0.024 U	0.024 U	0.024 U

Notes: U = non-detect (associated v
E = estimated value

TABLE G1
Passive and Active Sample VOC Concentrations at MCAS 137, Cherry Point

Matrix:	Indoor Air						Outdoor Air						
Sample Location:	Indoor Air Location #3						Outdoor Air						
Sampler Type:	ATD Tube			Summa			OVM		Radiello	WMS	SKC	ATD Tube	Summa
Sample Location:	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C	137-OA-1	137-OA-1-OVM Lab Dup	137-OA-1	137-OA-1	137-OA-1	137-OA-1	137-OA-1
Client Sample ID:	137-IA-3A-ATD	137-IA-3B-ATD	137-IA-3C-ATD	137-IA-3A-SUM	137-IA-3B-SUM	137-IA-3C-SUM	137-OA-1-OVM	137-OA-1-OVM Lab	137-OA-1-RAD	137-OA-1-WMS	137-OA-1-SKC	137-OA-1-ATD	137-OA-1-SUM
Sampler Type/Sorbent:	Regular/Carbopack B	Regular/Carbopack B	Regular/Carbopack B	--	--	--	Regular/charcoal	Regular/charcoal	Yellow body/thermal	Regular/Carbopack B	Regular II/Carbograph 5	Regular/Carbopack B	--
Deployment Date/Time:	11-01-06	11-01-06	11-01-06	11-01-06	11-01-06	11-01-06	1-6-11 2:50 PM	1-6-11 2:50 PM	1-6-11 2:53 PM	1-6-11 2:57 PM	1-6-11 2:58 PM	11-01-06	11-01-06
Collection Date/Time:	11-01-13	11-01-13	11-01-13	1/13/11	1/13/11	1/13/11	1-13-11 12:21 PM	1-13-11 12:21 PM	1-13-11 12:20 PM	1-13-11 12:18 PM	1-13-11 12:22 PM	11-01-13	1/13/11
Exposure Duration (min):	9995	9993	9993				9931	9931	9927	9921	9924	9935	
Exposure Duration (days):	6.94	6.94	6.94	--	--	--	6.90	6.90	6.89	6.89	6.89	6.90	--
Laboratory Sample ID:	1101206E-47A	1101206E-48A	1101206E-49A	P1100149-007	P1100149-008	P1100149-009	1101206C-30A	1101206C-30AA	1101206A-10A	1101206D-40A	1101206B-20A	1101206E-50A	P11001449-010
Volatile Organic Compounds ($\mu g/m^3$)													
1,1,1-Trichloroethane	0.54 U	0.54 U	0.54 U	0.14 U	0.13 U	0.14 U	0.24 U	0.24 U	0.14 U	0.18 U	0.019 U	0.54 U	0.14 U
1,1,2-Trichloroethane	0.46 U	0.46 U	0.46 U	0.14 U	0.13 U	0.14 U	0.25 U	0.25 U	0.027 U	0.069 U	0.018 U	0.46 U	0.14 U
1,1-Dichloroethane	0.40 U	0.40 U	0.40 U	0.14 U	0.13 U	0.14 U	0.23 U	0.23 U	0.0087 U	0.17 U	0.016 U	0.40 U	0.14 U
1,1-Dichloroethene	0.35 U	0.35 U	0.35 U	0.14 U	0.13 U	0.14 U	**0.45 J**	**0.45 J**	0.0026 U	0.24 U	**0.024**	0.35 U	0.14 U
1,2-Dichloroethane	0.40 U	0.40 U	0.40 U	0.14 U	0.13 U	0.14 U	**0.23 J**	**0.23 J**	**0.065**	0.078 U	**0.021**	0.40 U	0.14 U
Benzene	**1.7**	**2.3**	**1.7**	**0.88**	**0.88**	**0.88**	**0.77**	**0.82**	**0.83**	**0.6**	**0.77**	**1.2**	**1**
cis-1,2-Dichloroethene	0.43 U	0.43 U	0.43 U	0.14 U	0.13 U	0.14 U	0.021 U	0.021 U	0.0031 U	0.1 U	**0.014**	0.43 U	0.14 U
Ethyl Benzene	**0.8**	**0.9**	**0.87**	0.70 U	0.65 U	0.70 U	0.28 U	0.28 U	**0.17**	**0.12**	**0.14**	0.74 U	0.69 U
m,p-Xylene	**2.1**	**2.4**	**2.3**	**1.4**	**1.2**	**1.4**	0.28 U	0.28 U	**0.42**	**0.35**	**0.33**	0.74 U	0.69 U
o-Xylene	**0.93**	**1.1**	**1**	0.70 U	0.65 U	0.70 U	0.28 U	0.28 U	**0.17**	**0.13**	**0.15**	0.74 U	0.69 U
Tetrachloroethene	0.83 U	0.83 U	0.83 U	**0.21**	**0.23**	**0.25**	**0.082**	**0.083**	**0.055**	**0.085**	**0.072**	0.83 U	0.14 U
Toluene	**7.5**	**8.4**	**7.8**	**4.9**	**5.2**	**5.2**	**0.85**	**0.87**	**1.1**	**0.81**	**0.9**	**1.8**	**1.5**
trans-1,2-Dichloroethene	**27**	**27**	**27**	**39**	**37**	**38**	0.43 U	0.43 U	**0.041**	0.15 U	**0.19**	0.45 U	**0.18**
Trichloroethene	0.54 U	0.54 U	0.54 U	0.14 U	0.13 U	0.14 U	0.024 U	0.024 U	**0.0064**	0.083 U	0.018 U	0.54 U	0.14 U

Notes: U = non-detect (associated v
E = estimated value

TABLE G1
Passive and Active Sample VOC Concentrations at MCAS 137, Cherry Point

Matrix: / Sample Location: / Sampler Type: / Sample Location:	Lab Blank	Lab Blank	Lab Blank	Lab Blank	Lab Blank	Trip Blank	Trip Blank-OVM	Trip Blank	Trip Blank	Trip Blank
Client Sample ID:	Lab Blank - OVM	Lab Blank - RAD	Lab Blank - WMS	Lab Blank-SKC	Lab Blank - ATD	Trip Blank-SKC	Trip Blank-OVM	Trip Blank-RAD	Trip Blank-WMS	Trip Blank-ATD
Sampler Type/Sorbent:	--	--	--	--	--	Regular II/Carbograph 5	Regular/charcoal	Yellow body/thermal	Regular/Carbopack B	Regular/Carbopack B
Deployment Date/Time:	1-6-11 2:50 PM	1-6-11 2:53 PM	1-6-11 2:57 PM	1-6-11 2:58 PM	11-01-06	1-6-11 2:58 PM	1-6-11 2:50 PM	1-6-11 2:53 PM	1-6-11 2:57 PM	11-01-06
Collection Date/Time:	1-13-11 10:53 PM	1-13-11 10:50 AM	1-13-11 10:45 AM	1-13-11 10:53 AM	11-01-13	1-13-11 10:53 AM	1-13-11 10:53 AM	1-13-11 10:50 AM	1-13-11 10:45 AM	11-01-13
Exposure Duration (min):	10024	9837	9828	9835	9851	9835	9843	9837	9828	9851
Exposure Duration (days):										
Laboratory Sample ID:	1101206C-52A	1101206A-55A	1101206D-54A	1101206B-56A	1101206E-53A	1101206B-55A	1101206C-51A	1101206A-54A	1101206D-53A	1101206E-52A
Volatile Organic Compounds ($\mu g/m^3$)										
1,1,1-Trichloroethane	0.24 U	0.14 U	0.18 U	0.033 U	0.55 U	0.029 U	0.24 U	0.14 U	0.18 U	0.55 U
1,1,2-Trichloroethane	0.25 U	0.027 U	0.069 U	0.024 U	0.47 U	0.024 U	0.25 U	0.027 U	0.069 U	0.47 U
1,1-Dichloroethane	0.22 U	0.0088 U	0.17 U	0.017 U	0.41 U	0.015 U	0.22 U	0.0088 U	0.17 U	0.41 U
1,1-Dichloroethene	**0.45 J**	0.0026 U	0.24 U	0.023 U	0.36 U	0.02 U	**0.45 J**	0.0026 U	0.24 U	0.36 U
1,2-Dichloroethane	**0.22 J**	0.0088 U	0.078 U	0.019 U	0.41 U	0.017 U	**0.22 J**	0.0088 U	0.078 U	0.41 U
Benzene	0.42 U	0.012 U	0.074 U	0.17 U	0.46 U	0.15 U	0.42 U	**0.051**	**0.19**	**0.93**
cis-1,2-Dichloroethene	0.021 U	0.0032 U	0.1 U	0.02 U	0.44 U	0.018 U	0.021 U	0.0032 U	0.1 U	0.44 U
Ethyl Benzene	0.27 U	0.0087 U	0.033 U	0.028 U	0.74 U	**0.048**	0.27 U	**0.03**	0.033 U	0.74 U
m,p-Xylene	0.27 U	0.0084 U	0.035 U	0.031 U	0.74 U	0.027 U	0.27 U	**0.054**	**0.05**	0.74 U
o-Xylene	0.27 U	0.0091 U	0.031 U	0.031 U	0.74 U	0.027 U	0.27 U	**0.018**	0.031 U	0.74 U
Tetrachloroethene	0.026 U	0.0059 U	0.064 U	0.039 U	0.84 U	0.034 U	0.026 U	0.0059 U	0.064 U	0.84 U
Toluene	0.24 U	0.0064 U	0.045 U	0.024 U	0.60 U	**0.14**	0.24 U	**0.13**	**0.23**	0.60 U
trans-1,2-Dichloroethene	0.42 U	0.0033 U	0.15 U	0.022 U	0.45 U	0.02 U	0.42 U	0.0033 U	0.15 U	0.45 U
Trichloroethene	0.024 U	0.0040 U	0.082 U	0.027 U	0.55 U	0.024 U	0.024 U	0.0040 U	0.082 U	0.55 U

Notes: U = non-detect (associated v
E = estimated value

TABLE G2
MCAS INDOOR AIR CONCENTRATION STATISTICS

Sample Location:	**Indoor Air Location #1**																	
Sample Location:	137-IA-1 Series																	
Sampler Type:	OVM			Radiello			WMS			SKC			ATD Tube			Summa		
Client Sample ID:	137-IA-1A-OVM			137-IA-1A-RAD			137-IA-1A-WMS			137-IA-1A-SKC			137-IA-1A-ATD			137-IA-1A-SUM		
Sampler Type/Sorbent:	Regular/charcoal			Yellow body/thermal			Regular/Carbopack B			Regular II/Carbograph 5			Regular/Carbopack B			--		
Deployment Date/Time:	1-6-11			1-6-11			1-6-11			1-6-11			1-6-11			1-6-11		
Collection Date/Time:	1-13-11			1-13-11			1-13-11			1-13-11			1-13-11			1/13/11		
Exposure Duration (min):	9944			9935			9913			9921			9921					
Exposure Duration (days):	6.9			6.9			6.9			6.9			6.9			--		
Laboratory Sample ID:	1101206C			1101206A			1101206D			1101206B			1101206E			P1100149		
Volatile Organic Compounds	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV
(µg/m³)																		
1,1,1-Trichloroethane	**6.93**	0.92	0.13	**15.00**	NA	NA	**3.47**	0.21	0.06	**3.00**	0.35	0.12	**8.17**	0.12	0.01	**10.67**	0.58	0.05
1,1,2-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethane	**3.77**	0.21	0.06	**0.49**	0.02	0.05	**0.41**	0.09	0.23	**4.03**	0.21	0.05	**2.33**	0.31	0.13	**6.03**	0.21	0.03
1,1-Dichloroethene	**0.86**	0.07	0.08	**0.02**	0.005	0.20	**0.29**	0.06	0.22	**1.43**	0.06	0.04	**1.01**	0.16	0.16	**2.23**	0.15	0.07
1,2-Dichloroethane	**0.23**	NA	NA	**0.06**	NA	NA	ND	ND	ND	**0.14**	0.01	0.04	ND	ND	ND	ND	ND	ND
Benzene	**0.77**	0.03	0.03	**0.87**	0.04	0.05	**0.55**	0.04	0.08	**1.27**	0.06	0.05	**1.67**	0.12	0.07	**0.71**	0.05	0.06
cis-1,2-Dichloroethene	**1.10**	NA	NA	**0.06**	0.002	0.03	**0.13**	0.03	0.20	**1.63**	0.06	0.04	**1.17**	0.06	0.05	**1.73**	0.06	0.03
Ethyl Benzene	**0.40**	0.01	0.03	**0.66**	0.02	0.04	**0.28**	0.02	0.05	**0.73**	0.03	0.04	**0.88**	0.08	0.08	ND	ND	ND
m,p-Xylene	**1.50**	0.10	0.07	**2.33**	0.15	0.07	**1.17**	0.06	0.05	**2.70**	0.17	0.06	**3.23**	0.40	0.12	**1.80**	0.10	0.06
o-Xylene	**0.54**	0.02	0.03	**0.94**	0.04	0.04	**0.42**	0.01	0.02	**1.03**	0.06	0.06	**1.23**	0.15	0.12	**0.76**	0.13	0.17
Tetrachloroethene	**0.08**	0.002	0.03	**0.06**	0.001	0.02	**0.07**	0.002	0.03	**0.09**	0.01	0.08	ND	ND	ND	**0.15**	0.03	0.20
Toluene	**9.67**	0.42	0.04	**10.37**	1.10	0.11	**7.30**	0.35	0.05	**13.00**	NA	NA	**22.67**	0.58	0.03	**15.33**	0.58	0.04
trans-1,2-Dichloroethene	**2.87**	0.06	0.02	**0.45**	0.01	0.03	**0.69**	0.05	0.08	**4.53**	0.15	0.03	**3.27**	0.12	0.04	**4.17**	0.06	0.01
Trichloroethene	**3.40**	0.26	0.08	**1.47**	0.06	0.04	**1.87**	0.12	0.06	**3.30**	0.17	0.05	**4.47**	0.12	0.03	**4.80**	0.10	0.02
Average COV			0.05			0.06			0.09			0.05			0.08			0.07

TABLE G2
MCAS INDOOR AIR CONCENTRATION STATISTICS

Sample Location:	**Indoor Air Location #2**																	
Sample Location:	137-IA-2 Series																	
Sampler Type:	OVM			Radiello			WMS			SKC			ATD Tube			Summa		
Client Sample ID:	137-IA-2A-OVM			137-IA-2A-RAD			137-IA-2A-WMS			137-IA-2A-SKC			137-IA-2A-ATD			137-IA-2A-SUM		
Sampler Type/Sorbent:	Regular/charcoal			Yellow body/thermal			Regular/Carbopack B			Regular II/Carbograph 5			Regular/Carbopack B			--		
Deployment Date/Time:	1-6-11			1-6-11			1-6-11			1-6-11			1-6-11			1-6-11		
Collection Date/Time:	1-13-11			1-13-11			1-13-11			1-13-11			1-13-11			1/13/11		
Exposure Duration (min):	9927			9912			9913			9904			9913					
Exposure Duration (days):	6.9			6.9			6.9			6.9			6.9			--		
Laboratory Sample ID:	1101206C			1101206A			1101206D			1101206B			1101206E			P1100149		
Volatile Organic Compounds	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV
($\mu g/m^3$)																		
1,1,1-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1,2-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethene	**0.45**	NA	NA	ND	ND	ND	ND	ND	ND	**0.03**	0.01	0.22	ND	ND	ND	ND	ND	ND
1,2-Dichloroethane	**0.23**	NA	NA	**0.01**	0.001	0.08	ND	ND	ND	**0.06**	0.002	0.03	ND	ND	ND	ND	ND	ND
Benzene	**0.90**	0.04	0.04	**0.93**	0.04	0.04	**0.60**	0.01	0.02	**1.73**	0.12	0.07	**1.73**	0.12	0.07	**0.87**	0.02	0.02
cis-1,2-Dichloroethene	**0.02**	0.001	0.04	ND	ND	ND	ND	ND	ND	**0.16**	0.00	0.00	ND	ND	ND	ND	ND	ND
Ethyl Benzene	**0.49**	0.04	0.08	**0.77**	0.02	0.03	**0.32**	0.03	0.08	**0.87**	0.03	0.03	**0.99**	0.01	0.01	ND	ND	ND
m,p-Xylene	**1.30**	0.10	0.08	**2.07**	0.06	0.03	**1.01**	0.09	0.08	**2.60**	0.10	0.04	**2.80**	NA	NA	**1.70**	NA	NA
o-Xylene	**0.51**	0.04	0.07	**0.87**	0.02	0.03	**0.36**	0.02	0.06	**1.02**	0.07	0.07	**1.10**	NA	NA	ND	ND	ND
Tetrachloroethene	**0.19**	0.01	0.05	**0.15**	0.01	0.04	**0.13**	0.01	0.04	**0.24**	0.02	0.06	ND	ND	ND	**0.27**	0.01	0.04
Toluene	**3.50**	0.20	0.06	**4.60**	0.17	0.04	**3.10**	0.36	0.12	**6.33**	0.21	0.03	**8.00**	0.17	0.02	**5.57**	0.15	0.03
trans-1,2-Dichloroethene	**30.67**	1.53	0.05	**2.57**	0.31	0.12	**4.93**	1.48	0.30	**28.33**	0.58	0.02	**30.00**	1.73	0.06	**48.33**	1.15	0.02
Trichloroethene	**0.03**	0.001	0.04	**0.01**	0.001	0.13	ND	ND	ND	**0.03**	0.005	0.15	ND	ND	ND	ND	ND	ND
Average COV			0.06			0.06			0.10			0.07			0.04			0.03

TABLE G2
MCAS INDOOR AIR CONCENTRATION STATISTICS

Sample Location:	**Indoor Air Location #3**																	
Sample Location:	137-IA-3 Series																	
Sampler Type:	OVM			Radiello			WMS			SKC			ATD Tube			Summa		
Client Sample ID:	137-IA-3A-OVM			137-IA-3A-RAD			137-IA-3A-WMS			137-IA-3A-SKC			137-IA-3A-ATD			137-IA-3A-SUM		
Sampler Type/Sorbent:	Regular/charcoal			Yellow body/thermal			Regular/Carbopack B			Regular II/Carbograph 5			Regular/Carbopack B			--		
Deployment Date/Time:	1-6-11			1-6-11			1-6-11			1-6-11			1-6-11			1-6-11		
Collection Date/Time:	1-13-11			1-13-11			1-13-11			1-13-11			1-13-11			1/13/11		
Exposure Duration (min):	10022			10005			9974			9997			9994					
Exposure Duration (days):	7.0			6.9			6.9			6.9			6.9			--		
Laboratory Sample ID:	1101206C			1101206A			1101206D			1101206B			1101206E			P1100149		
Volatile Organic Compounds	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV	Average	St. Dev.	COV
($\mu g/m^3$)																		
1,1,1-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1,2-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethene	**0.45**	NA	NA	ND	ND	ND	ND	ND	ND	**0.02**	0.002	0.09	ND	ND	ND	ND	ND	ND
1,2-Dichloroethane	**0.22**	NA	NA	**0.02**	0.002	0.11	ND	ND	ND	**0.06**	0.003	0.05	ND	ND	ND	ND	ND	ND
Benzene	**1.10**	0.10	0.09	**1.00**	NA	NA	**0.64**	0.03	0.04	**1.57**	0.06	0.04	**1.90**	0.35	0.18	**0.88**	NA	NA
cis-1,2-Dichloroethene	**0.02**	0.003	0.13	ND	ND	ND	ND	ND	ND	**0.14**	0.01	0.04	ND	ND	ND	ND	ND	ND
Ethyl Benzene	**0.49**	0.04	0.07	**0.66**	0.04	0.06	**0.30**	0.03	0.09	**0.78**	0.04	0.05	**0.86**	0.05	0.06	ND	ND	ND
m,p-Xylene	**1.33**	0.12	0.09	**1.70**	0.10	0.06	**0.91**	0.07	0.08	**2.20**	0.10	0.05	**2.27**	0.15	0.07	**1.33**	0.12	0.09
o-Xylene	**0.46**	0.07	0.16	**0.74**	0.05	0.06	**0.35**	0.03	0.08	**0.89**	0.03	0.04	**1.01**	0.09	0.08	ND	ND	ND
Tetrachloroethene	**0.18**	0.02	0.11	**0.12**	0.01	0.08	**0.12**	0.01	0.08	**0.19**	0.01	0.06	ND	ND	ND	**0.23**	0.02	0.09
Toluene	**3.97**	0.25	0.06	**4.57**	0.23	0.05	**2.50**	0.10	0.04	**6.13**	0.25	0.04	**7.90**	0.46	0.06	**5.10**	0.17	0.03
trans-1,2-Dichloroethene	**30.33**	4.51	0.15	**2.93**	0.61	0.21	**2.03**	0.42	0.20	**26.33**	0.58	0.02	**27.00**	NA	NA	**38.00**	1.00	0.03
Trichloroethene	**0.02**	0.001	0.05	**0.01**	0.001	0.07	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Average COV			0.10			0.09			0.09			0.05			0.09			0.06

Notes:
NA - At least one of the three triplicate samples yielded non-detect result, so statistics were not calculated
ND - All results were non-detect

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APPENDIX H

Summary of Compounds Detected in Trip Blanks

May 2015

Site	Trip Blank				Results	
	Sampler Type	Sample ID	Sorbent	Sampler ID	Analyte	Mass (ng)
San Diego OTC	ATD	QCTB-ATD	Chromosorb 106	1005423	*No detections*	
	WMS	QCTB-WMS	Anasorb 747	PS-E03	*No detections*	
	Radiello	QCTB-RAD	Charcoal	--	*No detections*	
	OVM 3500	QCTB-3M	Charcoal	--	*No detections*	
	SKC Ultra	QCTB-SKC	Chromosorb 106	--	*No detections*	
Hill AFB	ATD-CP	TRIP BLANK-CP	Carbopack B	--	*No detections*	
		TRIP BLANK-CP	Carbopack B	--	*No detections*	
	ATD-TA	TRIP BLANK-TA	Tenax TA	--	*No detections*	
		TRIP BLANK-TA	Tenax TA	--	*No detections*	
	WMS	Trip Blank-1	Anasorb 747	I-89	*No detections*	
		Trip Blank-WMS	Anasorb 747	I-84	*No detections*	
	WMS-PH	Trip blank-2	Carbopack B	PH-01	1,2-Dichloroethane	0.324
					Chloroform	1.4
					Carbon tetrachloride	0.5
					Tetrachloroethene	0.36
		Trip blank WMS - PH	Carbopack B	PH-03	*No detections*	
	Radiello	Trip Blank	Charcoal	11404	*No detections*	
	SKC Ultra	Trip Blank	Carbopack X	C02600	1,1-Dichoroethane	2.8
					2-Butanone	145.2
					n-Hexane	17.8
					Chloroform	3.3
					Benzene	103.0
					Trichloroethene	1.8
					Tetrachloroethene	3.3
					1,2,4-Trimethylbenzene	5.2
					Naphthalene	5.4
CRREL	ATD-CP	OA-Trip-ATD	Carbopack B	G0136280	*No detections*	
	WMS	Trip Blank	Carbopack B	ESTCP-B18	Acetone	99
	Radiello	OA-Trip-Rad	Carbograph 4	DL120	Acetone	30
					Dichloromethane	60
					Benzene	20
					Toluene	50
					Ethylbenzene	10
					m,p-Xylene	20
					1,2,4-Trimethylbenzene	10
					Styrene	0.01
	OVM 3500	OA-Trip-3M	Charcoal	CV9362	Hexane	360.0
					2,2,4-Trimethylpentane	320 J

					Benzene	350.0
					Toluene	92.0
	SKC Ultra	OA-Trip-SKC	Carbograph 5	--	Freon 12	8.59
					Freon 11	19.181
					Ethanol	1415.58
					Acetone	1826.84
					Methylene Chloride	114.81
					2-Butanone	431.01
					n-Hexane	187
					Tetrahydrofuran	10.12
					Benzene	61.87
					Isooctane	7.9
					Trichloroethene	3.77
					Toluene	120.3
					Ethylbenzene	39.4
					m,p-Xylene	61.55
					o-Xylene	25.75
					1,2,4-Trimethylbenzene	10.3
Cherry Point	ATD	Trip blank - ATD	Carbopack B	--	Benzene	3.2
	WMS	Trip blank - WMS	Carbopack B	--	Benzene	4.1
					Toluene	9.8
					m,p-Xylene	3.1
	Radiello	Trip blank - RAD	Carbograph 4	--	Benzene	14
					Toluene	39
					Ethylbenzene	7.7
					m,p-Xylene	14
					o-Xylene	4.4
	OVM 3500	Trip blank - OVM	Charcoal	--	*No detections*	
	SKC Ultra	Trip blank - SKC	Carbograph 5		Toluene	12
					Ethylbenzene	4.3
NAS-JAX	ATD	TRIP BLANK ATD	Carbopack B	--	*No detections*	
	WMS	TRIP BLANK WMS	Anasorb 747	WMS-A-09	*No detections*	
	OVM 3500	TRIP BLANK OVM	Charcoal	XV5881	*No detections*	
	Radiello	Trip blank	Charcoal	IN926	*No detections*	
	SKC Ultra	Trip blank	Carbograph 5	--	Trichloroethene	23.4

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APPENDIX I

Statistical Analysis of the Low Concentration Laboratory Tests

May 2015

Statistical Analysis of Low Concentration Laboratory Tests

Part 1: Center point (a.k.a. ANOVA) tests

Purpose/Objective:

1. The purpose of the first 6 Center-Point (ANOVA) runs where all five factors were fixed at the midpoint values was to assess a) the process error of the samplers and b) the stability of chamber performance in replicated experimental conditions.

2. The purpose of the two additional Center-Point tests that were interspersed in the middle of the fractional factorial runs was to monitor/validate the stability of the chamber performance over time.

Statistical Analysis Methods:

A: ANOVA analysis of the initial 6 center-point experiments

1. Block on run - which is defined as a chamber and day combination.

2. The treatment was the sampler type – six samplers were included in the analysis (five passive samplers and the active ATD-Tube sampler used as the control) and the lab reported concentrations were used as the response

3. Two types of analyses were conducted: (i) a global one which included all analytes and (ii) an analyte specific one, ie. analyte by analyte

4. Pairwise comparisons between the results of different samplers for each analyte were made using Tukey's method (Ramsey et al., 2002).

5. PROC GLM was used for the analysis (SAS 9.2).

B: ANOVA analysis of the initial 6 and interspersed center-point runs combined

1. Main factors were the sampler type (only the five passive samplers) and the experiment (i.e., initial 6 center-point runs runs vs. center-point runs interspersed in the middle of the fractional factorial tests).

2. The relative concentration (passive sampler concentration divided by average of all active sampler concentrations measured for the chamber, C/Co) values were used as the response.

3. Only the analyte specific analysis was conducted, i.e., the statistical analysis was performed for one analyte at a time.

4. The relative percent difference (RPD) was calculated between the mean C/Co of the initial 6 center-point runs and the mean C/Co of the interspersed center-point runs.

5. PROC GLM was used for the analysis (SAS 9.2). Code was written in R (version 2.13) to calculate means and RPDs.

Results:

A: ANOVA analysis of the initial 6 center-point runs

1. Results from the global analysis (i.e. all analytes for both absolute concentrations (C) and relative concentrations (C/Co)), indicated a poor fit because there was too much variability between analytes. Therefore, the ANOVA analysis was performed on one analyte at a time to assess the process error and chamber performance.

2. Results from the analyte-specific analyses indicate that the relative concentrations (C/Co) provide a better fit to the regression models (lower p-values for the main effects) compared to the absolute concentration values (see Table 1a and 1b). Therefore, relative concentrations (C/Co) were considered in subsequent analyses.

3. Model diagnostics confirm that model assumptions are being met (the data are normally distributed with no extreme or influential outliers). Model fit diagnostics include:
   a) Plot of predicted values vs. standardized residuals: These plots are used to identify any extreme y values as values that fall outside of the y range of (-2, 2). The plot is also used to assess whether the assumption of a constant variance is supported if the residuals show no apparent patterns.
   b) Plot of leverages vs. standardized residuals: These plots are used to identify any unusual x values that could have a high potential for influence as values that fall outside the range of (1/n, 1).
   c) Plot of Cook's distance: These plots are used to identify influential cases (i.e., measures overall influence of a measurement or the effect of omitting an observation on the estimated regression line). The value should be <=1.
   d) Quantile-Quantile (QQ) plot of the residuals: These plots are used to identify whether the data re normally distributed. These plots should follow a straight-line pattern (along the qqline) with very few departures in the tails.

4. Sampler type was statistically significant for all analytes at the 5% level of significance. This means that the accuracy of the uptake rate for any particular combination of sampler and uptake rate can be resolved against the variability in the results from several replicate measurements. In other words the precision is high

enough that the effect of small differences between the actual and assumed uptake rates can be distinguished statistically.

5. For any given analyte, between 70%-100% of the pairwise comparisons between the samplers indicate a statistically significant difference between the samplers (Table 2a and 2b). This also shows that the uncertainty in the uptake rate is large compared to the reproducibility of the passive sampler measurements.

B: ANOVA analysis of initial 6 and Interspersed center-point runs

1. The addition of the two additional sets of center-point data conducted at the mid-point of the fractional factorial tests (a.k.a. interspersed ANOVA runs) rendered results similar to the ANOVA analysis of the initial 6 center-point runs (Table 3). Sampler Type remained statistically significant at the 5% level of significance. Additionally, Experiment (the comparison of the first 6 tests to the interspersed runs) was statistically significant at the 5% level of significance; however, the statistical significance is more of a testament to the high precision (low variability) which allows subtle differences between the results of the earlier and later tests to be discerned.

2. RPDs between the means of the initial 6 center-point runs and the means of the interspersed runs were within +-16% for all analytes, with the exception of Naphthalene (26.5%), as shown in Table 4a. The range that is typically acceptable for agreement between laboratory duplicates is +/- 25%. On closer inspection of the RPD on a compound-by compound basis for each sampler type (Table 4b), the ATD tubes performed well for naphthalene, and the overall RPD for naphthalene would have been acceptable if not for a single comparison (the WMS samplers in the initial and interspersed tests showed an RPD of 82%). Therefore, the initial 6 center-point runs are considered to be sufficiently similar to the interspersed center-point runs to justify pooling them together in subsequent analyses.

Table 1a - Summary of Model Statistics and Sampler Means - Laboratory Concentrations (ppbv)

Data Set	R^2	Root MSE	P-value for Main Effects		Sampler Type Means					
			Block	Sample Type	ATD Carbopack	ATD Tenax	Active	WMS	Radiello	SKC Ultra
All Analytes	0.10	13.60	1.00	<0.0001	32.52	23.04	34.17	39.25	35.76	34.81
1,1,1-Trichloroethane	0.96	1.95	0.03	<0.0001	25.16	20.20	35.38	48.57	39.17	46.60
1,2,4-Trimethylbenzene	0.96	1.90	0.05	<0.0001	25.71	22.65	33.28	25.06	50.58	33.01
1,2-Dichloroethane	0.96	1.62	0.46	<0.0001	21.90	21.86	36.18	41.70	34.37	45.56
2-Butanone (MEK)	0.98	2.16	0.59	<0.0001	7.83	24.24	34.61	54.17	17.62	24.42
Benzene	0.97	1.73	0.09	<0.0001	65.22	36.57	39.94	47.81	41.29	40.54
Carbon tetrachloride	0.94	2.02	0.04	<0.0001	29.69	22.33	36.60	51.00	34.10	34.90
Hexane	0.84	5.11	1.00	<0.0001	68.16	24.99	49.42	46.33	46.17	45.28
Naphthalene	0.98	0.36	0.01	<0.0001	3.13	3.06	3.02	1.45	9.71	0.99
Tetrachloroethene	0.87	1.75	0.20	<0.0001	44.12	31.57	36.09	35.76	44.31	40.23
Trichloroethene	0.92	1.71	0.74	<0.0001	34.31	22.92	37.21	40.69	40.27	36.56

Table 1b - Summary of Model Statistics and Sampler Means - Standardized Concentrations (C/Co)

Data Set	R^2	Root MSE	P-value for Main Effects		Sampler Type Means				
			Block	Sample Type	ATD Carbopack	ATD Tenax	PDMS	Radiello	SKC Ultra
All Analytes	0.16	0.42	0.19	<0.0001	0.93	0.71	1.10	1.25	0.96
1,1,1-Trichloroethane	0.97	0.06	0.01	<0.0001	0.71	0.57	1.38	1.11	1.32
1,2,4-Trimethylbenzene	0.98	0.05	<0.0001	<0.0001	0.78	0.68	0.75	1.52	1.00
1,2-Dichloroethane	0.97	0.05	0.01	<0.0001	0.61	0.60	1.15	0.95	1.26
2-Butanone (MEK)	0.98	0.07	0.00	<0.0001	0.23	0.70	1.57	0.51	0.71
Benzene	0.98	0.04	<0.0001	<0.0001	1.63	0.92	1.20	1.03	1.01
Carbon tetrachloride	0.95	0.06	0.02	<0.0001	0.81	0.61	1.40	0.93	0.95
Hexane	0.90	0.11	<0.0001	<0.0001	1.38	0.51	0.96	0.94	0.92
Naphthalene	0.98	0.14	<0.0001	<0.0001	1.04	1.01	0.48	3.21	0.33
Tetrachloroethene	0.89	0.05	<0.0001	<0.0001	1.22	0.88	0.99	1.23	1.12
Trichloroethene	0.94	0.05	<0.0001	<0.0001	0.92	0.62	1.09	1.08	0.98

Table 2a - Summary of Pairwise Differences Between Sampler Types - Laboratory Concentrations (ppbv)

Pairwise Comparison	All Analytes	111TCA	124TMB	12DCA	MEK	BENZ	CTET	HEX	NAPH	PCE	TCE
ATDC-ATDT	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
ATDC-ACTIVE	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
ATDC-PDMS	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDC-RAD	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
ATDC-SKC	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDT-ACTIVE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
ATDT-PDMS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDT-RAD	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDT-SKC	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
ACTIVE-PDMS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes
ACTIVE-RAD	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
ACTIVE-SKC	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No
PDMS-RAD	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
PDMS-SKC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
RAD-SKC	No	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Percentage of Differences	**53%**	**100%**	**87%**	**93%**	**93%**	**80%**	**93%**	**67%**	**80%**	**87%**	**87%**

Table 2b - Summary of Pairwise Differences Between Sampler Types - Standardized Concentrations (C/Co)

Pairwise Comparison	All Analytes	111TCA	124TMB	12DCA	MEK	BENZ	CTET	HEX	NAPH	PCE	TCE
ATDC-ATDT	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
ATDC-PDMS	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDC-RAD	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
ATDC-SKC	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
ATDT-PDMS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDT-RAD	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ATDT-SKC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PDMS-RAD	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
PDMS-SKC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
RAD-SKC	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Percentage of Differences	**90%**	**100%**	**90%**	**90%**	**90%**	**90%**	**90%**	**70%**	**90%**	**90%**	**90%**

Table 3 - Summary of Model Statistics and Sampler Means - Standardized Concentrations (C/Co) - Addition of Interspersed Data

Data Set	R^2	Root MSE	P-value for Main Effects		Experiment Means		Sampler Type Means				
			Experiment	Sample Type	ANOVA	Interspersed	ATD Carbopack	ATD Tenax	WMS	Radiello	SKC Ultra
1,1,1-Trichloroethane	0.91	0.10	<0.0001	<0.0001	0.834	1.016	1.02	0.83	1.29	1.07	1.20
1,2,4-Trimethylbenzene	0.89	0.10	<0.0001	<0.0001	0.739	0.946	0.75	0.67	0.69	1.39	0.96
1,2-Dichloroethane	0.89	0.09	<0.0001	<0.0001	0.683	0.915	0.59	0.59	1.07	0.90	1.13
2-Butanone (MEK)	0.91	0.13	<0.0001	<0.0001	0.629	0.743	0.22	0.70	1.45	0.44	0.76
Benzene	0.90	0.09	<0.0001	<0.0001	1.060	1.158	1.65	0.93	1.13	1.00	0.96
Carbon tetrachloride	0.90	0.08	<0.0001	<0.0001	0.785	0.941	0.80	0.60	1.31	0.91	0.90
Hexane	0.73	0.17	<0.0001	<0.0001	0.677	0.942	1.24	0.49	0.92	0.88	0.85
Naphthalene	0.88	0.35	<0.0001	<0.0001	0.706	1.215	0.96	0.94	0.37	2.76	0.40
Tetrachloroethene	0.79	0.07	<0.0001	<0.0001	0.953	1.088	1.21	0.89	0.93	1.17	1.06
Trichloroethene	0.84	0.07	<0.0001	<0.0001	0.792	0.939	0.92	0.61	1.03	1.03	0.91

Table 4a - Relative Percent Difference (RPD) Between Means of initial 6 Center-point runs and 2 Interspersed Center-point runs by Analyte

Analyte	Mean ANOVA	Mean Interspersed	RPD (%)
111TCA	0.834	1.016	9.9
124TMB	0.739	0.946	12.3
12DCA	0.683	0.915	14.5
MEK	0.629	0.743	8.3
BEN	1.060	1.158	4.4
CT	0.785	0.941	9.1
HEX	0.677	0.942	16.4
NAPH	0.706	1.215	26.5
PCE	0.953	1.088	6.6
TCE	0.792	0.939	8.5

Table 4b - Relative Percent Differences Between Means of ANOVA runs and Interspersed runs by Sampler Type

SamplerType	Analyte	Mean ANOVA	Mean Interspersed	RPD (%)
ATDCarbopack	111TCA	0.711378395	0.716781794	0.4
ATDCarbopack	124TMB	0.775155722	0.682923421	6.3
ATDCarbopack	12DCA	0.605616561	0.563117634	3.6
ATDCarbopack	BEN	1.631786046	1.685888091	1.6
ATDCarbopack	CT	0.812316976	0.748435037	4.1
ATDCarbopack	HEX	1.38402711	0.825376208	**25.3**
ATDCarbopack	MEK	0.226926263	0.208141234	4.3
ATDCarbopack	NAPH	1.036086614	0.742260075	16.5
ATDCarbopack	PCE	1.224500108	1.18547906	1.6
ATDCarbopack	TCE	0.921863865	0.922644493	0
ATDTenax	111TCA	0.571302975	0.565036186	0.6
ATDTenax	124TMB	0.68248757	0.64686321	2.7
ATDTenax	12DCA	0.604447948	0.533479864	6.2
ATDTenax	BEN	0.915693364	0.981085004	3.4
ATDTenax	CT	0.611153724	0.566224179	3.8
ATDTenax	HEX	0.507885585	0.429386086	8.4
ATDTenax	MEK	0.701611178	0.713902833	0.9
ATDTenax	NAPH	1.010806669	0.735210039	15.8
ATDTenax	PCE	0.87607626	0.917712061	2.3
ATDTenax	TCE	0.615839771	0.604087632	1
WMS	111TCA	1.375011695	1.045543183	13.6
WMS	124TMB	0.754265424	0.497572056	20.5
WMS	12DCA	1.152744848	0.809790466	17.5
WMS	BEN	1.197107441	0.945419162	11.7
WMS	CT	1.397268135	1.043404029	14.5
WMS	HEX	0.961654585	0.794996371	9.5
WMS	MEK	1.569650838	1.0846355	18.3
WMS	NAPH	0.483025483	0.049216576	**81.5**
WMS	PCE	0.99147122	0.757614035	13.4
WMS	TCE	1.094457405	0.830959799	13.7
Radiello	111TCA	1.107400384	0.97592583	6.3
Radiello	124TMB	1.524096642	0.998026966	20.9
Radiello	12DCA	0.950478839	0.751924545	11.7
Radiello	BEN	1.03215862	0.907331976	6.4
Radiello	CT	0.932619817	0.8381223	5.3
Radiello	HEX	0.937374294	0.704296713	14.2
Radiello	MEK	0.509404931	0.222219094	**39.3**
Radiello	NAPH	3.213440522	1.390542521	**39.6**
Radiello	PCE	1.229232626	0.998553127	10.4
Radiello	TCE	1.081823831	0.890339086	9.7
SKCUltra	111TCA	1.317104154	0.86733309	20.6
SKCUltra	124TMB	0.996272417	0.867825252	6.9
SKCUltra	12DCA	1.260321388	0.756080695	25
SKCUltra	BEN	1.014455442	0.780015317	13.1
SKCUltra	CT	0.953613949	0.727740749	13.4
SKCUltra	HEX	0.919032377	0.630996808	18.6
SKCUltra	MEK	0.707701228	0.915886704	12.8
SKCUltra	NAPH	0.329264285	0.611634217	**30**
SKCUltra	PCE	1.117091182	0.903377933	10.6
SKCUltra	TCE	0.982522779	0.711148257	16

Half Fractional Factorial 2^{5-1} – Low Concentration Laboratory Tests

Purpose/Objective:

1. The purpose of the fractional factorial test and analysis is to assess if the controllable factors (ie. humidity, temperature, face velocity, concentration, exposure time) have an effect on the C/Co concentrations, specifically whether the uptake rates change in response to changes in these factors within ranges typically anticipated for indoor air quality monitoring programs.

2. To develop to the extent practical a mathematical model to provide a correction factor for the reported concentration of the passive samplers using default uptake rates if the average humidity, temperature, face velocity, concentration, exposure time are known for a particular sampling event.

3. Evaluate the accuracy of the passive sampler performance with model developed in (2).

Methods:

1. Two sets of models were developed - i) Main effects only and ii) Main effects and first order interactions.

2. A total of 139 out of 2400 measured concentrations via passive samplers in the fractional factorial tests were nondetect values, all of which were for the lowest concentration chambers (where the target concentrations were 1 ppbv, except naphthalene). Two methods were used to analyze data sets with nondetect values: i) substitution method - a C/Co value of 1 was used for all nondetect results and ii) restricted maximum likelihood (REML) - nondetect

3. Therefore four models were developed for each Sampler Type - Analyte combination (4 x 50 combinations = 200 in total).

4. The analyses were run with coded variables (low value of each factor = -1, high value = +1), however, slope estimates for each factor are reported on the original scale (ie. uncoded), so the main effects are values in units of relative concentration (C/Co) divided by the units each factor was measured in (humidity in %RH, temperature in ^{o}C, face velocity in m/s, concentration in ppbv, and exposure time in days).

5. Fractional factorial data was used to develop the model and the center point data (both ANOVA runs and interspersed runs combined) was used as a test set to validate the model.

6. A correction factor was calculated by dividing the C/Co values predicted by the model by observed C/Co value from the center point data. This factor was used to assess the accuracy of the predictive model.

7. PROC GLM was used for complete data sets, PROC MIXED was used for data sets with nondetect values (SAS 9.2).

Results:

1. Results from both mothod of dealing with the non-detect results (substitution of a value of 1 ppbv and the REML method) rendered similar results: more than half of the main effect and interaction terms are statistically significant for the majority of the Sampler Type-Analyte combinations. This means the precision of the passive sampler measurements was high enough to allow changes in the uptake rate attributable to changes in the chamber conditions to be determined with statistical confidence.

2. REML models were used to construct a table of slope estimates based on the main effect model (Table #). The regression models with slope estimates for the main effects of each factor were used to calculate predicted C/Co values for the center point data (Table #).

3. Most of the first-order interaction terms were also statistically significant. As a result, there may be some curvature in the relationships and a linear regression model may not be the most representative method for calculating the uptake rate as a function of the factor values for any particular sampler/compound pair. Generally, the second half of the factorial test strategy is required in order to develop a regression model for first-order interactions and other higher order effects (#reference#). As such, we only consider a linear model of the main effects to be supported by the experimental data. Ultimately, it is probably simpler and more defensible to derive site-specific uptake rates using inter-method duplicate samples as a QA/QC component of a passive field sampling campaign because the large number of potential compounds of concern for vapor intrusion (e.g., 114 compounds in the OSWER 2002 draft guidance) makes it difficult to conduct laboratory testing for all possible field conditions.

Table 1a: Main Effects Only Model - REML Method - Summary of Model Statistics and Main Effect P-values

Sampler Type	Analyte	R-Square	Root MSE	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	0.65397	0.131494	0.0778	0.0281	0.0106	0.0003	<.0001
ATDC	1,2,4-Trimethylbenzene	0.408658	0.082824	0.3181	0.0009	0.1245	0.5664	0.0011
ATDC	1,2-Dichloroethane	0.457001	0.182717	0.0012	0.6819	0.7406	<.0001	0.1371
ATDC	2-Butanone (MEK)	NA	0.231041122	0.0693	0.4097	0.0603	0.7378	0.0119
ATDC	Hexane	0.190167	0.425402	0.7999	0.2913	0.4002	0.0272	0.1177
ATDC	Benzene	0.339602	0.438782	0.4718	0.2468	0.0547	0.0023	0.0331
ATDC	Carbon tetrachloride	0.556859	0.175896	0.0434	0.2975	0.3501	<.0001	<.0001
ATDC	Naphthalene	0.259426	0.150481	0.2629	0.6088	0.293	0.007	0.0778
ATDC	Trichloroethene	0.540726	0.095064	0.0113	0.2781	0.0002	<.0001	0.9484
ATDC	Tetrachloroethene	0.327887	0.144003	0.8513	0.004	0.0071	0.8484	0.0727
ATDT	1,1,1-Trichloroethane	0.77989	0.097321	<.0001	0.2715	0.0021	<.0001	<.0001
ATDT	1,2,4-Trimethylbenzene	0.238568	0.133566	0.9169	0.8868	0.0121	0.0296	0.2864
ATDT	1,2-Dichloroethane	0.541289	0.181049	0.9154	0.8908	0.4733	<.0001	<.0001
ATDT	2-Butanone (MEK)	0.663055	0.488904	0.7719	0.0799	0.1479	<.0001	<.0001
ATDT	Hexane	0.427453	0.251521	0.6362	0.21	0.6114	<.0001	0.1148
ATDT	Benzene	0.603391	0.265519	0.8106	0.0059	0.438	<.0001	0.0442
ATDT	Carbon tetrachloride	0.795919	0.095384	<.0001	0.0229	0.0159	<.0001	<.0001
ATDT	Naphthalene	0.238298	0.404096	0.311	0.2147	0.565	0.025	0.0347
ATDT	Trichloroethene	0.818063	0.057885	0.5875	0.0002	0.0153	<.0001	0.475
ATDT	Tetrachloroethene	0.426854	0.114163	0.3221	0.4522	0.11	<.0001	0.9827
RADIELLO	1,1,1-Trichloroethane	NA	0.308025973	0.1005	0.0261	0.003	0.0899	0.0548
RADIELLO	1,2,4-Trimethylbenzene	0.552465	0.140001	0.6688	0.0007	<.0001	0.1133	0.0451
RADIELLO	1,2-Dichloroethane	NA	0.171201636	0.0005	0.054	0.0002	0.0327	<.0001
RADIELLO	2-Butanone (MEK)	NA	0.229085137	<.0001	0.5801	0.0003	0.0738	<.0001
RADIELLO	Hexane	0.597975	0.16907	0.1795	0.0066	0.0021	<.0001	0.0035
RADIELLO	Benzene	0.530781	0.110247	0.0047	0.0496	0.0012	<.0001	0.6113
RADIELLO	Carbon tetrachloride	0.235885	0.246583	0.4994	0.0143	0.0513	0.1724	0.9018
RADIELLO	Naphthalene	NA	0.747997326	0.6635	0.0008	0.933	0.1183	0.0005
RADIELLO	Trichloroethene	NA	0.095571962	0.001	0.0032	<.0001	0.0002	0.0169
RADIELLO	Tetrachloroethene	NA	0.125976188	0.2158	0.0023	<.0001	0.3477	0.9109
SKC	1,1,1-Trichloroethane	0.478283	0.251787	0.0906	0.1691	0.0055	0.0096	0.0001
SKC	1,2,4-Trimethylbenzene	0.575654	0.300275	0.1362	0.3054	0.0012	0.0004	<.0001
SKC	1,2-Dichloroethane	0.381462	0.337603	<.0001	0.5187	0.1033	0.9879	0.6424
SKC	2-Butanone (MEK)	0.518151	0.19019	<.0001	0.2819	0.3914	0.0073	0.0028
SKC	Hexane	0.397091	0.247041	0.0006	0.0398	0.012	0.4921	0.1584
SKC	Benzene	0.336701	0.472786	0.0318	0.0551	0.9085	0.0218	0.0125
SKC	Carbon tetrachloride	0.79087	0.124783	0.0223	0.2682	0.032	<.0001	<.0001
SKC	Naphthalene	0.495836	0.180924	0.1182	0.1437	0.6579	<.0001	0.1122
SKC	Trichloroethene	0.619333	0.201723	<.0001	0.9977	0.0306	0.5618	<.0001
SKC	Tetrachloroethene	0.333153	0.242376	0.4868	0.0368	0.018	0.0097	0.1261
WMS	1,1,1-Trichloroethane	NA	0.285236744	0.0224	0.9489	0.0042	0.6355	0.4719
WMS	1,2,4-Trimethylbenzene	NA	0.148761554	0.7716	0.7992	<.0001	0.1467	0.0194
WMS	1,2-Dichloroethane	NA	0.268588905	0.7347	0.1749	0.0054	0.0325	0.1887
WMS	2-Butanone (MEK)	NA	2.203814874	0.5881	0.3369	0.14	0.0319	0.0027
WMS	Hexane	NA	6.668125674	0.6198	0.4942	0.022	0.0003	0.0001
WMS	Benzene	NA	1.503828448	0.5712	0.9017	0.0328	0.0012	0.0099
WMS	Carbon tetrachloride	NA	0.333916157	0.0016	0.3838	0.0035	0.0766	0.0553
WMS	Naphthalene	NA	0.021307276	0.9025	0.4298	<.0001	0.5432	0.006
WMS	Trichloroethene	NA	0.19679939	0.6289	0.0325	0.0006	0.8376	0.0124
WMS	Tetrachloroethene	NA	0.157448404	0.5923	0.1477	<.0001	0.9894	0.0074

red highlighted cells indicate statistical significance when alpha=0.05, therefore, p-value<0.05 = significant

R-Sqaure = 1- SSResiduals/SSTotal

Root MSE = standard deviation of the model

Table 1b: Main Effects Only Model - REML Method - Adjusted Main Effect Slope Estimates

Sampler Type	Analyte	Intercept	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	-0.200	0.002	0.009	-0.514	0.051	0.005
ATDC	1,2,4-Trimethylbenzene	1.211	-0.001	-0.009	-0.190	-0.005	-0.002
ATDC	1,2-Dichloroethane	-0.445	0.006	0.002	-0.089	0.078	0.002
ATDC	2-Butanone (MEK)	0.006	0.006	-0.007	-0.841	-0.010	0.006
ATDC	Hexane	0.469	-0.001	-0.013	0.528	0.095	0.004
ATDC	Benzene	0.300	0.003	-0.015	1.267	0.139	0.006
ATDC	Carbon tetrachloride	-0.328	0.004	0.005	-0.243	0.078	0.005
ATDC	Naphthalene	1.087	-0.002	-0.002	0.234	-0.042	0.002
ATDC	Trichloroethene	0.730	0.002	-0.003	-0.570	0.044	0.000
ATDC	Tetrachloroethene	1.697	0.000	-0.013	-0.596	0.003	-0.002
ATDT	1,1,1-Trichloroethane	0.548	-0.004	-0.003	-0.460	0.060	0.005
ATDT	1,2,4-Trimethylbenzene	0.617	0.000	0.001	-0.506	0.029	0.001
ATDT	1,2-Dichloroethane	-0.215	0.000	-0.001	0.189	0.091	0.005
ATDT	2-Butanone (MEK)	-2.851	0.001	0.025	1.040	0.300	0.017
ATDT	Hexane	-0.490	-0.001	0.009	0.186	0.125	0.002
ATDT	Benzene	-0.619	0.001	0.022	-0.300	0.182	0.003
ATDT	Carbon tetrachloride	0.560	-0.004	-0.007	-0.346	0.080	0.004
ATDT	Naphthalene	0.680	-0.004	-0.015	0.338	0.090	0.005
ATDT	Trichloroethene	0.128	0.000	0.007	-0.211	0.072	0.000
ATDT	Tetrachloroethene	0.451	0.001	0.003	-0.269	0.057	0.000
RADIELLO	1,1,1-Trichloroethane	1.516	0.005	-0.021	-1.440	-0.053	0.004
RADIELLO	1,2,4-Trimethylbenzene	2.000	-0.001	-0.015	-1.129	-0.022	-0.002
RADIELLO	1,2-Dichloroethane	0.109	0.007	-0.011	-1.211	0.052	0.007
RADIELLO	2-Butanone (MEK)	-1.399	0.023	-0.005	-1.736	0.058	0.011
RADIELLO	Hexane	0.442	0.002	-0.014	-0.798	0.092	0.003
RADIELLO	Benzene	0.681	0.003	-0.006	-0.553	0.050	0.000
RADIELLO	Carbon tetrachloride	1.470	0.002	-0.018	-0.714	-0.033	0.000
RADIELLO	Naphthalene	1.772	0.004	-0.090	-0.103	0.141	0.021
RADIELLO	Trichloroethene	0.666	0.004	-0.010	-0.933	0.055	0.002
RADIELLO	Tetrachloroethene	1.414	0.002	-0.014	-1.219	0.015	0.000
SKC	1,1,1-Trichloroethane	1.678	0.004	-0.010	-1.064	-0.066	-0.006
SKC	1,2,4-Trimethylbenzene	2.187	0.004	-0.009	-1.512	-0.111	-0.009
SKC	1,2-Dichloroethane	-0.134	0.015	-0.006	-0.811	0.000	-0.001
SKC	2-Butanone (MEK)	0.090	0.009	0.006	-0.238	-0.052	-0.004
SKC	Hexane	0.697	0.009	-0.015	-0.937	0.016	-0.002
SKC	Benzene	-0.249	0.010	-0.027	-0.079	0.108	0.007
SKC	Carbon tetrachloride	1.321	0.003	-0.004	-0.400	-0.059	-0.008
SKC	Naphthalene	1.456	-0.003	-0.008	-0.116	-0.101	-0.002
SKC	Trichloroethene	0.712	0.008	0.000	-0.652	-0.011	-0.008
SKC	Tetrachloroethene	1.576	0.002	-0.015	-0.861	-0.063	0.002
WMS	1,1,1-Trichloroethane	1.989	-0.007	-0.001	-1.408	-0.015	0.001
WMS	1,2,4-Trimethylbenzene	1.010	0.000	0.001	-1.761	0.024	-0.002
WMS	1,2-Dichloroethane	1.400	-0.001	0.012	-1.283	-0.064	-0.002
WMS	2-Butanone (MEK)	-6.487	0.014	0.075	-5.746	0.593	0.056
WMS	Hexane	-23.561	-0.034	-0.139	24.087	2.646	0.172
WMS	Benzene	-5.015	0.008	-0.005	4.852	0.509	0.024
WMS	Carbon tetrachloride	2.056	-0.012	-0.009	-1.683	0.066	0.004
WMS	Naphthalene	0.155	0.000	-0.001	-0.186	-0.002	0.000
WMS	Trichloroethene	0.971	-0.001	0.014	-1.202	0.004	-0.003
WMS	Tetrachloroethene	1.127	-0.001	0.007	-1.514	0.000	-0.003

Table 1c: Main Effects Only Model - REML Method - Predicted Values Using ANOVA Data

Sampler Type	Analyte	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n	Obs'd C/Co	Predict'd C/Co	Correction Factor	RPD (%)
ATDC	1,1,1-Trichloroethane	60	20	0.23	4.0	50	0.713	0.461	0.646	21.5
ATDC	1,2,4-Trimethylbenzene	60	20	0.23	4.0	50	0.752	0.840	1.117	5.5
ATDC	1,2-Dichloroethane	60	20	0.23	4.0	50	0.595	0.343	0.577	26.8
ATDC	2-Butanone (MEK)	60	20	0.23	4.0	50	1.645	0.260	0.158	72.7
ATDC	Hexane	60	20	0.23	4.0	50	0.796	0.842	1.057	2.8
ATDC	Benzene	60	20	0.23	4.0	50	1.244	1.317	1.058	2.8
ATDC	Carbon tetrachloride	60	20	0.23	4.0	50	0.222	0.507	2.281	39.0
ATDC	Naphthalene	60	20	0.23	4.0	50	0.963	0.910	0.945	2.8
ATDC	Trichloroethene	60	20	0.23	4.0	50	1.215	0.858	0.706	17.2
ATDC	Tetrachloroethene	60	20	0.23	4.0	50	0.922	1.252	1.357	15.2
ATDT	1,1,1-Trichloroethane	60	20	0.23	4.0	50	0.570	0.618	1.084	4.0
ATDT	1,2,4-Trimethylbenzene	60	20	0.23	4.0	50	0.674	0.661	0.982	0.9
ATDT	1,2-Dichloroethane	60	20	0.23	4.0	50	0.587	0.435	0.742	14.8
ATDT	2-Butanone (MEK)	60	20	0.23	4.0	50	0.932	0.039	0.041	92.0
ATDT	Hexane	60	20	0.23	4.0	50	0.600	0.286	0.477	35.4
ATDT	Benzene	60	20	0.23	4.0	50	0.488	0.681	1.394	16.5
ATDT	Carbon tetrachloride	60	20	0.23	4.0	50	0.705	0.601	0.853	7.9
ATDT	Naphthalene	60	20	0.23	4.0	50	0.942	0.843	0.895	5.5
ATDT	Trichloroethene	60	20	0.23	4.0	50	0.886	0.495	0.559	28.3
ATDT	Tetrachloroethene	60	20	0.23	4.0	50	0.613	0.734	1.198	9.0
RADIELLO	1,1,1-Trichloroethane	60	20	0.23	4.0	50	1.293	1.041	0.806	10.8
RADIELLO	1,2,4-Trimethylbenzene	60	20	0.23	4.0	50	0.690	1.236	1.791	28.3
RADIELLO	1,2-Dichloroethane	60	20	0.23	4.0	50	1.067	0.627	0.587	26.0
RADIELLO	2-Butanone (MEK)	60	20	0.23	4.0	50	1.134	0.281	0.248	60.3
RADIELLO	Hexane	60	20	0.23	4.0	50	1.309	0.634	0.484	34.7
RADIELLO	Benzene	60	20	0.23	4.0	50	0.920	0.799	0.868	7.1
RADIELLO	Carbon tetrachloride	60	20	0.23	4.0	50	1.448	0.916	0.633	22.5
RADIELLO	Naphthalene	60	20	0.23	4.0	50	0.375	1.757	4.691	64.9
RADIELLO	Trichloroethene	60	20	0.23	4.0	50	0.933	0.799	0.857	7.7
RADIELLO	Tetrachloroethene	60	20	0.23	4.0	50	1.029	1.030	1.001	0.1
SKC	1,1,1-Trichloroethane	60	20	0.23	4.0	50	1.075	0.911	0.848	8.3
SKC	1,2,4-Trimethylbenzene	60	20	0.23	4.0	50	1.393	1.028	0.738	15.1
SKC	1,2-Dichloroethane	60	20	0.23	4.0	50	0.901	0.433	0.480	35.1
SKC	2-Butanone (MEK)	60	20	0.23	4.0	50	1.001	0.323	0.323	51.2
SKC	Hexane	60	20	0.23	4.0	50	0.909	0.670	0.737	15.2
SKC	Benzene	60	20	0.23	4.0	50	0.879	0.593	0.675	19.4
SKC	Carbon tetrachloride	60	20	0.23	4.0	50	0.438	0.679	1.553	21.7
SKC	Naphthalene	60	20	0.23	4.0	50	2.758	0.617	0.224	63.4
SKC	Trichloroethene	60	20	0.23	4.0	50	1.172	0.628	0.536	30.2
SKC	Tetrachloroethene	60	20	0.23	4.0	50	1.034	1.032	0.998	0.1
WMS	1,1,1-Trichloroethane	60	20	0.23	4.0	50	1.205	1.239	1.028	1.4
WMS	1,2,4-Trimethylbenzene	60	20	0.23	4.0	50	0.964	0.578	0.600	25.0
WMS	1,2-Dichloroethane	60	20	0.23	4.0	50	1.134	0.905	0.798	11.2
WMS	2-Butanone (MEK)	60	20	0.23	4.0	50	0.956	-0.270	-0.283	178.8
WMS	Hexane	60	20	0.23	4.0	50	0.897	-3.629	-4.045	-165.7
WMS	Benzene	60	20	0.23	4.0	50	0.847	-0.272	-0.321	194.7
WMS	Carbon tetrachloride	60	20	0.23	4.0	50	0.760	1.251	1.646	24.4
WMS	Naphthalene	60	20	0.23	4.0	50	0.400	0.074	0.186	68.7
WMS	Trichloroethene	60	20	0.23	4.0	50	1.064	0.756	0.711	16.9
WMS	Tetrachloroethene	60	20	0.23	4.0	50	0.915	0.724	0.792	11.6

red highlights indicate an RPD of >25%

Table 1d: Main Effects Only Model - REML Method - Summary of Main Effect Slope Estimates

Sampler Type	Analyte	Intercept	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	0.479	0.069	0.087	-0.103	0.152	0.260
ATDC	1,2,4-Trimethylbenzene	0.845	-0.024	-0.087	-0.038	-0.014	-0.085
ATDC	1,2-Dichloroethane	0.347	0.186	0.022	-0.018	0.233	0.081
ATDC	2-Butanone (MEK)	0.289	0.169	-0.075	-0.168	-0.029	0.294
ATDC	Hexane	0.828	-0.032	-0.133	0.106	0.285	0.199
ATDC	Benzene	1.282	0.093	-0.151	0.253	0.416	0.283
ATDC	Carbon tetrachloride	0.517	0.107	0.054	-0.049	0.234	0.254
ATDC	Naphthalene	0.904	-0.050	-0.023	0.047	-0.125	0.080
ATDC	Trichloroethene	0.875	0.074	-0.031	-0.114	0.131	-0.002
ATDC	Tetrachloroethene	1.269	0.008	-0.128	-0.119	0.008	-0.077
ATDT	1,1,1-Trichloroethane	0.634	-0.124	-0.031	-0.092	0.179	0.246
ATDT	1,2,4-Trimethylbenzene	0.677	-0.004	0.006	-0.101	0.087	0.042
ATDT	1,2-Dichloroethane	0.432	0.006	-0.007	0.038	0.273	0.244
ATDT	2-Butanone (MEK)	0.016	0.041	0.253	0.208	0.900	0.853
ATDT	Hexane	0.282	-0.035	0.092	0.037	0.375	0.117
ATDT	Benzene	0.691	0.018	0.222	-0.060	0.545	0.159
ATDT	Carbon tetrachloride	0.613	-0.135	-0.065	-0.069	0.239	0.199
ATDT	Naphthalene	0.836	-0.120	-0.147	0.068	0.271	0.255
ATDT	Trichloroethene	0.502	-0.009	0.068	-0.042	0.215	0.012
ATDT	Tetrachloroethene	0.742	0.033	0.025	-0.054	0.171	0.001
RADIELLO	1,1,1-Trichloroethane	1.086	0.153	-0.210	-0.288	-0.158	0.180
RADIELLO	1,2,4-Trimethylbenzene	1.269	-0.017	-0.149	-0.226	-0.065	-0.083
RADIELLO	1,2-Dichloroethane	0.667	0.225	-0.114	-0.242	0.157	0.363
RADIELLO	2-Butanone (MEK)	0.338	0.701	-0.046	-0.347	0.174	0.533
RADIELLO	Hexane	0.659	0.067	-0.139	-0.160	0.277	0.151
RADIELLO	Benzene	0.815	0.095	-0.064	-0.111	0.150	-0.016
RADIELLO	Carbon tetrachloride	0.938	0.049	-0.182	-0.143	-0.099	0.009
RADIELLO	Naphthalene	1.771	0.107	-0.904	-0.021	0.424	1.025
RADIELLO	Trichloroethene	0.828	0.116	-0.102	-0.187	0.165	0.099
RADIELLO	Tetrachloroethene	1.067	0.053	-0.138	-0.244	0.046	0.005
SKC	1,1,1-Trichloroethane	0.940	0.126	-0.102	-0.213	-0.197	-0.305
SKC	1,2,4-Trimethylbenzene	1.068	0.132	-0.090	-0.302	-0.332	-0.448
SKC	1,2-Dichloroethane	0.456	0.462	-0.063	-0.162	0.001	-0.046
SKC	2-Butanone (MEK)	0.328	0.275	0.060	-0.048	-0.155	-0.174
SKC	Hexane	0.697	0.264	-0.151	-0.187	0.049	-0.102
SKC	Benzene	0.599	0.303	-0.269	-0.016	0.325	0.356
SKC	Carbon tetrachloride	0.687	0.085	-0.040	-0.080	-0.178	-0.399
SKC	Naphthalene	0.619	-0.083	-0.078	-0.023	-0.303	-0.085
SKC	Trichloroethene	0.643	0.251	0.000	-0.130	-0.034	-0.388
SKC	Tetrachloroethene	1.058	0.049	-0.151	-0.172	-0.190	0.109
WMS	1,1,1-Trichloroethane	1.282	-0.212	-0.006	-0.282	-0.044	0.067
WMS	1,2,4-Trimethylbenzene	0.630	-0.014	0.012	-0.352	0.071	-0.118
WMS	1,2-Dichloroethane	0.943	-0.029	0.116	-0.257	-0.193	-0.116
WMS	2-Butanone (MEK)	-0.070	0.427	0.746	-1.149	1.780	2.790
WMS	Hexane	-4.266	-1.010	-1.393	4.817	7.937	8.529
WMS	Benzene	-0.406	0.251	-0.055	0.970	1.526	1.189
WMS	Carbon tetrachloride	1.304	-0.356	-0.092	-0.337	0.197	0.214
WMS	Naphthalene	0.080	0.001	-0.006	-0.037	-0.005	-0.022
WMS	Trichloroethene	0.790	-0.030	0.137	-0.240	0.013	-0.167
WMS	Tetrachloroethene	0.768	-0.027	0.073	-0.303	-0.001	-0.144

Table 1e: Main Effects Only Model - REML Method - 95% Confidence Intervals for Main Effect Slope Estimates

Sampler Type	Analyte	Intercept	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	(0.384, 0.573)	(-0.008, 0.147)	(0.01, 0.165)	(-0.18, -0.025)	(0.074, 0.229)	(0.183, 0.338)
ATDC	1,2,4-Trimethylbenzene	(0.785, 0.904)	(-0.073, 0.024)	(-0.136, -0.038)	(-0.087, 0.011)	(-0.063, 0.035)	(-0.134, -0.036)
ATDC	1,2-Dichloroethane	(0.215, 0.478)	(0.079, 0.294)	(-0.086, 0.13)	(-0.126, 0.09)	(0.125, 0.341)	(-0.027, 0.189)
ATDC	2-Butanone (MEK)	(0.081, 0.496)	(-0.014, 0.353)	(-0.258, 0.109)	(-0.344, 0.008)	(-0.205, 0.147)	(0.071, 0.518)
ATDC	Hexane	(0.522, 1.134)	(-0.283, 0.219)	(-0.384, 0.118)	(-0.145, 0.357)	(0.034, 0.536)	(-0.052, 0.45)
ATDC	Benzene	(0.966, 1.598)	(-0.166, 0.352)	(-0.409, 0.108)	(-0.005, 0.512)	(0.158, 0.675)	(0.024, 0.542)
ATDC	Carbon tetrachloride	(0.39, 0.643)	(0.003, 0.211)	(-0.05, 0.158)	(-0.152, 0.055)	(0.13, 0.338)	(0.15, 0.358)
ATDC	Naphthalene	(0.795, 1.012)	(-0.139, 0.039)	(-0.111, 0.066)	(-0.042, 0.136)	(-0.214, -0.036)	(-0.009, 0.168)
ATDC	Trichloroethene	(0.806, 0.943)	(0.018, 0.13)	(-0.087, 0.026)	(-0.17, -0.058)	(0.075, 0.187)	(-0.058, 0.054)
ATDC	Tetrachloroethene	(1.165, 1.372)	(-0.077, 0.093)	(-0.213, -0.043)	(-0.204, -0.034)	(-0.077, 0.093)	(-0.162, 0.007)
ATDT	1,1,1-Trichloroethane	(0.565, 0.703)	(-0.181, -0.068)	(-0.088, 0.025)	(-0.149, -0.035)	(0.122, 0.236)	(0.189, 0.303)
ATDT	1,2,4-Trimethylbenzene	(0.582, 0.772)	(-0.082, 0.074)	(-0.072, 0.083)	(-0.179, -0.023)	(0.009, 0.165)	(-0.036, 0.119)
ATDT	1,2-Dichloroethane	(0.303, 0.561)	(-0.1, 0.111)	(-0.113, 0.098)	(-0.068, 0.143)	(0.167, 0.378)	(0.138, 0.349)
ATDT	2-Butanone (MEK)	(-0.333, 0.365)	(-0.244, 0.326)	(-0.032, 0.538)	(-0.077, 0.493)	(0.615, 1.185)	(0.568, 1.138)
ATDT	Hexane	(0.103, 0.462)	(-0.181, 0.112)	(-0.054, 0.239)	(-0.109, 0.184)	(0.228, 0.521)	(-0.03, 0.263)
ATDT	Benzene	(0.502, 0.881)	(-0.136, 0.173)	(0.068, 0.377)	(-0.215, 0.095)	(0.39, 0.699)	(0.004, 0.314)
ATDT	Carbon tetrachloride	(0.545, 0.681)	(-0.19, -0.079)	(-0.121, -0.009)	(-0.125, -0.014)	(0.184, 0.295)	(0.144, 0.255)
ATDT	Naphthalene	(0.547, 1.124)	(-0.355, 0.116)	(-0.382, 0.088)	(-0.168, 0.303)	(0.036, 0.507)	(0.019, 0.49)
ATDT	Trichloroethene	(0.461, 0.543)	(-0.043, 0.025)	(0.034, 0.102)	(-0.076, -0.009)	(0.181, 0.248)	(-0.022, 0.046)
ATDT	Tetrachloroethene	(0.661, 0.824)	(-0.033, 0.1)	(-0.042, 0.092)	(-0.12, 0.013)	(0.105, 0.238)	(-0.066, 0.067)
RADIELLO	1,1,1-Trichloroethane	(0.863, 1.31)	(-0.031, 0.337)	(-0.394, -0.026)	(-0.472, -0.104)	(-0.343, 0.026)	(-0.004, 0.365)
RADIELLO	1,2,4-Trimethylbenzene	(1.169, 1.369)	(-0.099, 0.064)	(-0.23, -0.067)	(-0.307, -0.144)	(-0.147, 0.016)	(-0.165, -0.002)
RADIELLO	1,2-Dichloroethane	(0.524, 0.81)	(0.108, 0.341)	(-0.231, 0.002)	(-0.359, -0.126)	(0.014, 0.299)	(0.221, 0.506)
RADIELLO	2-Butanone (MEK)	(0.144, 0.533)	(0.531, 0.87)	(-0.215, 0.123)	(-0.516, -0.178)	(-0.018, 0.366)	(0.318, 0.747)
RADIELLO	Hexane	(0.539, 0.78)	(-0.032, 0.165)	(-0.238, -0.041)	(-0.258, -0.061)	(0.178, 0.375)	(0.052, 0.249)
RADIELLO	Benzene	(0.736, 0.894)	(0.031, 0.159)	(-0.129, 0)	(-0.175, -0.046)	(0.086, 0.214)	(-0.081, 0.048)
RADIELLO	Carbon tetrachloride	(0.762, 1.114)	(-0.095, 0.192)	(-0.326, -0.038)	(-0.286, 0.001)	(-0.242, 0.045)	(-0.135, 0.152)
RADIELLO	Naphthalene	(1.185, 2.356)	(-0.389, 0.604)	(-1.4, -0.407)	(-0.517, 0.476)	(-0.114, 0.962)	(0.487, 1.564)
RADIELLO	Trichloroethene	(0.748, 0.908)	(0.051, 0.181)	(-0.167, -0.037)	(-0.252, -0.121)	(0.085, 0.245)	(0.019, 0.178)
RADIELLO	Tetrachloroethene	(0.965, 1.169)	(-0.032, 0.137)	(-0.223, -0.053)	(-0.328, -0.159)	(-0.052, 0.144)	(-0.093, 0.104)
SKC	1,1,1-Trichloroethane	(0.76, 1.119)	(-0.021, 0.273)	(-0.248, 0.045)	(-0.36, -0.066)	(-0.344, -0.051)	(-0.452, -0.158)
SKC	1,2,4-Trimethylbenzene	(0.854, 1.283)	(-0.043, 0.307)	(-0.265, 0.085)	(-0.477, -0.128)	(-0.507, -0.157)	(-0.623, -0.273)
SKC	1,2-Dichloroethane	(0.216, 0.697)	(0.265, 0.659)	(-0.26, 0.133)	(-0.359, 0.034)	(-0.195, 0.198)	(-0.242, 0.151)
SKC	2-Butanone (MEK)	(0.193, 0.464)	(0.165, 0.386)	(-0.051, 0.171)	(-0.158, 0.063)	(-0.266, -0.044)	(-0.285, -0.064)
SKC	Hexane	(0.521, 0.873)	(0.12, 0.408)	(-0.295, -0.007)	(-0.331, -0.043)	(-0.095, 0.193)	(-0.246, 0.042)
SKC	Benzene	(0.262, 0.936)	(0.028, 0.579)	(-0.545, 0.006)	(-0.291, 0.26)	(0.05, 0.601)	(0.081, 0.632)
SKC	Carbon tetrachloride	(0.598, 0.776)	(0.013, 0.158)	(-0.113, 0.032)	(-0.153, -0.007)	(-0.251, -0.105)	(-0.472, -0.326)
SKC	Naphthalene	(0.49, 0.748)	(-0.189, 0.022)	(-0.183, 0.028)	(-0.129, 0.082)	(-0.409, -0.198)	(-0.19, 0.021)
SKC	Trichloroethene	(0.499, 0.787)	(0.134, 0.369)	(-0.118, 0.117)	(-0.248, -0.013)	(-0.152, 0.083)	(-0.505, -0.27)
SKC	Tetrachloroethene	(0.886, 1.231)	(-0.092, 0.19)	(-0.292, -0.01)	(-0.313, -0.031)	(-0.331, -0.048)	(-0.032, 0.25)
WMS	1,1,1-Trichloroethane	(1.061, 1.503)	(-0.393, -0.032)	(-0.186, 0.175)	(-0.468, -0.095)	(-0.231, 0.143)	(-0.12, 0.254)
WMS	1,2,4-Trimethylbenzene	(0.514, 0.745)	(-0.108, 0.081)	(-0.082, 0.106)	(-0.45, -0.255)	(-0.026, 0.169)	(-0.215, -0.02)
WMS	1,2-Dichloroethane	(0.735, 1.151)	(-0.198, 0.141)	(-0.054, 0.286)	(-0.432, -0.081)	(-0.369, -0.017)	(-0.292, 0.06)
WMS	2-Butanone (MEK)	(-1.868, 1.729)	(-1.167, 2.021)	(-0.817, 2.309)	(-2.698, 0.4)	(0.165, 3.395)	(1.047, 4.534)
WMS	Hexane	(-9.191, 0.659)	(-5.093, 3.074)	(-5.477, 2.69)	(0.734, 8.901)	(3.854, 12.021)	(4.445, 12.612)
WMS	Benzene	(-1.488, 0.676)	(-0.636, 1.138)	(-0.942, 0.833)	(0.083, 1.858)	(0.639, 2.413)	(0.302, 2.076)
WMS	Carbon tetrachloride	(1.045, 1.562)	(-0.567, -0.145)	(-0.303, 0.119)	(-0.555, -0.118)	(-0.022, 0.415)	(-0.005, 0.432)
WMS	Naphthalene	(0.062, 0.097)	(-0.013, 0.015)	(-0.02, 0.009)	(-0.051, -0.023)	(-0.02, 0.011)	(-0.037, -0.007)
WMS	Trichloroethene	(0.638, 0.943)	(-0.154, 0.095)	(0.012, 0.261)	(-0.369, -0.112)	(-0.116, 0.142)	(-0.296, -0.038)
WMS	Tetrachloroethene	(0.646, 0.89)	(-0.126, 0.073)	(-0.027, 0.172)	(-0.406, -0.2)	(-0.104, 0.102)	(-0.247, -0.041)

Table 2a: Main Effects Only Model - Substitution Method - Summary of Model Statistics and Main Effect P-values

Sampler Type	Analyte	R-Square	Root MSE	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	0.65397	0.131494	0.0778	0.0281	0.0106	0.0003	<.0001
ATDC	1,2,4-Trimethylbenzene	0.408658	0.082824	0.3181	0.0009	0.1245	0.5664	0.0011
ATDC	1,2-Dichloroethane	0.457001	0.182717	0.0012	0.6819	0.7406	<.0001	0.1371
ATDC	2-Butanone (MEK)	0.685211	0.237604	0.8292	0.0687	0.0546	0.8199	<.0001
ATDC	Hexane	0.190167	0.425402	0.7999	0.2913	0.4002	0.0272	0.1177
ATDC	Benzene	0.339602	0.438782	0.4718	0.2468	0.0547	0.0023	0.0331
ATDC	Carbon tetrachloride	0.556859	0.175896	0.0434	0.2975	0.3501	<.0001	<.0001
ATDC	Naphthalene	0.259426	0.150481	0.2629	0.6088	0.293	0.007	0.0778
ATDC	Trichloroethene	0.540726	0.095064	0.0113	0.2781	0.0002	<.0001	0.9484
ATDC	Tetrachloroethene	0.327887	0.144003	0.8513	0.004	0.0071	0.8484	0.0727
ATDT	1,1,1-Trichloroethane	0.77989	0.097321	<.0001	0.2715	0.0021	<.0001	<.0001
ATDT	1,2,4-Trimethylbenzene	0.238568	0.133566	0.9169	0.8868	0.0121	0.0296	0.2864
ATDT	1,2-Dichloroethane	0.541289	0.181049	0.9154	0.8908	0.4733	<.0001	<.0001
ATDT	2-Butanone (MEK)	0.663055	0.488904	0.7719	0.0799	0.1479	<.0001	<.0001
ATDT	Hexane	0.427453	0.251521	0.6362	0.21	0.6114	<.0001	0.1148
ATDT	Benzene	0.603391	0.265519	0.8106	0.0059	0.438	<.0001	0.0442
ATDT	Carbon tetrachloride	0.795919	0.095384	<.0001	0.0229	0.0159	<.0001	<.0001
ATDT	Naphthalene	0.238298	0.404096	0.311	0.2147	0.565	0.025	0.0347
ATDT	Trichloroethene	0.818063	0.057885	0.5875	0.0002	0.0153	<.0001	0.475
ATDT	Tetrachloroethene	0.426854	0.114163	0.3221	0.4522	0.11	<.0001	0.9827
RADIELLO	1,1,1-Trichloroethane	0.390998	0.301086	0.0813	0.0214	0.0024	0.0645	0.0522
RADIELLO	1,2,4-Trimethylbenzene	0.552465	0.140001	0.6688	0.0007	<.0001	0.1133	0.0451
RADIELLO	1,2-Dichloroethane	0.62974	0.16889	0.0013	0.0856	0.0006	0.0551	<.0001
RADIELLO	2-Butanone (MEK)	0.661753	0.272766	<.0001	0.2386	0.0145	0.8488	<.0001
RADIELLO	Hexane	0.597975	0.16907	0.1795	0.0066	0.0021	<.0001	0.0035
RADIELLO	Benzene	0.530781	0.110247	0.0047	0.0496	0.0012	<.0001	0.6113
RADIELLO	Carbon tetrachloride	0.235885	0.246583	0.4994	0.0143	0.0513	0.1724	0.9018
RADIELLO	Naphthalene	0.360025	0.827239	0.1301	0.0002	0.2597	0.4227	0.0949
RADIELLO	Trichloroethene	0.669313	0.098347	0.0037	0.01	<.0001	<.0001	0.0016
RADIELLO	Tetrachloroethene	0.512088	0.124381	0.1682	0.0027	<.0001	0.1127	0.6241
SKC	1,1,1-Trichloroethane	0.478283	0.251787	0.0906	0.1691	0.0055	0.0096	0.0001
SKC	1,2,4-Trimethylbenzene	0.575654	0.300275	0.1362	0.3054	0.0012	0.0004	<.0001
SKC	1,2-Dichloroethane	0.381462	0.337603	<.0001	0.5187	0.1033	0.9879	0.6424
SKC	2-Butanone (MEK)	0.518151	0.19019	<.0001	0.2819	0.3914	0.0073	0.0028
SKC	Hexane	0.397091	0.247041	0.0006	0.0398	0.012	0.4921	0.1584
SKC	Benzene	0.336701	0.472786	0.0318	0.0551	0.9085	0.0218	0.0125
SKC	Carbon tetrachloride	0.79087	0.124783	0.0223	0.2682	0.032	<.0001	<.0001
SKC	Naphthalene	0.495836	0.180924	0.1182	0.1437	0.6579	<.0001	0.1122
SKC	Trichloroethene	0.619333	0.201723	<.0001	0.9977	0.0306	0.5618	<.0001
SKC	Tetrachloroethene	0.333153	0.242376	0.4868	0.0368	0.018	0.0097	0.1261
WMS	1,1,1-Trichloroethane	0.308787	0.267216	0.0201	0.6847	0.0016	0.7714	0.2584
WMS	1,2,4-Trimethylbenzene	0.319658	0.247594	0.8852	0.9036	0.0308	0.0006	0.3009
WMS	1,2-Dichloroethane	0.077256	0.293816	0.9017	0.2553	0.1948	0.5741	0.7377
WMS	2-Butanone (MEK)	0.291197	2.063753	0.0869	0.0848	0.0552	0.1272	0.0348
WMS	Hexane	0.446453	6.847496	0.8445	0.9973	0.003	0.0019	0.0008
WMS	Benzene	0.339924	1.520124	0.4382	0.7388	0.052	0.0022	0.0165
WMS	Carbon tetrachloride	0.47662	0.314861	0.001	0.177	0.0002	0.0891	0.0607
WMS	Naphthalene	0.513538	0.277123	0.1442	0.1608	0.2645	<.0001	0.0001
WMS	Trichloroethene	0.196594	0.235807	0.8942	0.0966	0.1389	0.0322	0.6672
WMS	Tetrachloroethene	0.215046	0.228665	0.8315	0.3666	0.0418	0.0174	0.7665

red highlighted cells indicate statistical significance when alpha=0.05

Table 2b: Main Effects Only Model - Substitution Method - Main Effect Slope Estimates

Sampler Type	Analyte	Intercept	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	0.479	0.069	0.087	-0.103	0.152	0.260
ATDC	1,2,4-Trimethylbenzene	0.845	-0.024	-0.087	-0.038	-0.014	-0.085
ATDC	1,2-Dichloroethane	0.347	0.186	0.022	-0.018	0.233	0.081
ATDC	2-Butanone (MEK)	0.355	0.015	-0.130	-0.137	0.016	0.622
ATDC	Hexane	0.828	-0.032	-0.133	0.106	0.285	0.199
ATDC	Benzene	1.282	0.093	-0.151	0.253	0.416	0.283
ATDC	Carbon tetrachloride	0.517	0.107	0.054	-0.049	0.234	0.254
ATDC	Naphthalene	0.904	-0.050	-0.023	0.047	-0.125	0.080
ATDC	Trichloroethene	0.875	0.074	-0.031	-0.114	0.131	-0.002
ATDC	Tetrachloroethene	1.269	0.008	-0.128	-0.119	0.008	-0.077
ATDT	1,1,1-Trichloroethane	0.634	-0.124	-0.031	-0.092	0.179	0.246
ATDT	1,2,4-Trimethylbenzene	0.677	-0.004	0.006	-0.101	0.087	0.042
ATDT	1,2-Dichloroethane	0.432	0.006	-0.007	0.038	0.273	0.244
ATDT	2-Butanone (MEK)	0.016	0.041	0.253	0.208	0.900	0.853
ATDT	Hexane	0.282	-0.035	0.092	0.037	0.375	0.117
ATDT	Benzene	0.691	0.018	0.222	-0.060	0.545	0.159
ATDT	Carbon tetrachloride	0.613	-0.135	-0.065	-0.069	0.239	0.199
ATDT	Naphthalene	0.836	-0.120	-0.147	0.068	0.271	0.255
ATDT	Trichloroethene	0.502	-0.009	0.068	-0.042	0.215	0.012
ATDT	Tetrachloroethene	0.742	0.033	0.025	-0.054	0.171	0.001
RADIELLO	1,1,1-Trichloroethane	1.084	0.155	-0.208	-0.281	-0.165	0.174
RADIELLO	1,2,4-Trimethylbenzene	1.269	-0.017	-0.149	-0.226	-0.065	-0.083
RADIELLO	1,2-Dichloroethane	0.680	0.169	-0.086	-0.182	0.096	0.303
RADIELLO	2-Butanone (MEK)	0.486	0.466	-0.094	-0.201	0.015	0.493
RADIELLO	Hexane	0.659	0.067	-0.139	-0.160	0.277	0.151
RADIELLO	Benzene	0.815	0.095	-0.064	-0.111	0.150	-0.016
RADIELLO	Carbon tetrachloride	0.938	0.049	-0.182	-0.143	-0.099	0.009
RADIELLO	Naphthalene	1.833	0.369	-0.966	0.273	-0.193	0.408
RADIELLO	Trichloroethene	0.808	0.087	-0.077	-0.140	0.162	0.096
RADIELLO	Tetrachloroethene	1.025	0.050	-0.114	-0.194	0.058	0.018
SKC	1,1,1-Trichloroethane	0.940	0.126	-0.102	-0.213	-0.197	-0.305
SKC	1,2,4-Trimethylbenzene	1.068	0.132	-0.090	-0.302	-0.332	-0.448
SKC	1,2-Dichloroethane	0.456	0.462	-0.063	-0.162	0.001	-0.046
SKC	2-Butanone (MEK)	0.328	0.275	0.060	-0.048	-0.155	-0.174
SKC	Hexane	0.697	0.264	-0.151	-0.187	0.049	-0.102
SKC	Benzene	0.599	0.303	-0.269	-0.016	0.325	0.356
SKC	Carbon tetrachloride	0.687	0.085	-0.040	-0.080	-0.178	-0.399
SKC	Naphthalene	0.619	-0.083	-0.078	-0.023	-0.303	-0.085
SKC	Trichloroethene	0.643	0.251	0.000	-0.130	-0.034	-0.388
SKC	Tetrachloroethene	1.058	0.049	-0.151	-0.172	-0.190	0.109
WMS	1,1,1-Trichloroethane	1.260	-0.186	-0.032	-0.260	-0.023	0.088
WMS	1,2,4-Trimethylbenzene	0.437	-0.010	0.009	-0.160	0.264	0.075
WMS	1,2-Dichloroethane	0.798	-0.011	0.098	-0.112	-0.048	0.029
WMS	2-Butanone (MEK)	-0.092	1.044	1.051	-1.175	0.927	1.299
WMS	Hexane	-5.666	0.390	0.007	6.217	6.537	7.129
WMS	Benzene	-0.313	0.343	-0.147	0.878	1.433	1.096
WMS	Carbon tetrachloride	1.342	-0.323	-0.125	-0.375	0.158	0.175
WMS	Naphthalene	-0.286	0.119	0.114	0.090	0.361	0.344
WMS	Trichloroethene	0.653	-0.009	0.116	-0.103	0.151	-0.029
WMS	Tetrachloroethene	0.604	-0.014	0.060	-0.139	0.163	0.020

Table 2c: Main Effects Only Model - Substitution Method - 95% Confidence Intervals for Main Effect Slope Estimates

Sampler Type	Analyte	Intercept	%Rel.Hum.	Temp	Velocity	Exp. Time	Conc'n
ATDC	1,1,1-Trichloroethane	(0.384, 0.573)	(-0.008, 0.147)	(0.01, 0.165)	(-0.18, -0.025)	(0.074, 0.229)	(0.183, 0.338)
ATDC	1,2,4-Trimethylbenzene	(0.785, 0.904)	(-0.073, 0.024)	(-0.136, -0.038)	(-0.087, 0.011)	(-0.063, 0.035)	(-0.134, -0.036)
ATDC	1,2-Dichloroethane	(0.215, 0.478)	(0.079, 0.294)	(-0.086, 0.13)	(-0.126, 0.09)	(0.125, 0.341)	(-0.027, 0.189)
ATDC	2-Butanone (MEK)	(0.184, 0.526)	(-0.125, 0.155)	(-0.27, 0.01)	(-0.278, 0.003)	(-0.124, 0.156)	(0.481, 0.762)
ATDC	Hexane	(0.522, 1.134)	(-0.283, 0.219)	(-0.384, 0.118)	(-0.145, 0.357)	(0.034, 0.536)	(-0.052, 0.45)
ATDC	Benzene	(0.966, 1.598)	(-0.166, 0.352)	(-0.409, 0.108)	(-0.005, 0.512)	(0.158, 0.675)	(0.024, 0.542)
ATDC	Carbon tetrachloride	(0.39, 0.643)	(0.003, 0.211)	(-0.05, 0.158)	(-0.152, 0.055)	(0.13, 0.338)	(0.15, 0.358)
ATDC	Naphthalene	(0.795, 1.012)	(-0.139, 0.039)	(-0.111, 0.066)	(-0.042, 0.136)	(-0.214, -0.036)	(-0.009, 0.168)
ATDC	Trichloroethene	(0.806, 0.943)	(0.018, 0.13)	(-0.087, 0.026)	(-0.17, -0.058)	(0.075, 0.187)	(-0.058, 0.054)
ATDC	Tetrachloroethene	(1.165, 1.372)	(-0.077, 0.093)	(-0.213, -0.043)	(-0.204, -0.034)	(-0.077, 0.093)	(-0.162, 0.007)
ATDT	1,1,1-Trichloroethane	(0.565, 0.703)	(-0.181, -0.068)	(-0.088, 0.025)	(-0.149, -0.035)	(0.122, 0.236)	(0.189, 0.303)
ATDT	1,2,4-Trimethylbenzene	(0.582, 0.772)	(-0.082, 0.074)	(-0.072, 0.083)	(-0.179, -0.023)	(0.009, 0.165)	(-0.036, 0.119)
ATDT	1,2-Dichloroethane	(0.303, 0.561)	(-0.1, 0.111)	(-0.113, 0.098)	(-0.068, 0.143)	(0.167, 0.378)	(0.138, 0.349)
ATDT	2-Butanone (MEK)	(-0.333, 0.365)	(-0.244, 0.326)	(-0.032, 0.538)	(-0.077, 0.493)	(0.615, 1.185)	(0.568, 1.138)
ATDT	Hexane	(0.103, 0.462)	(-0.181, 0.112)	(-0.054, 0.239)	(-0.109, 0.184)	(0.228, 0.521)	(-0.03, 0.263)
ATDT	Benzene	(0.502, 0.881)	(-0.136, 0.173)	(0.068, 0.377)	(-0.215, 0.095)	(0.39, 0.699)	(0.004, 0.314)
ATDT	Carbon tetrachloride	(0.545, 0.681)	(-0.19, -0.079)	(-0.121, -0.009)	(-0.125, -0.014)	(0.184, 0.295)	(0.144, 0.255)
ATDT	Naphthalene	(0.547, 1.124)	(-0.355, 0.116)	(-0.382, 0.088)	(-0.168, 0.303)	(0.036, 0.507)	(0.019, 0.49)
ATDT	Trichloroethene	(0.461, 0.543)	(-0.043, 0.025)	(0.034, 0.102)	(-0.076, -0.009)	(0.181, 0.248)	(-0.022, 0.046)
ATDT	Tetrachloroethene	(0.661, 0.824)	(-0.033, 0.1)	(-0.042, 0.092)	(-0.12, 0.013)	(0.105, 0.238)	(-0.066, 0.067)
RADIELLO	1,1,1-Trichloroethane	(0.869, 1.299)	(-0.02, 0.331)	(-0.383, -0.032)	(-0.457, -0.106)	(-0.34, 0.01)	(-0.002, 0.349)
RADIELLO	1,2,4-Trimethylbenzene	(1.169, 1.369)	(-0.099, 0.064)	(-0.23, -0.067)	(-0.307, -0.144)	(-0.147, 0.016)	(-0.165, -0.002)
RADIELLO	1,2-Dichloroethane	(0.56, 0.801)	(0.07, 0.267)	(-0.184, 0.013)	(-0.28, -0.083)	(-0.002, 0.195)	(0.205, 0.401)
RADIELLO	2-Butanone (MEK)	(0.291, 0.681)	(0.307, 0.625)	(-0.253, 0.065)	(-0.36, -0.042)	(-0.144, 0.174)	(0.334, 0.652)
RADIELLO	Hexane	(0.539, 0.78)	(-0.032, 0.165)	(-0.238, -0.041)	(-0.258, -0.061)	(0.178, 0.375)	(0.052, 0.249)
RADIELLO	Benzene	(0.736, 0.894)	(0.031, 0.159)	(-0.129, 0)	(-0.175, -0.046)	(0.086, 0.214)	(-0.081, 0.048)
RADIELLO	Carbon tetrachloride	(0.762, 1.114)	(-0.095, 0.192)	(-0.326, -0.038)	(-0.286, 0.001)	(-0.242, 0.045)	(-0.135, 0.152)
RADIELLO	Naphthalene	(1.243, 2.423)	(-0.113, 0.851)	(-1.448, -0.484)	(-0.209, 0.755)	(-0.675, 0.289)	(-0.074, 0.89)
RADIELLO	Trichloroethene	(0.738, 0.878)	(0.03, 0.145)	(-0.134, -0.019)	(-0.197, -0.083)	(0.105, 0.219)	(0.039, 0.153)
RADIELLO	Tetrachloroethene	(0.936, 1.114)	(-0.022, 0.123)	(-0.187, -0.042)	(-0.266, -0.121)	(-0.014, 0.131)	(-0.055, 0.09)
SKC	1,1,1-Trichloroethane	(0.76, 1.119)	(-0.021, 0.273)	(-0.248, 0.045)	(-0.36, -0.066)	(-0.344, -0.051)	(-0.452, -0.158)
SKC	1,2,4-Trimethylbenzene	(0.854, 1.283)	(-0.043, 0.307)	(-0.265, 0.085)	(-0.477, -0.128)	(-0.507, -0.157)	(-0.623, -0.273)
SKC	1,2-Dichloroethane	(0.216, 0.697)	(0.265, 0.659)	(-0.26, 0.133)	(-0.359, 0.034)	(-0.195, 0.198)	(-0.242, 0.151)
SKC	2-Butanone (MEK)	(0.193, 0.464)	(0.165, 0.386)	(-0.051, 0.171)	(-0.158, 0.063)	(-0.266, -0.044)	(-0.285, -0.064)
SKC	Hexane	(0.521, 0.873)	(0.12, 0.408)	(-0.295, -0.007)	(-0.331, -0.043)	(-0.095, 0.193)	(-0.246, 0.042)
SKC	Benzene	(0.262, 0.936)	(0.028, 0.579)	(-0.545, 0.006)	(-0.291, 0.26)	(0.05, 0.601)	(0.081, 0.632)
SKC	Carbon tetrachloride	(0.598, 0.776)	(0.013, 0.158)	(-0.113, 0.032)	(-0.153, -0.007)	(-0.251, -0.105)	(-0.472, -0.326)
SKC	Naphthalene	(0.49, 0.748)	(-0.189, 0.022)	(-0.183, 0.028)	(-0.129, 0.082)	(-0.409, -0.198)	(-0.19, 0.021)
SKC	Trichloroethene	(0.499, 0.787)	(0.134, 0.369)	(-0.118, 0.117)	(-0.248, -0.013)	(-0.152, 0.083)	(-0.505, -0.27)
SKC	Tetrachloroethene	(0.886, 1.231)	(-0.092, 0.19)	(-0.292, -0.01)	(-0.313, -0.031)	(-0.331, -0.048)	(-0.032, 0.25)
WMS	1,1,1-Trichloroethane	(1.07, 1.451)	(-0.342, -0.031)	(-0.187, 0.124)	(-0.416, -0.104)	(-0.178, 0.133)	(-0.067, 0.244)
WMS	1,2,4-Trimethylbenzene	(0.261, 0.614)	(-0.155, 0.134)	(-0.136, 0.153)	(-0.304, -0.016)	(0.119, 0.408)	(-0.069, 0.219)
WMS	1,2-Dichloroethane	(0.588, 1.008)	(-0.182, 0.161)	(-0.073, 0.269)	(-0.283, 0.059)	(-0.219, 0.123)	(-0.143, 0.2)
WMS	2-Butanone (MEK)	(-1.564, 1.381)	(-0.158, 2.247)	(-0.151, 2.254)	(-2.377, 0.027)	(-0.275, 2.129)	(0.097, 2.502)
WMS	Hexane	(-10.551, -0.78)	(-3.599, 4.379)	(-3.982, 3.996)	(2.228, 10.206)	(2.548, 10.526)	(3.139, 11.118)
WMS	Benzene	(-1.398, 0.771)	(-0.542, 1.229)	(-1.033, 0.738)	(-0.008, 1.763)	(0.547, 2.319)	(0.21, 1.982)
WMS	Carbon tetrachloride	(1.117, 1.566)	(-0.506, -0.139)	(-0.308, 0.059)	(-0.558, -0.191)	(-0.025, 0.342)	(-0.008, 0.359)
WMS	Naphthalene	(-0.484, -0.088)	(-0.042, 0.28)	(-0.047, 0.276)	(-0.071, 0.252)	(0.2, 0.522)	(0.182, 0.505)
WMS	Trichloroethene	(0.484, 0.821)	(-0.146, 0.128)	(-0.022, 0.253)	(-0.24, 0.035)	(0.013, 0.288)	(-0.167, 0.108)
WMS	Tetrachloroethene	(0.441, 0.767)	(-0.147, 0.119)	(-0.073, 0.193)	(-0.272, -0.005)	(0.03, 0.297)	(-0.113, 0.153)

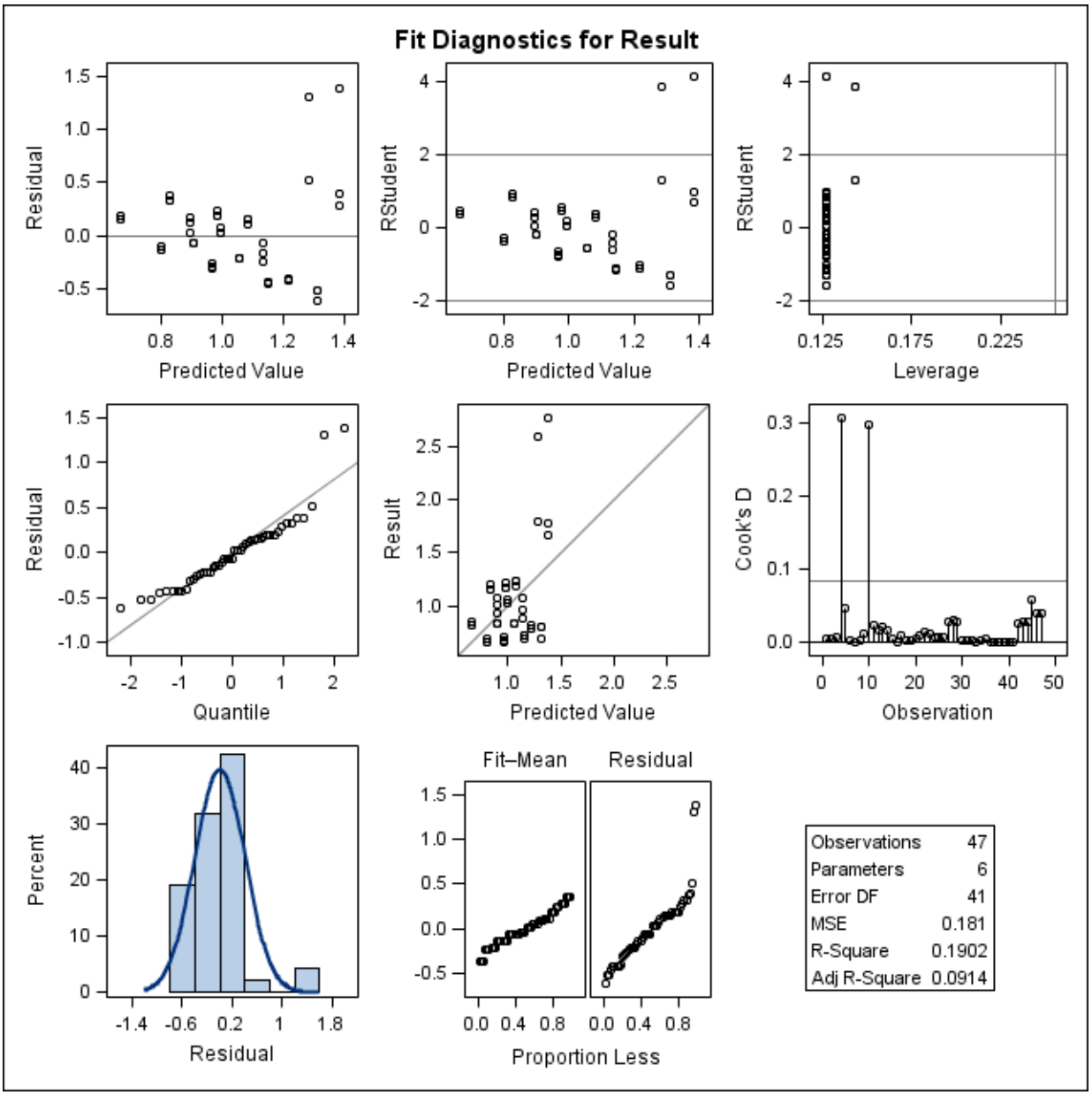
Citations:

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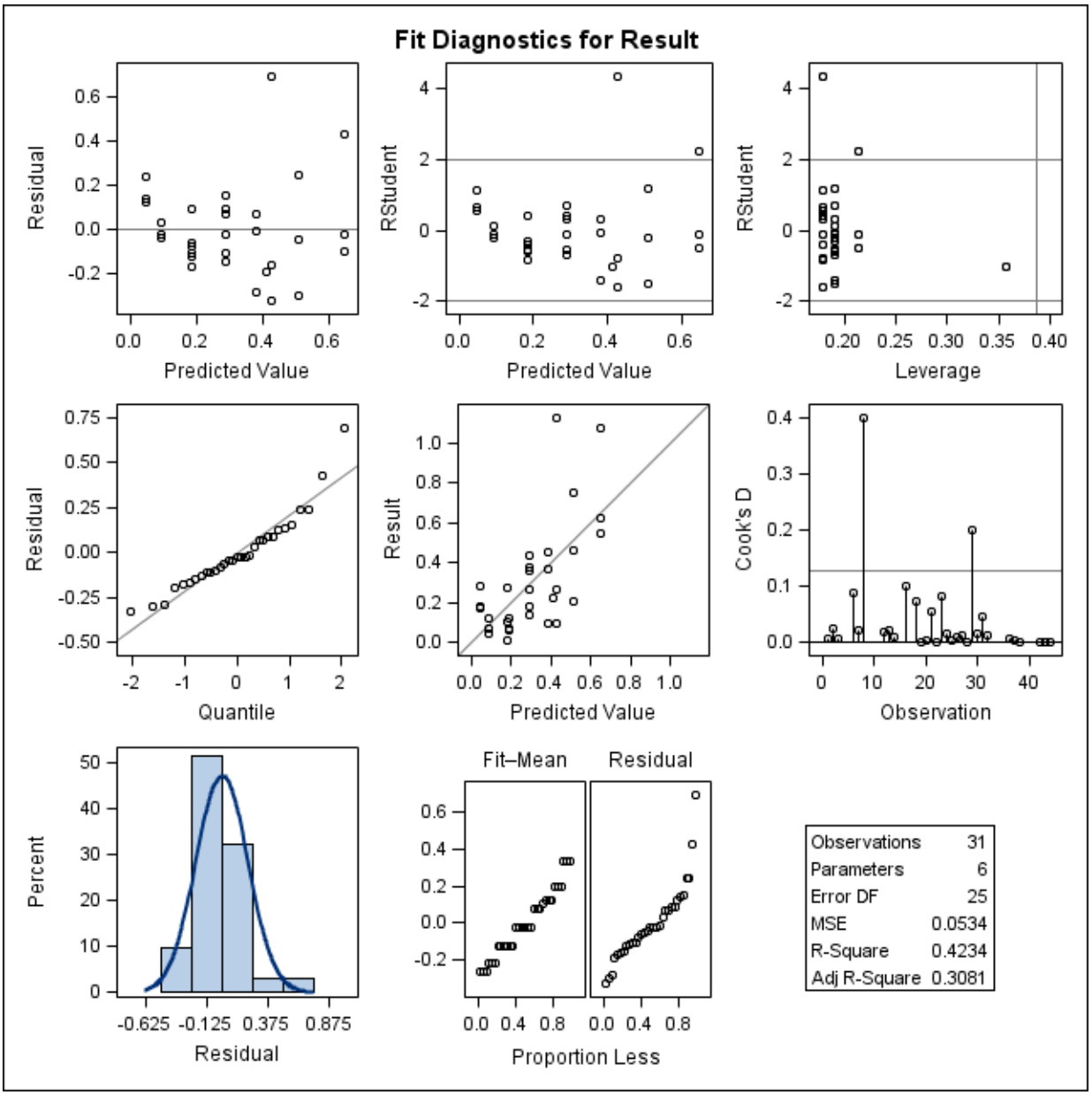
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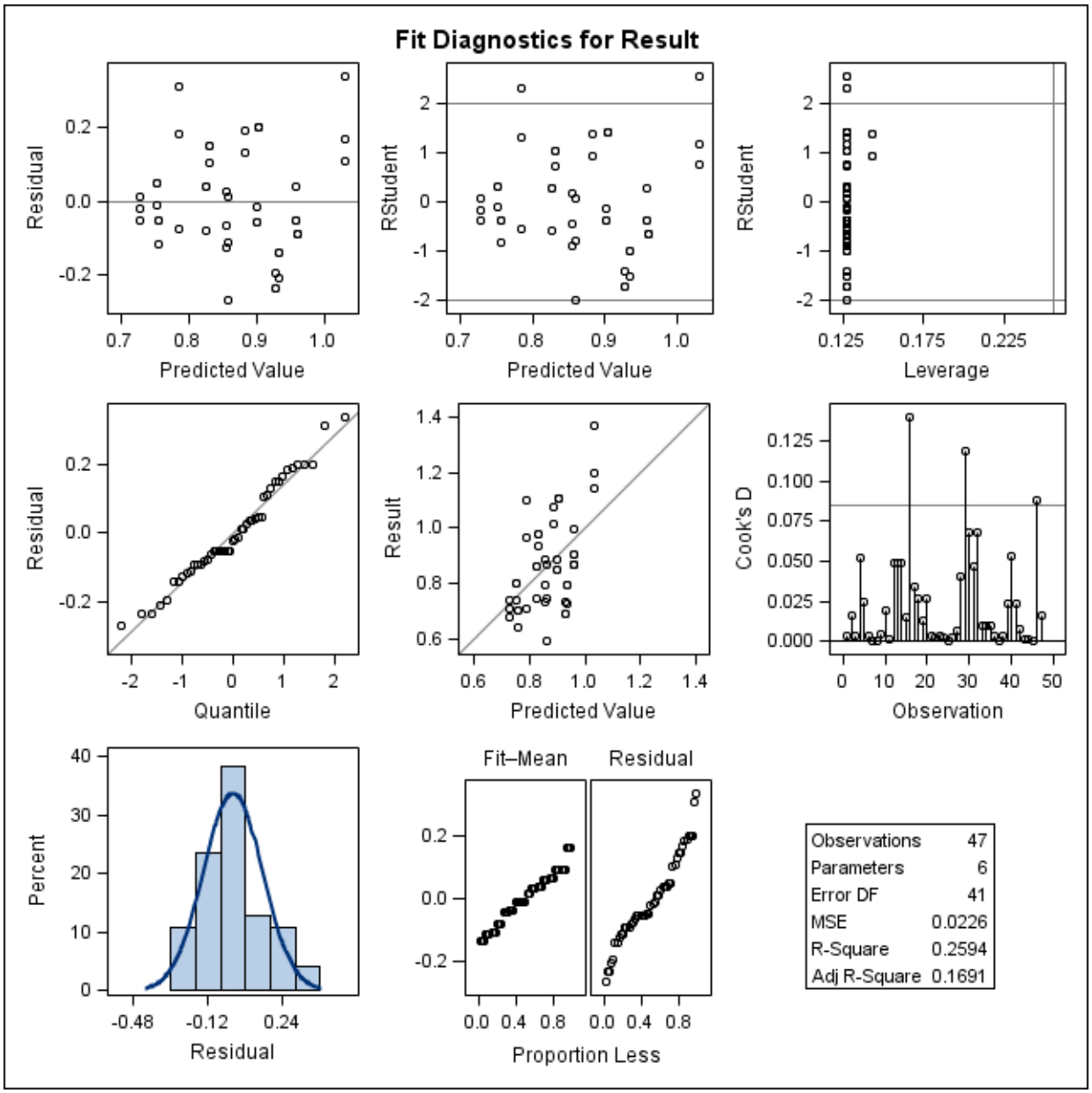
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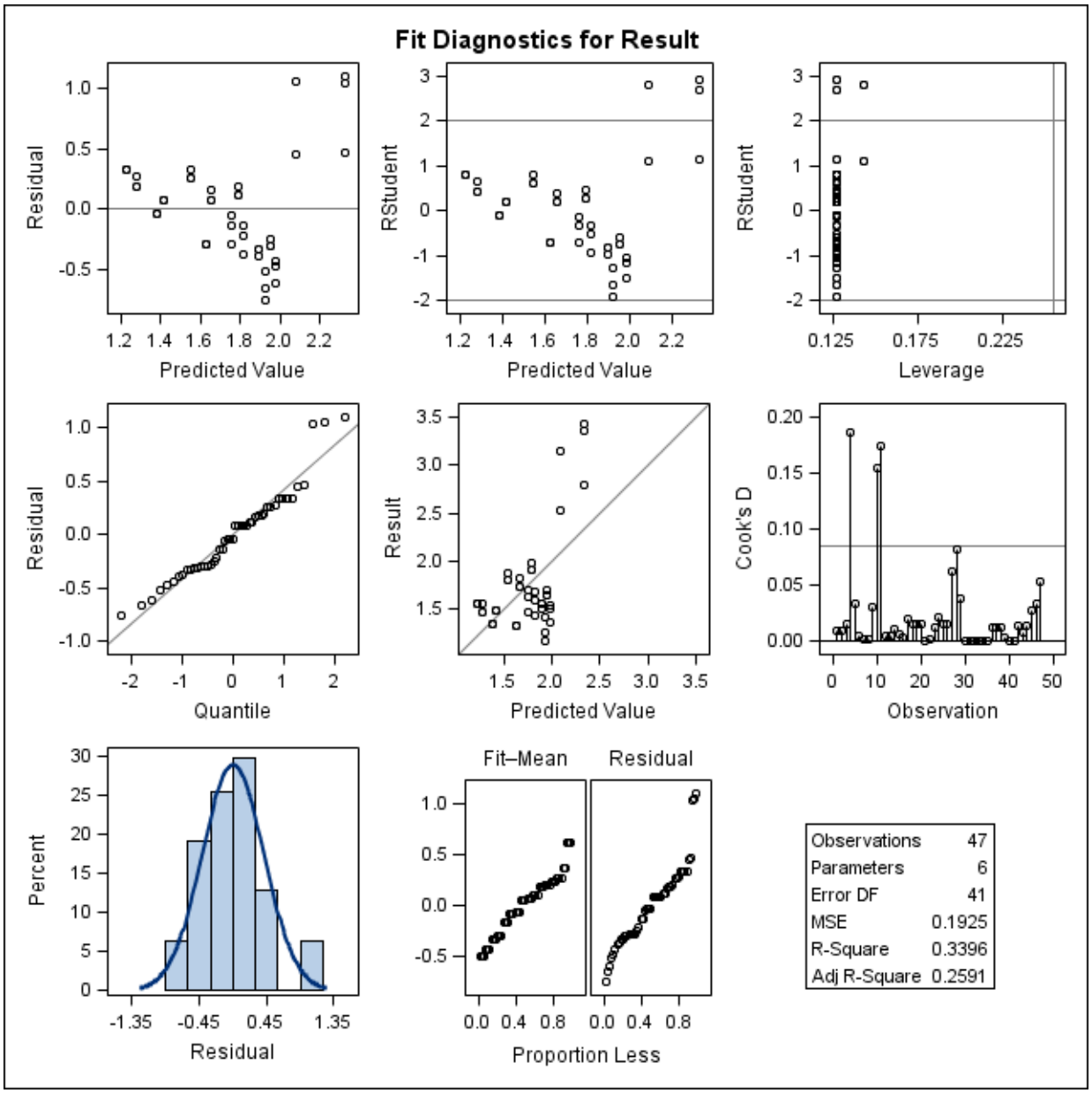
ATD Carbopack B - Benzene



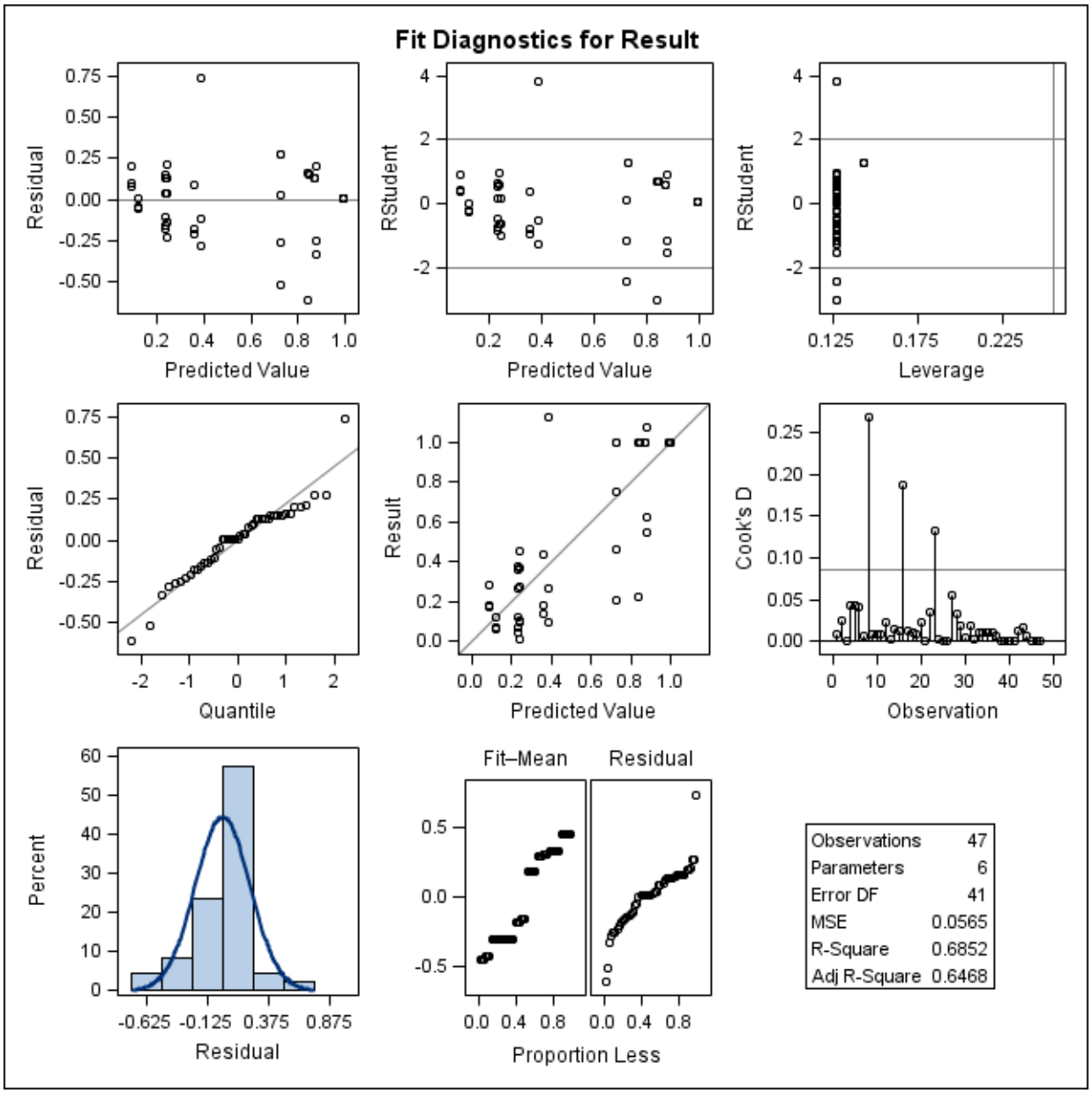
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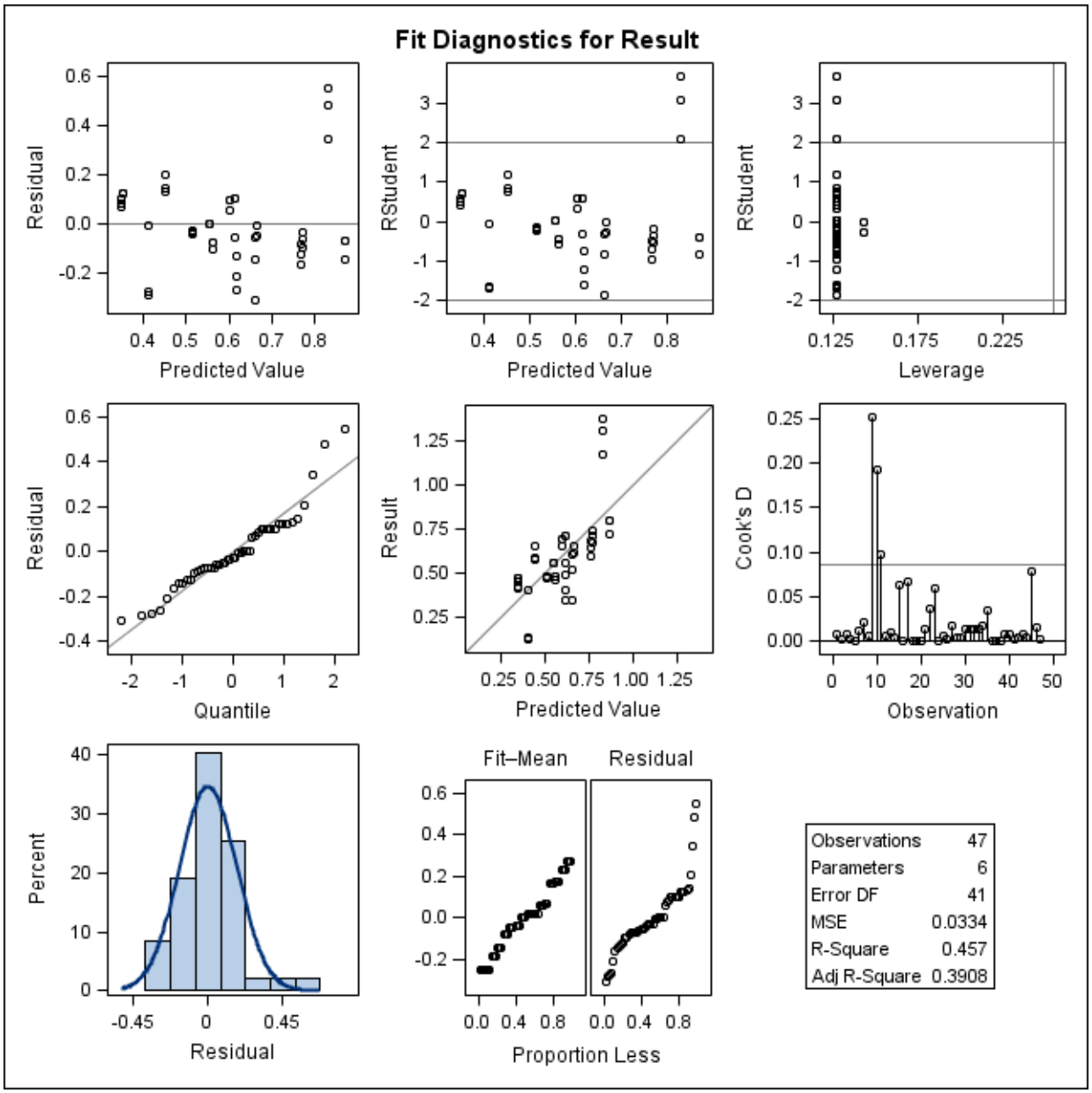
ATD Carbopack B - 1,2-Dichloroethane



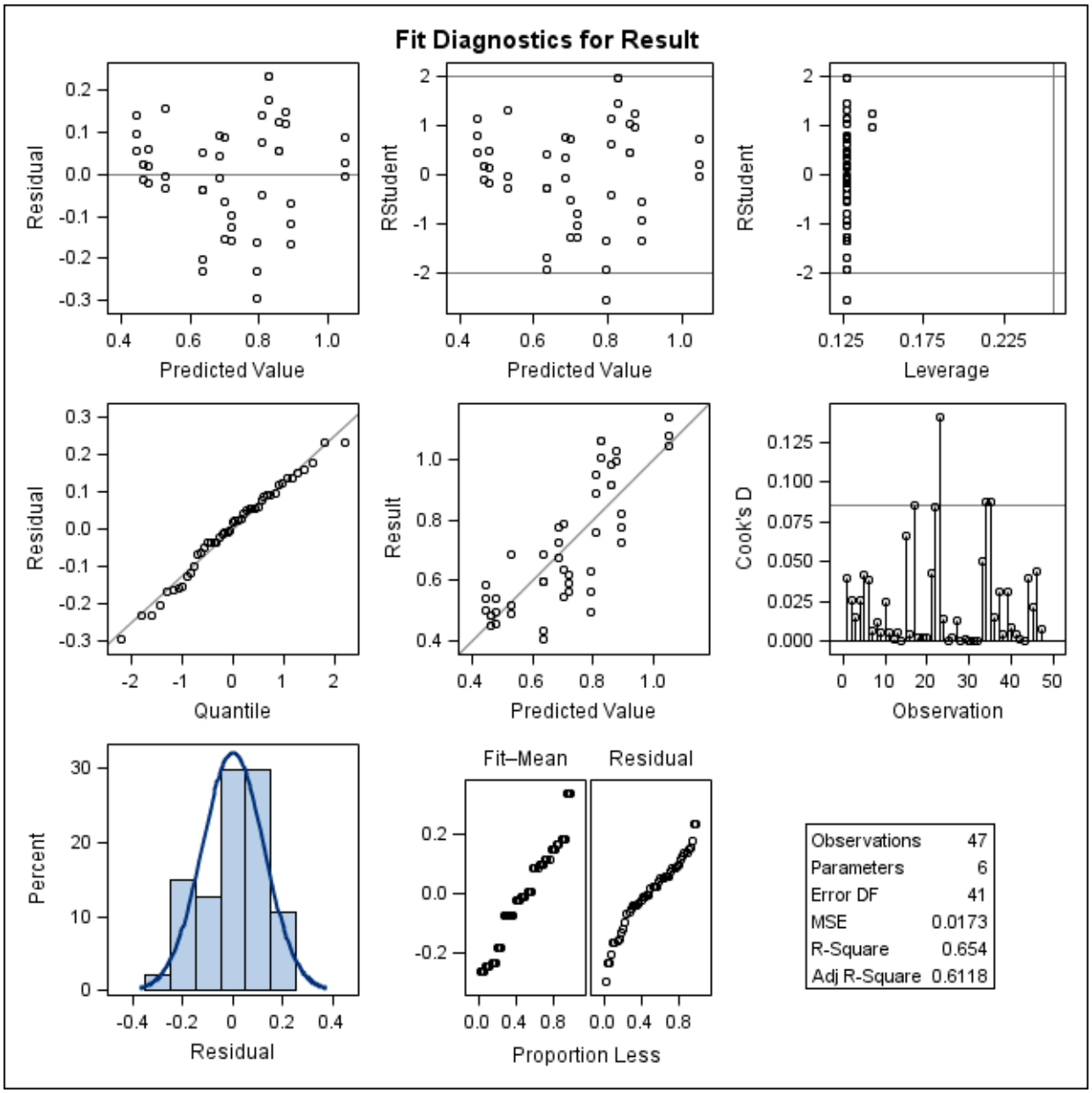
ATD Carbopack B - n-Hexane



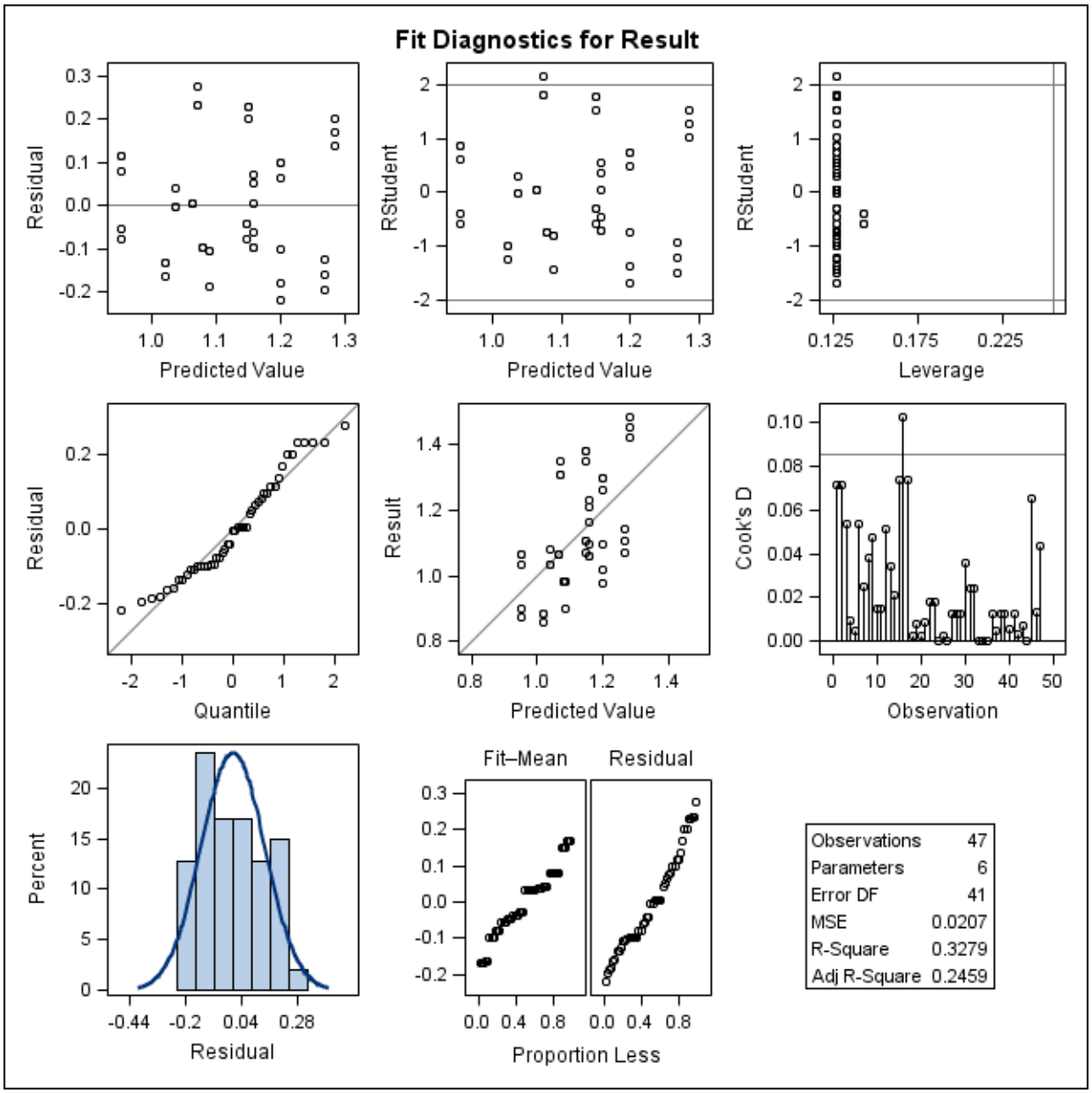
ATD Carbopack B - Methylethyl Ketone



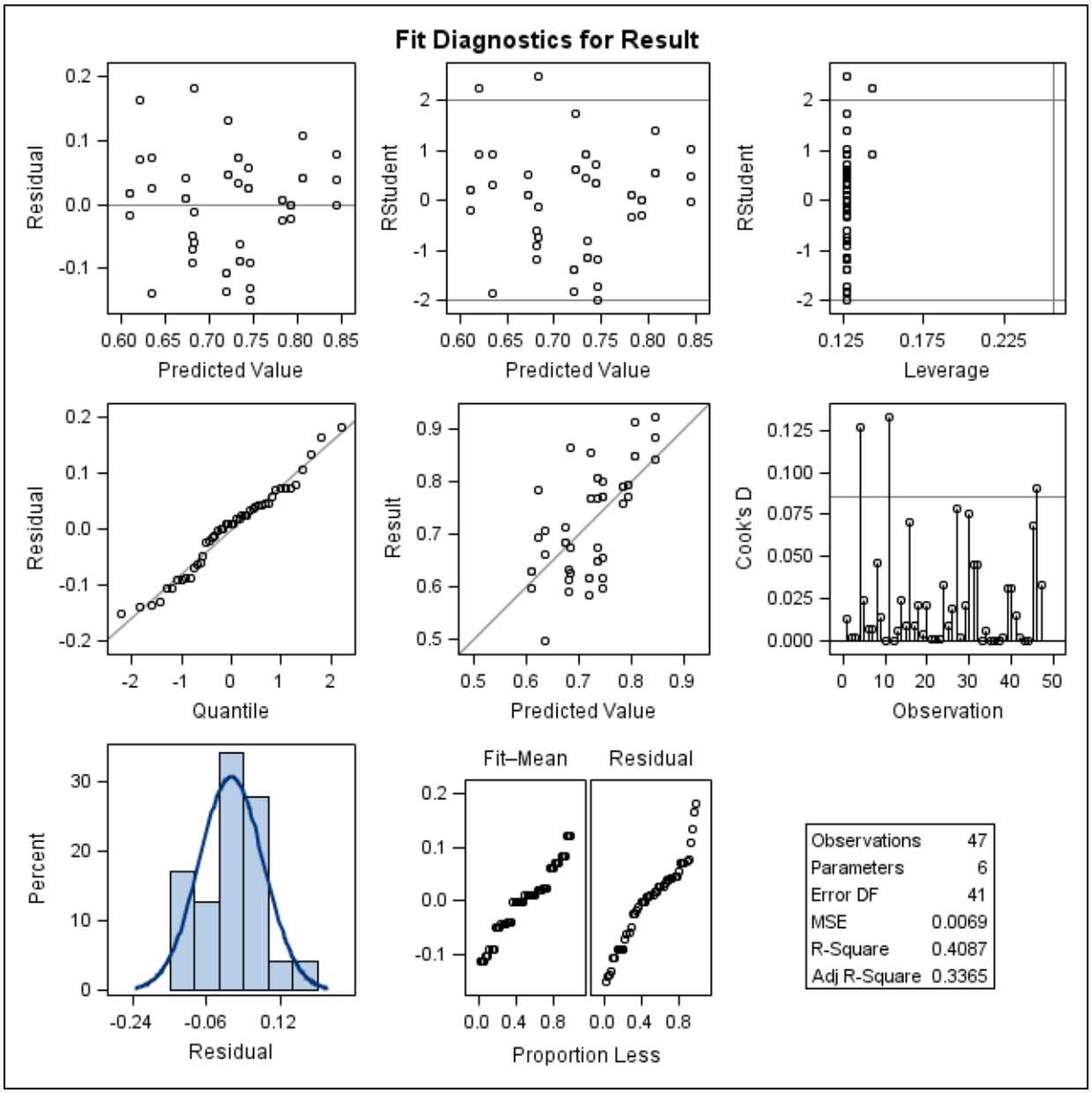
ATD Carbopack B – Naphthalene



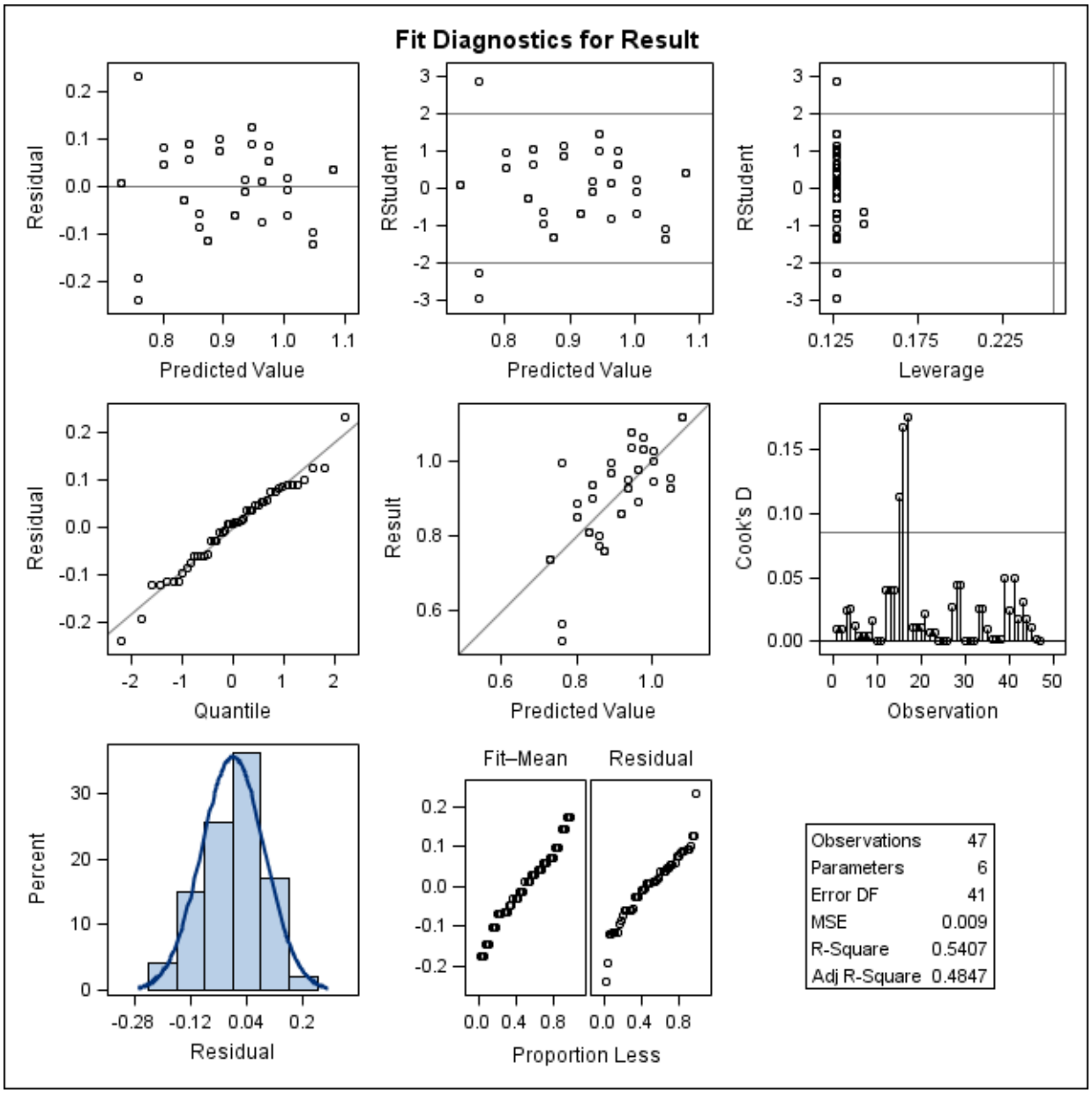
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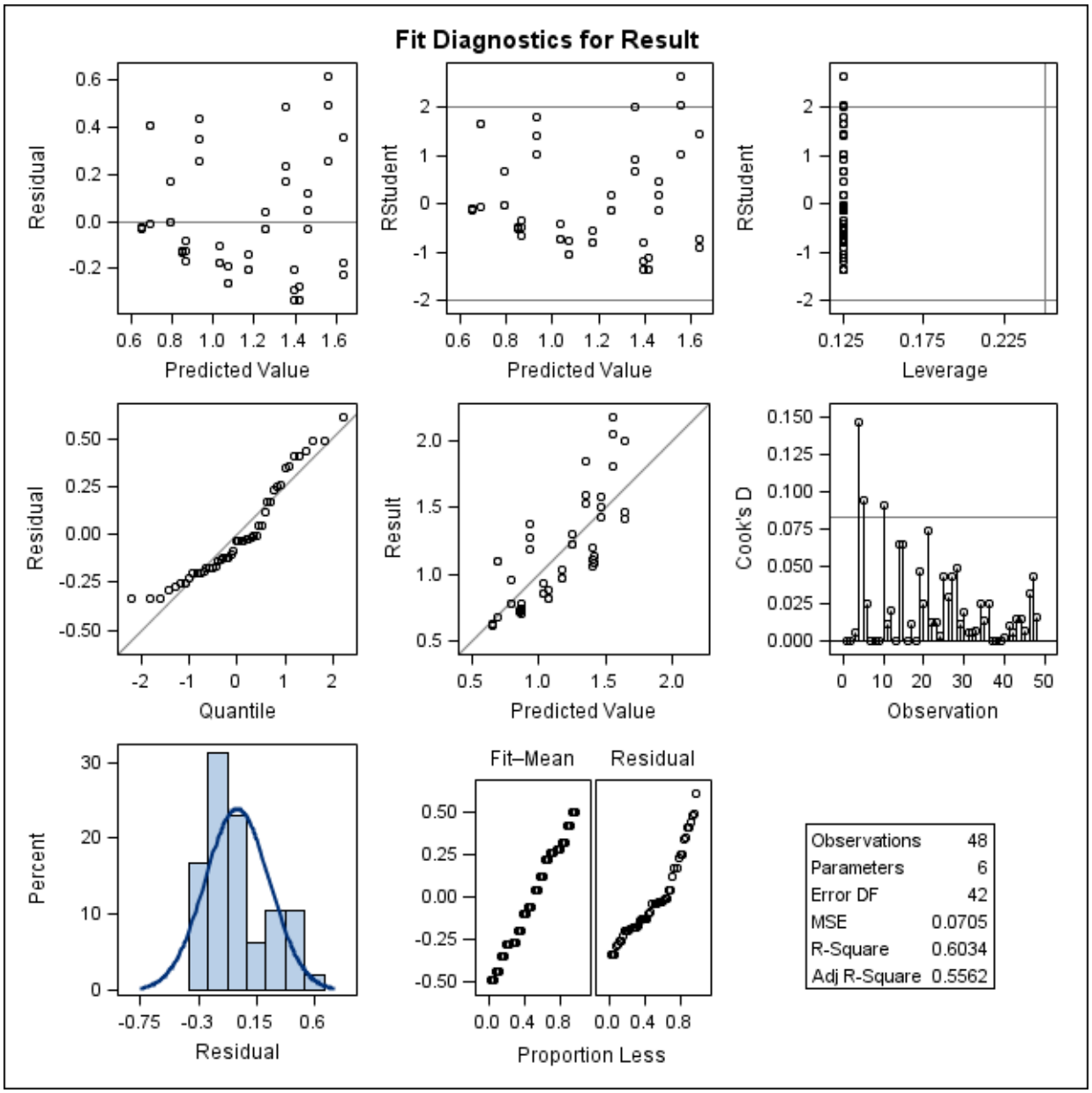
ATD Carbopack B - 1,1,1-Trichloroethane



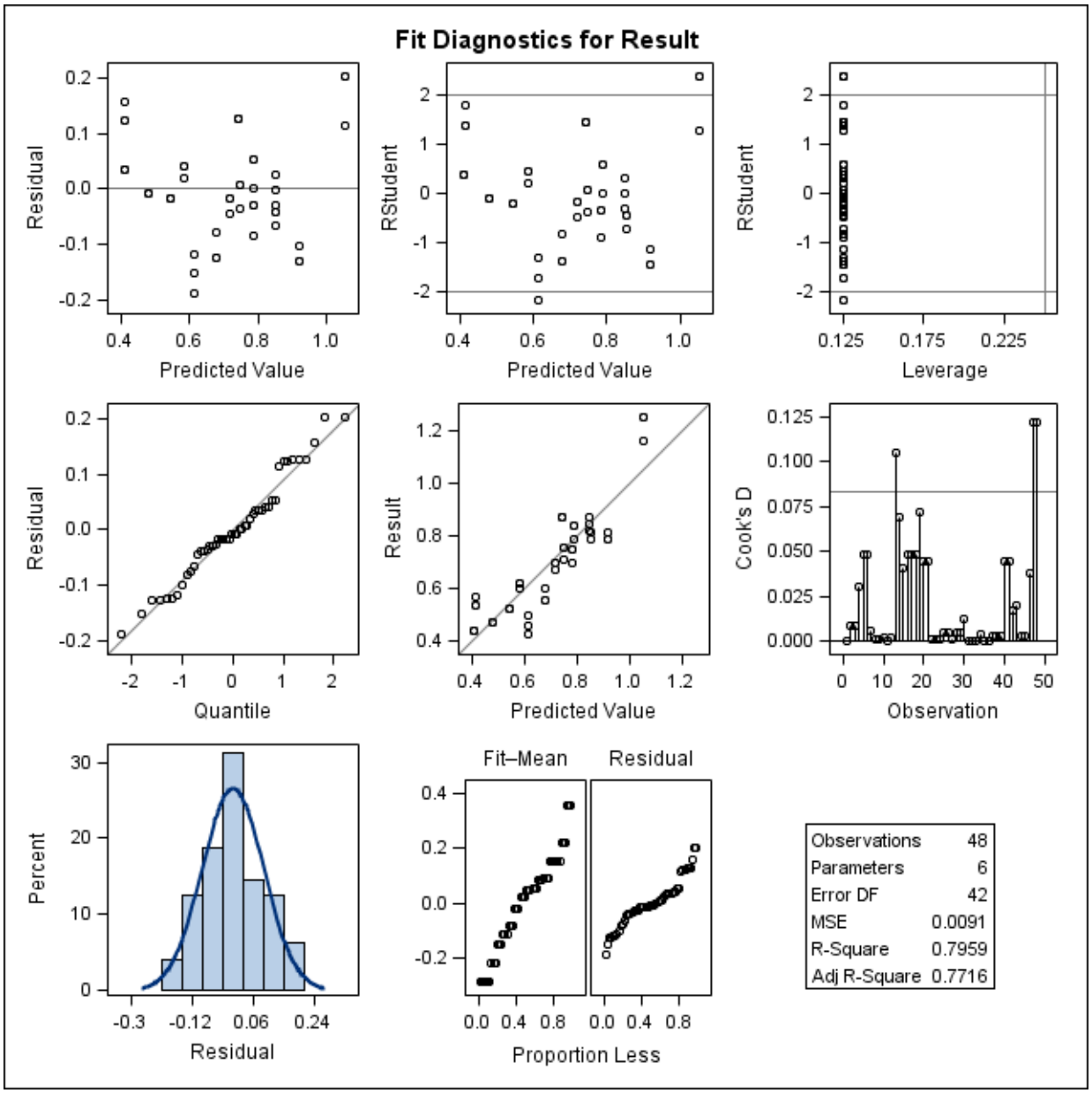
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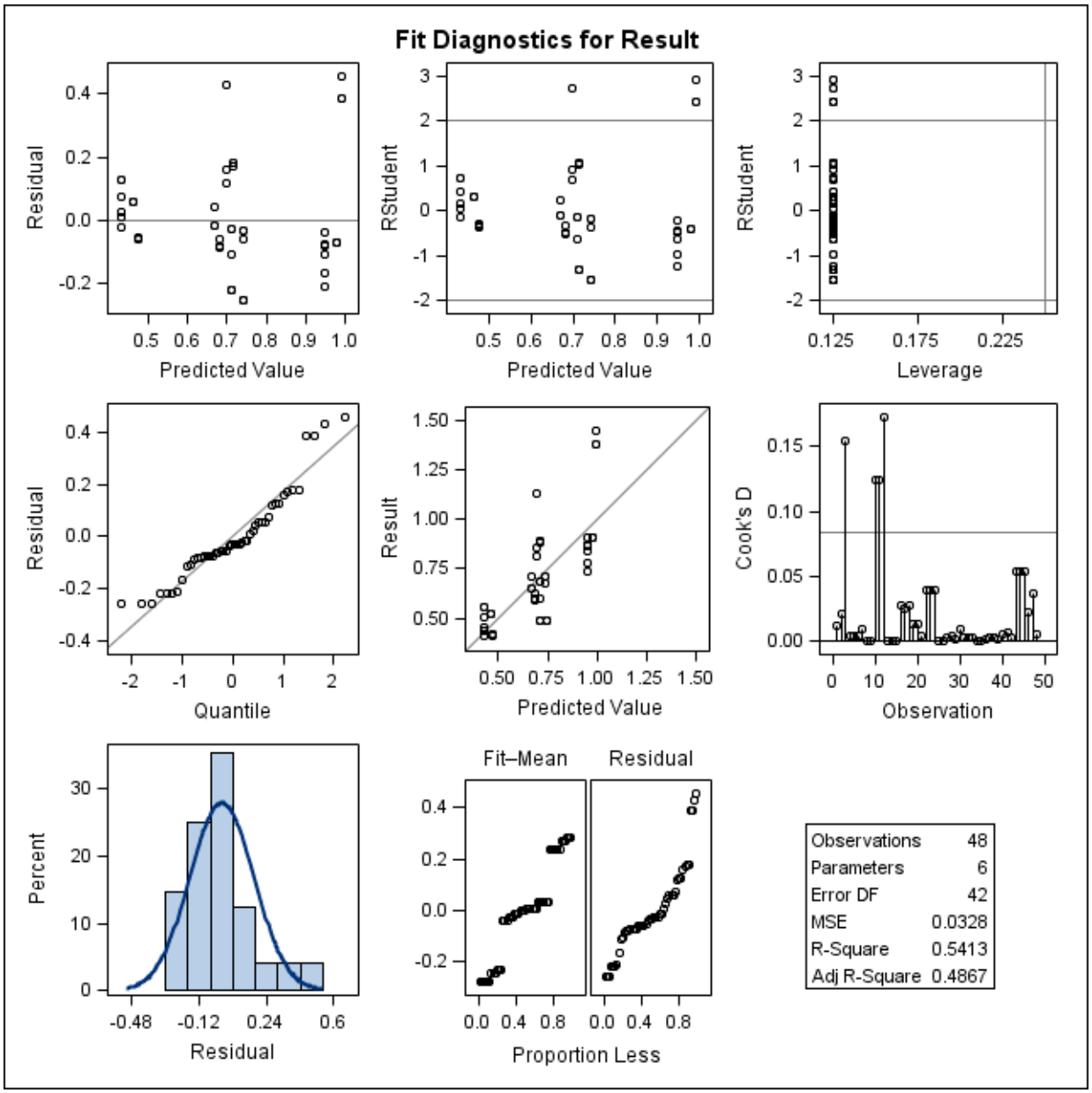
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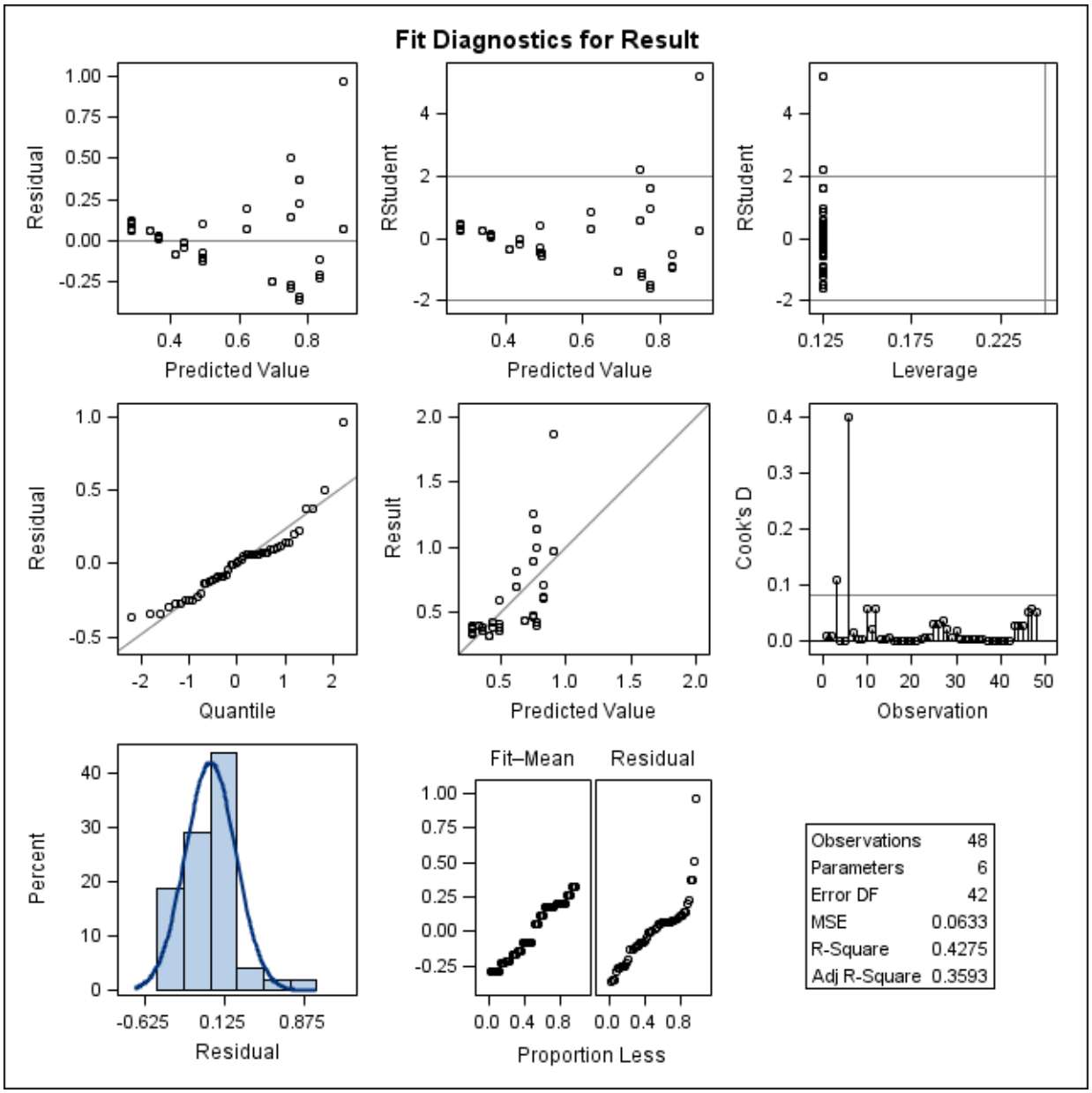
ATD Tenax TA – Benzene



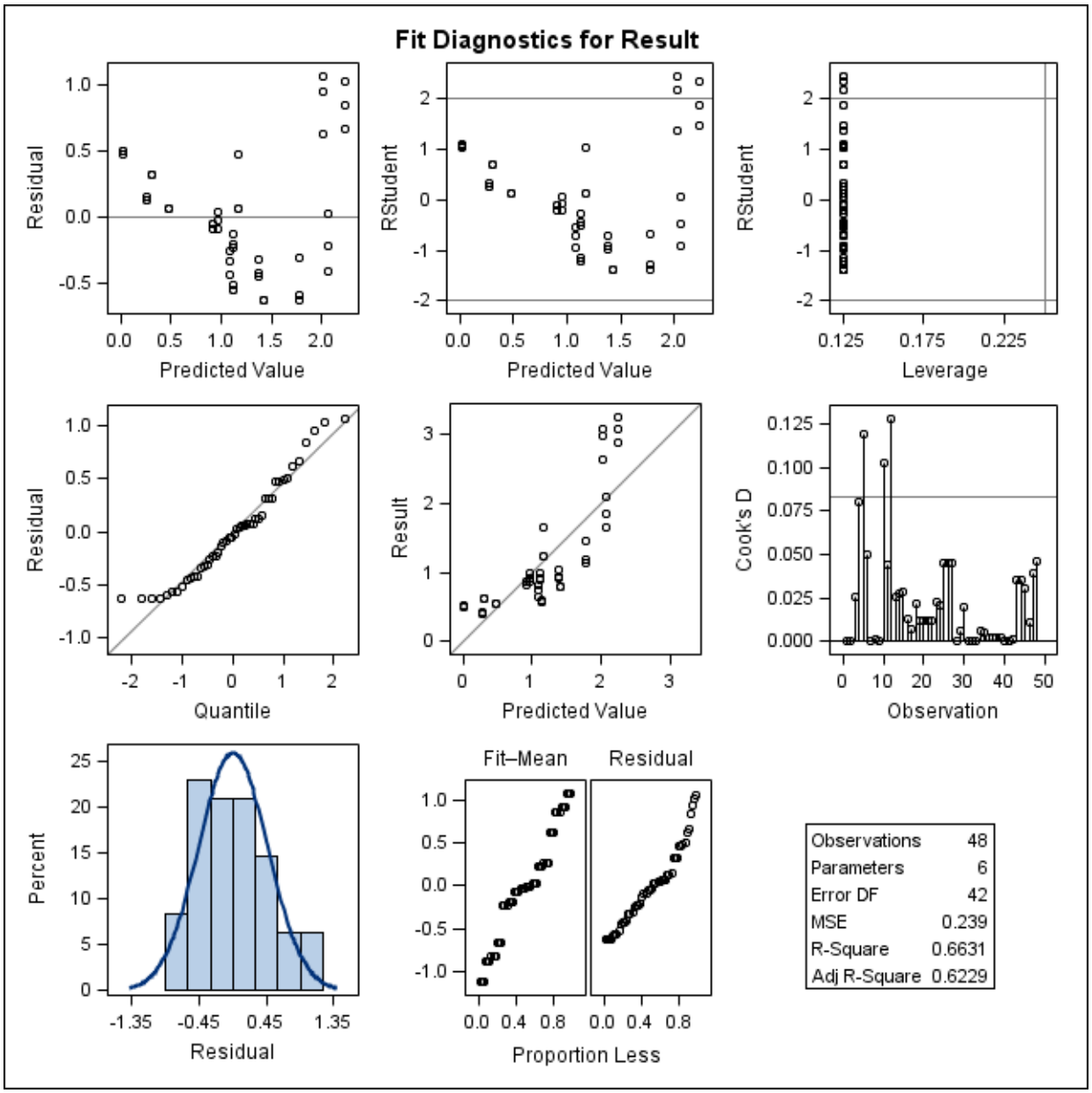
ATD Tenax TA - Carbon Tetrachloride



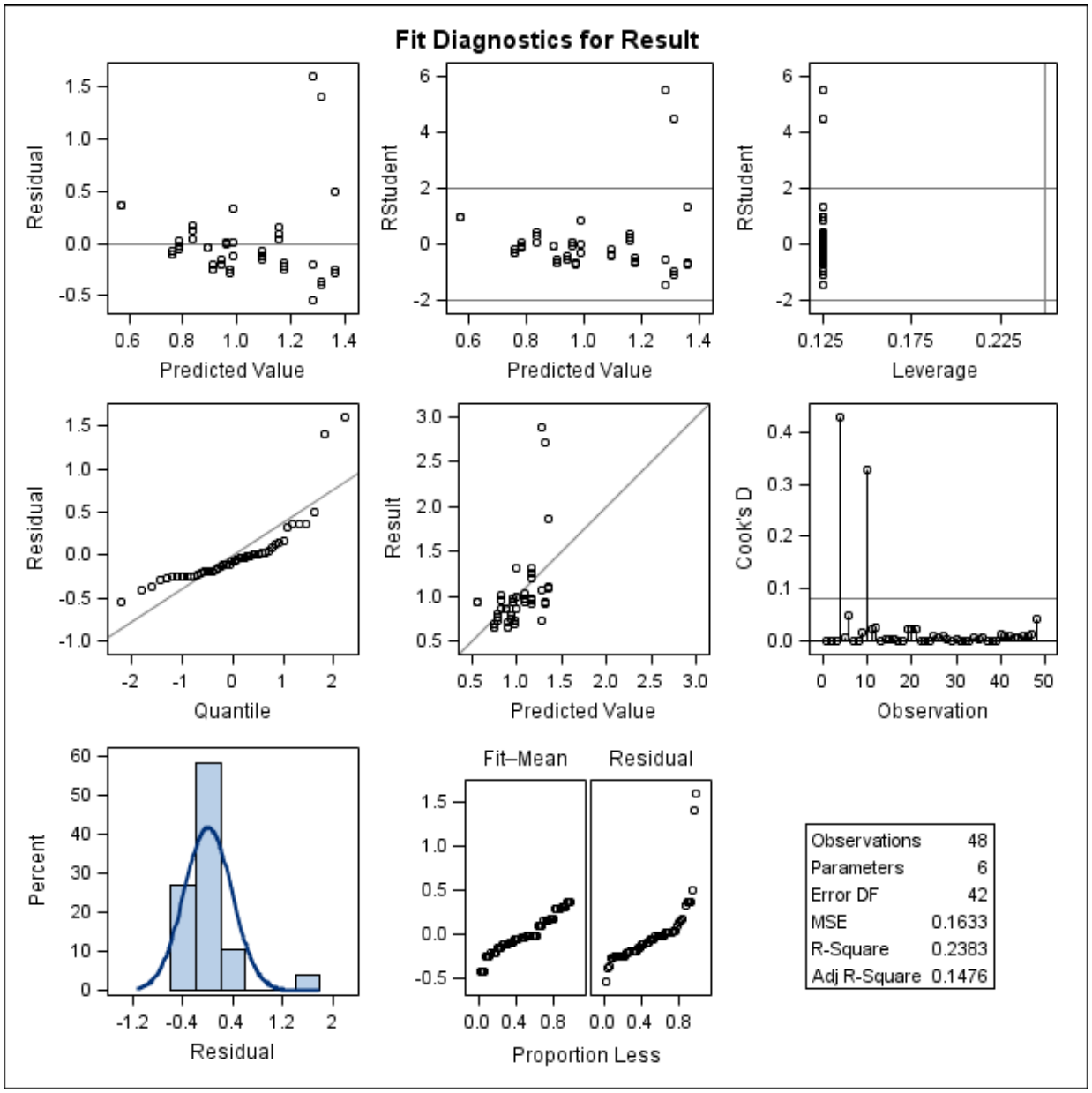
ATD Tenax TA – 1,2-Dichloroethane



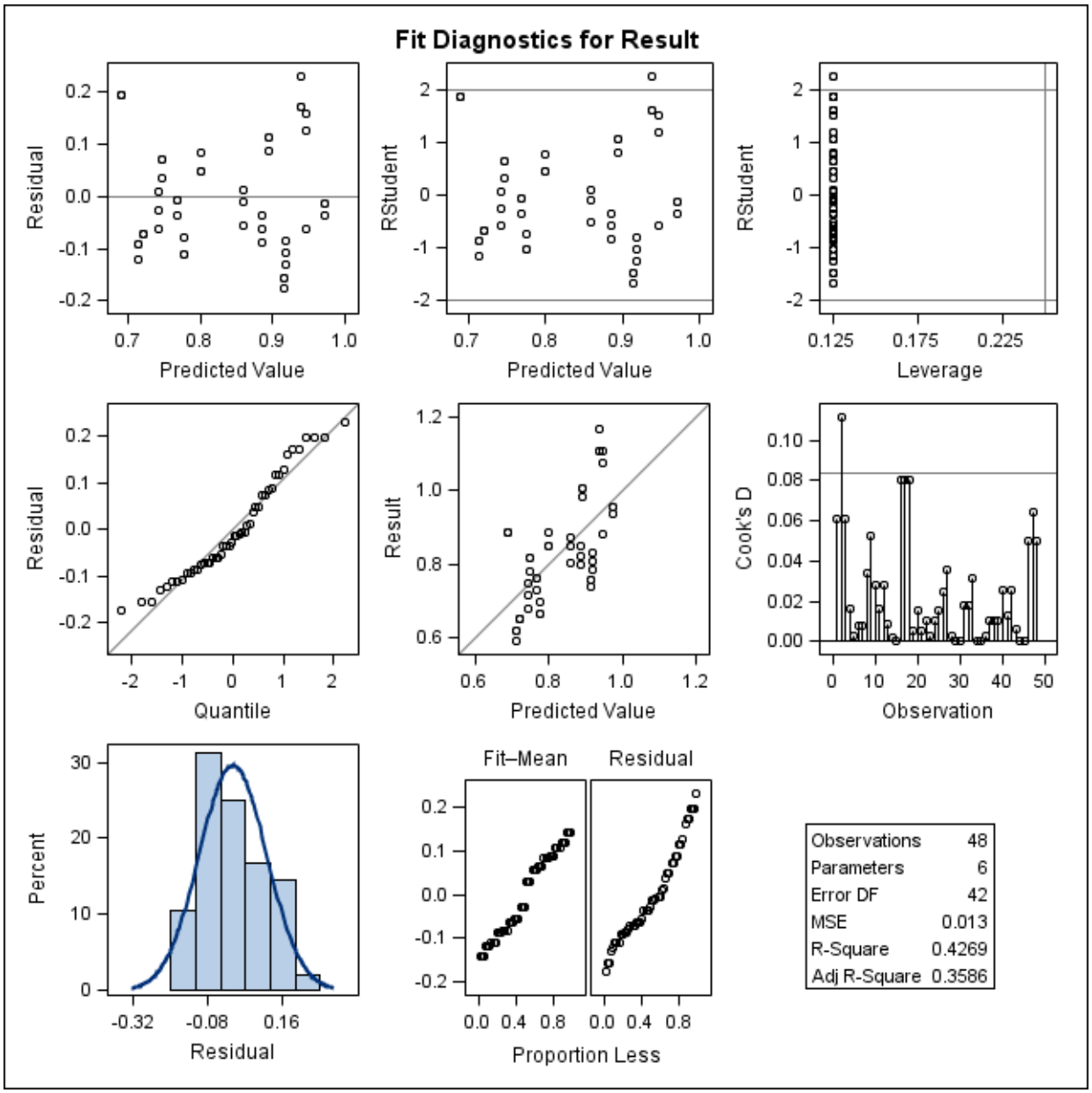
ATD Tenax TA – n-Hexane



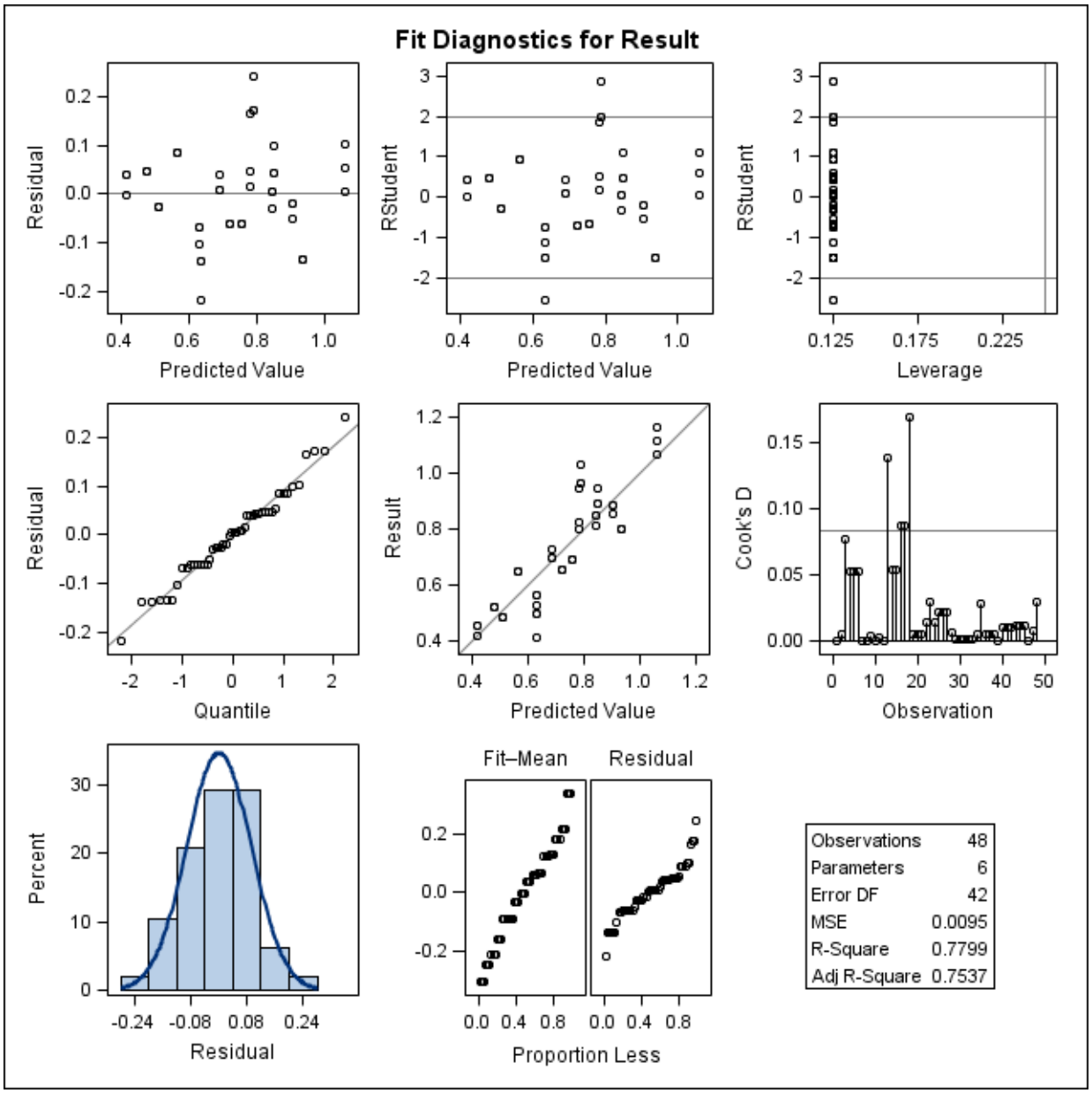
ATD Tenax TA – Methylethyl Ketone



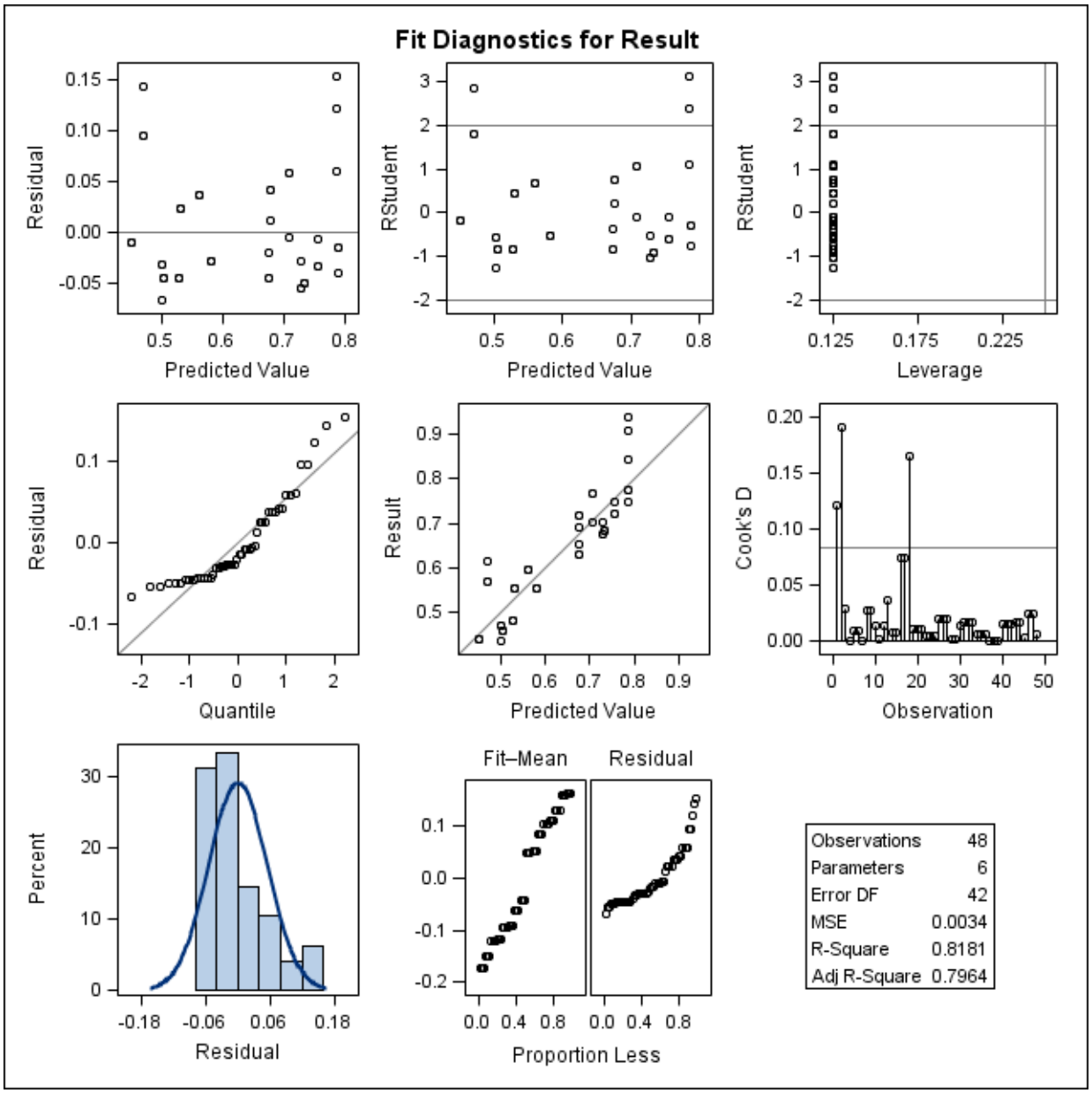
ATD Tenax TA – Naphthalene



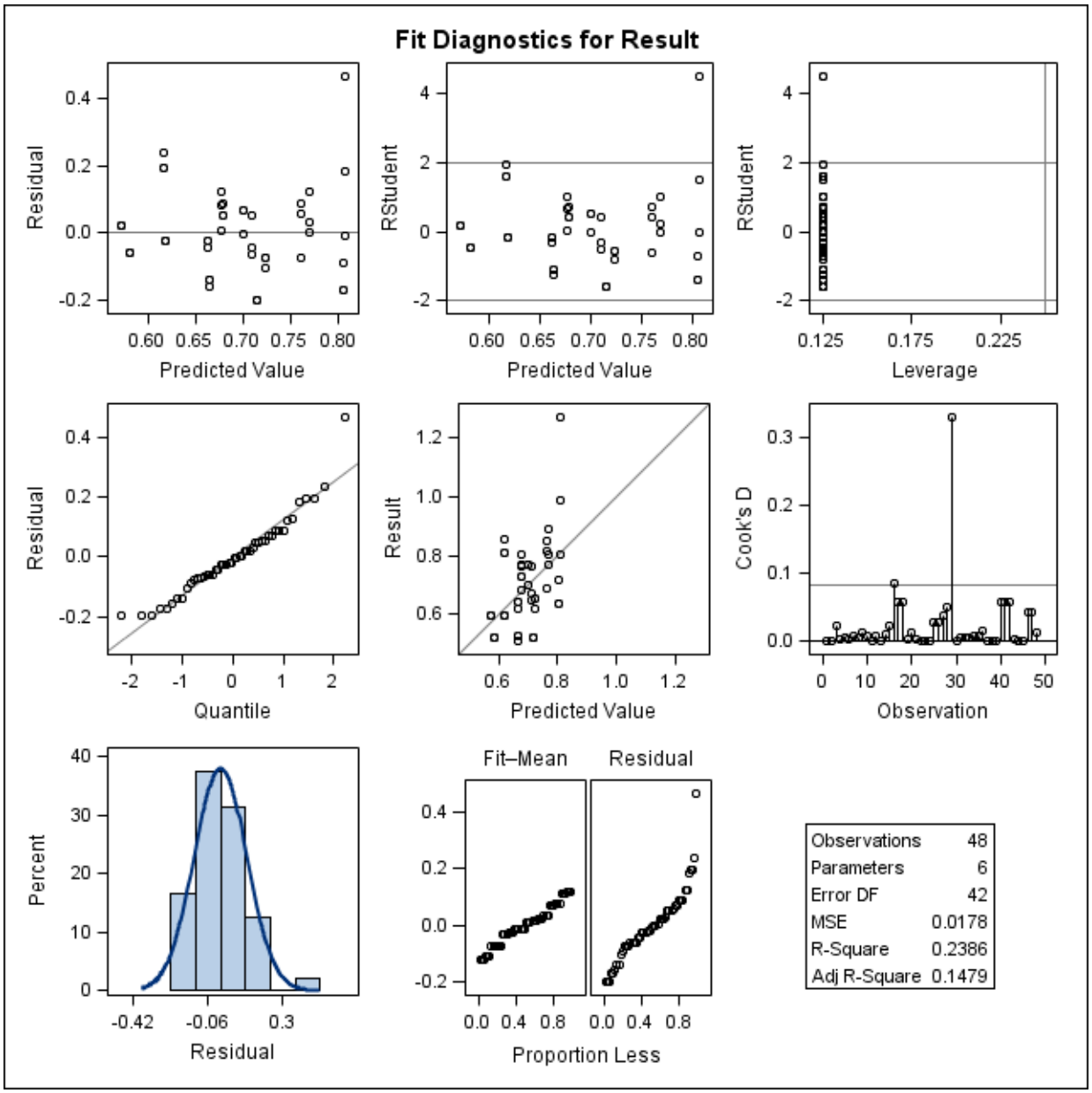
ATD Tenax TA – Tetrachloroethene



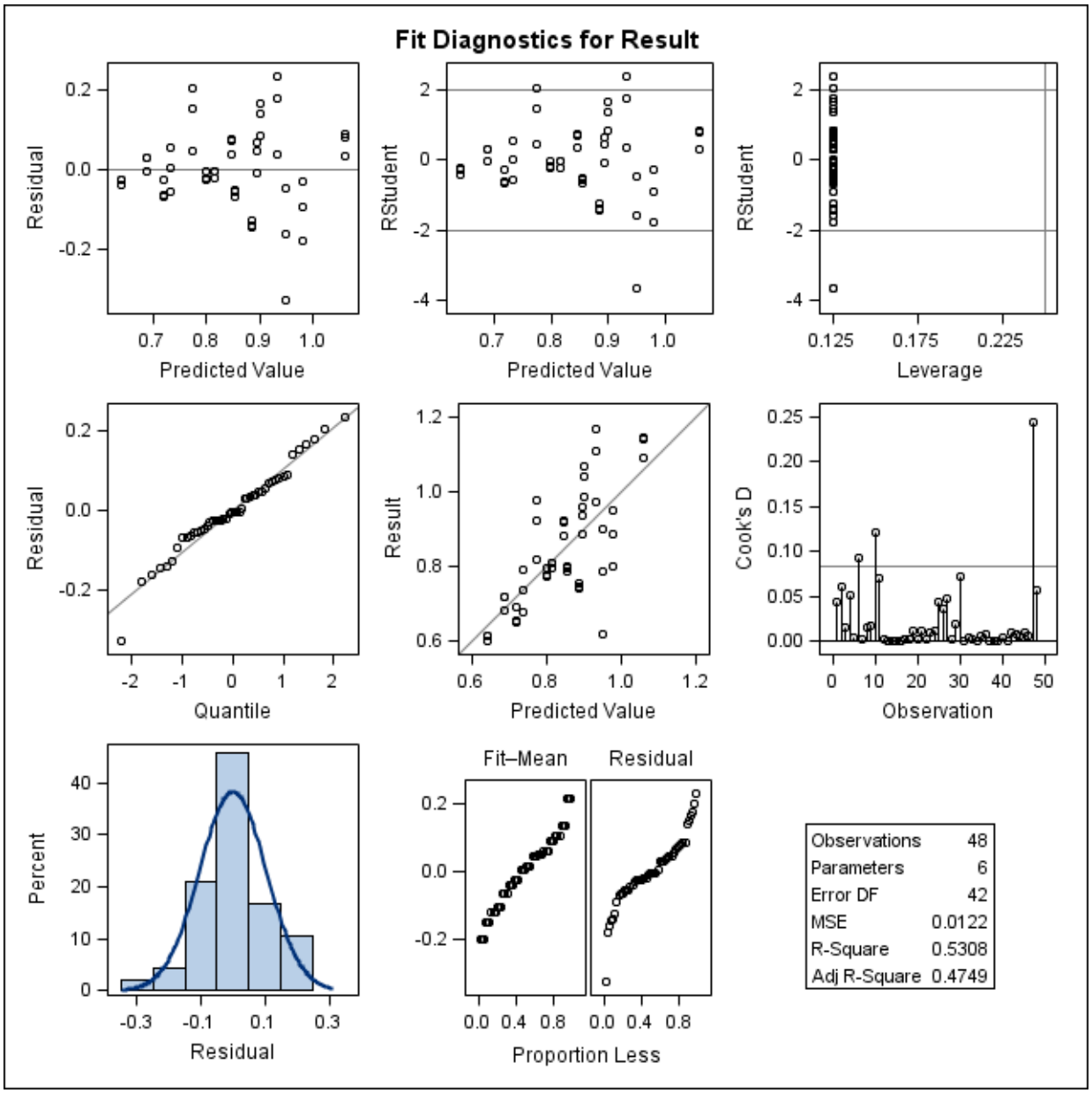
ATD Tenax TA – 1,1,1-Trichloroethane



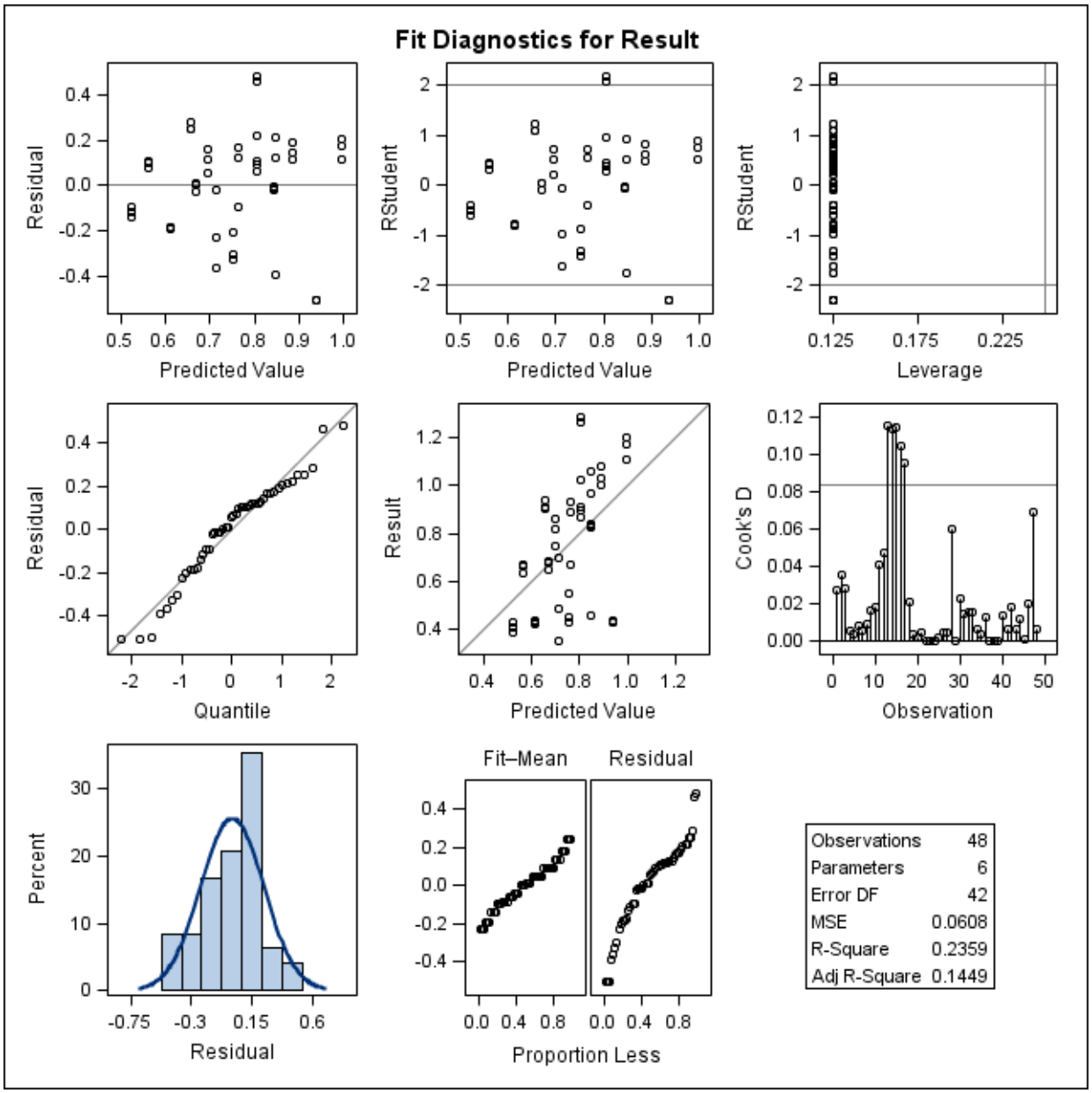
ATD Tenax TA – Trichloroethene



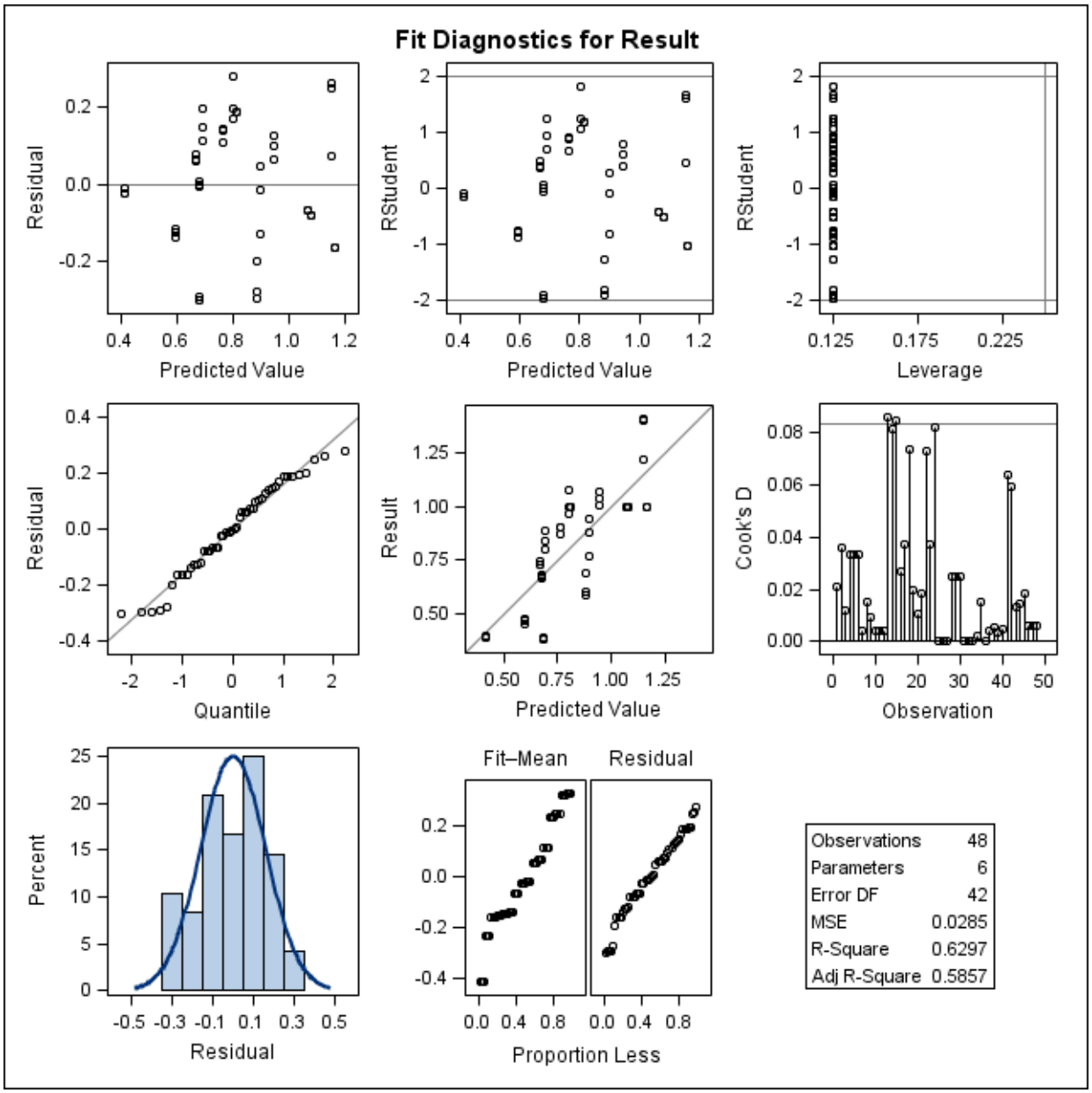
ATD Tenax TA – 1,2,4-Trimethylbenzene



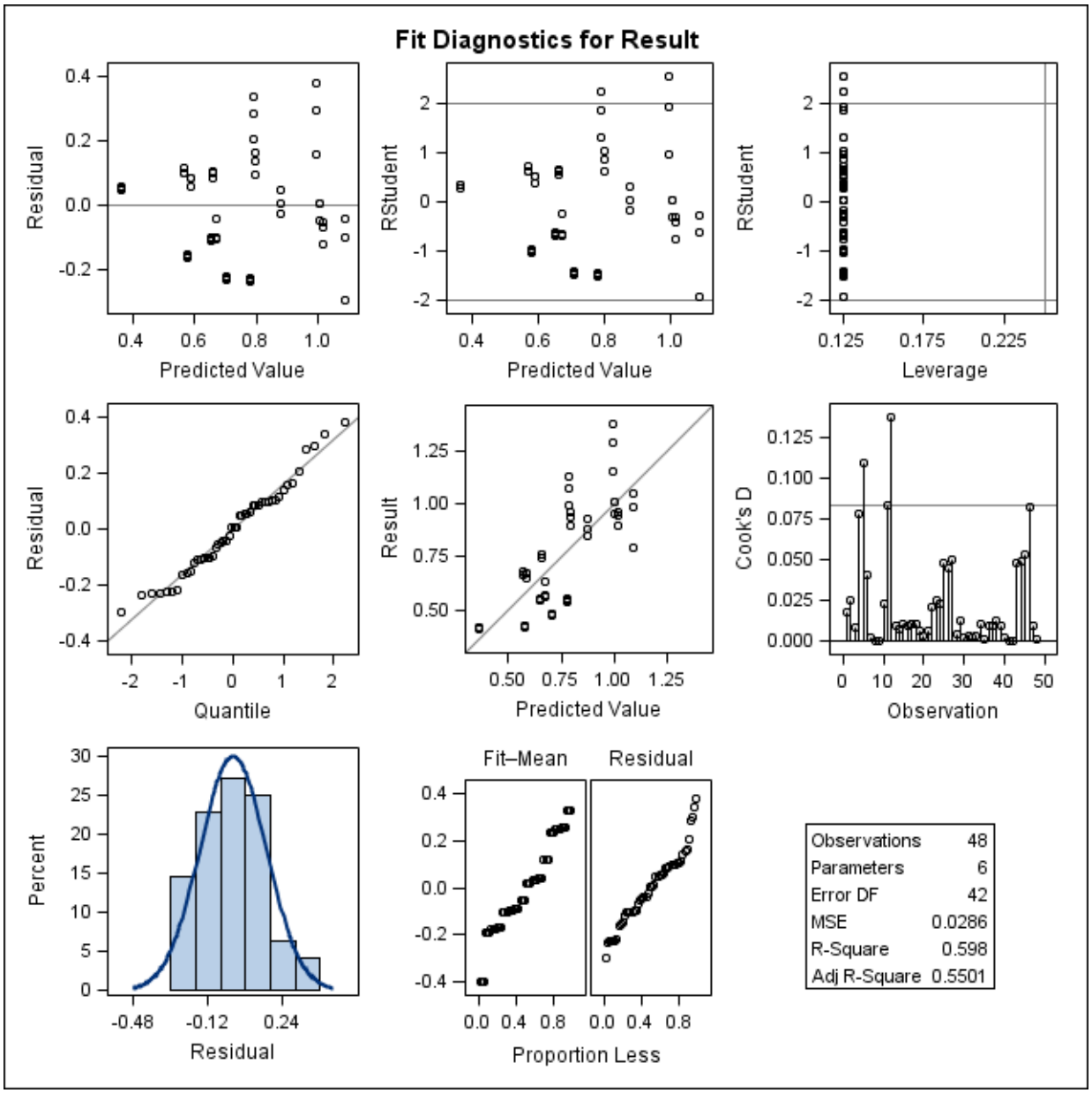
Radiello - Benzene



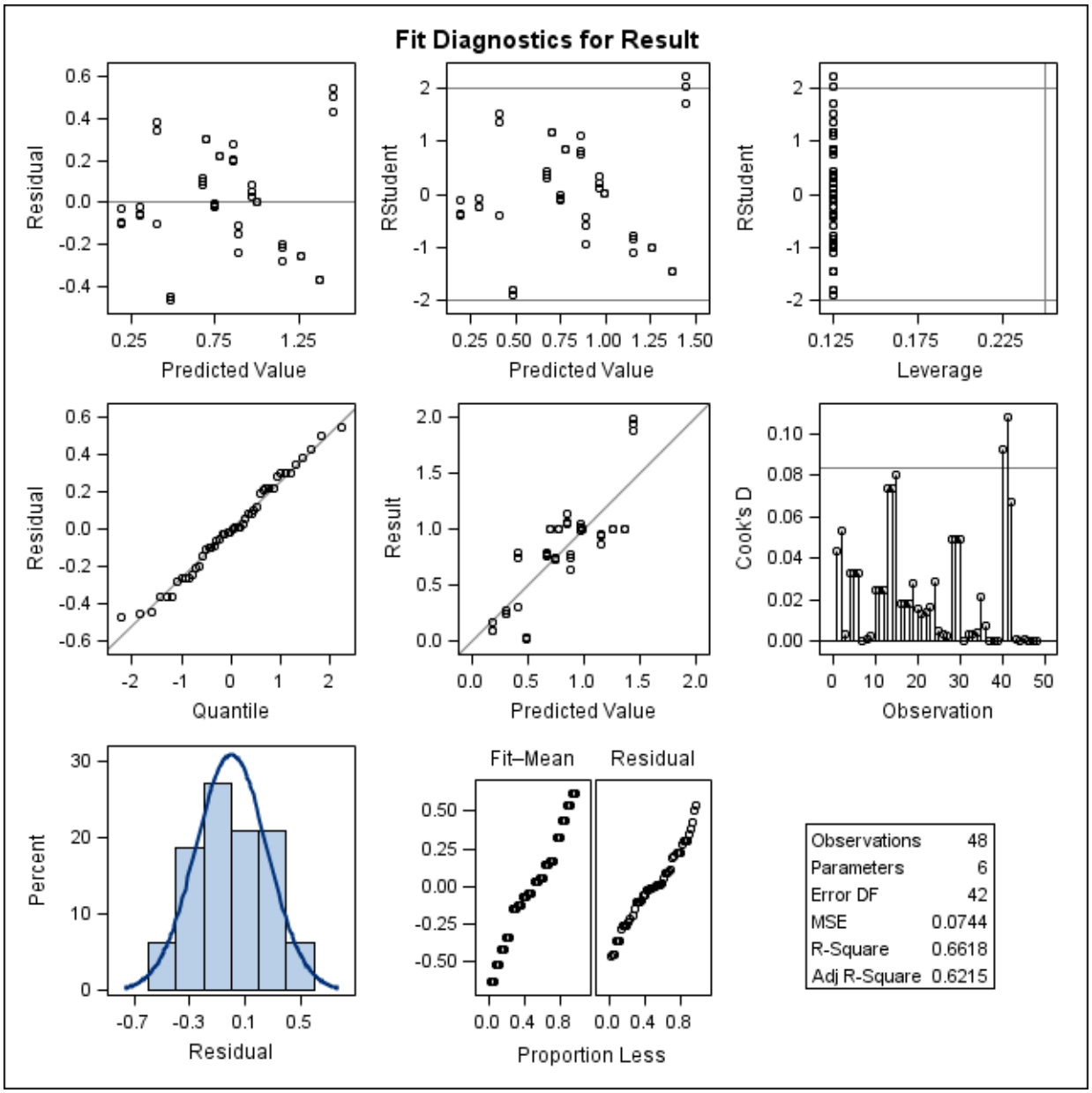
Radiello - Carbon Tetrachloride



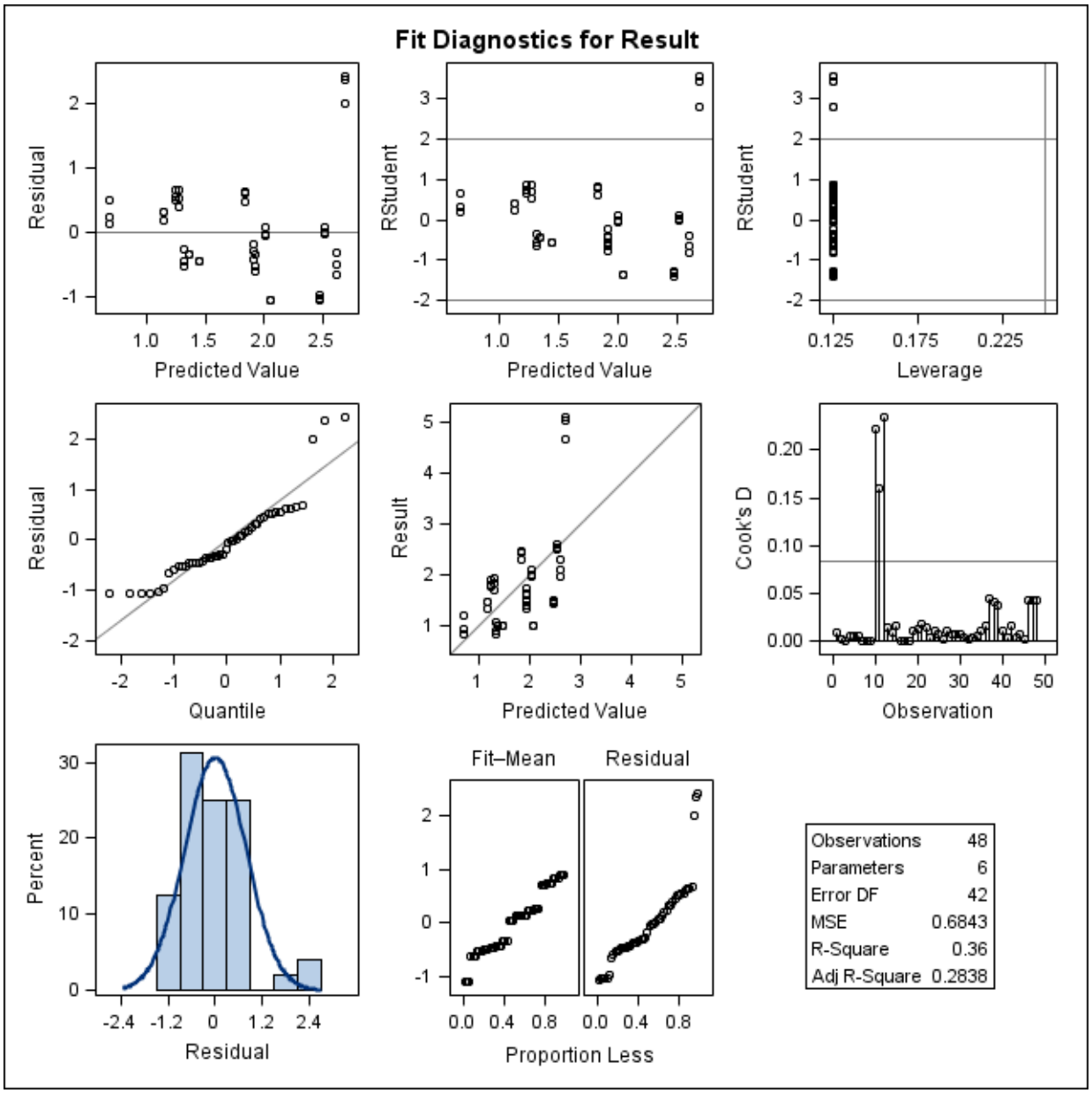
Radiello - 1,2-Dichloroethane



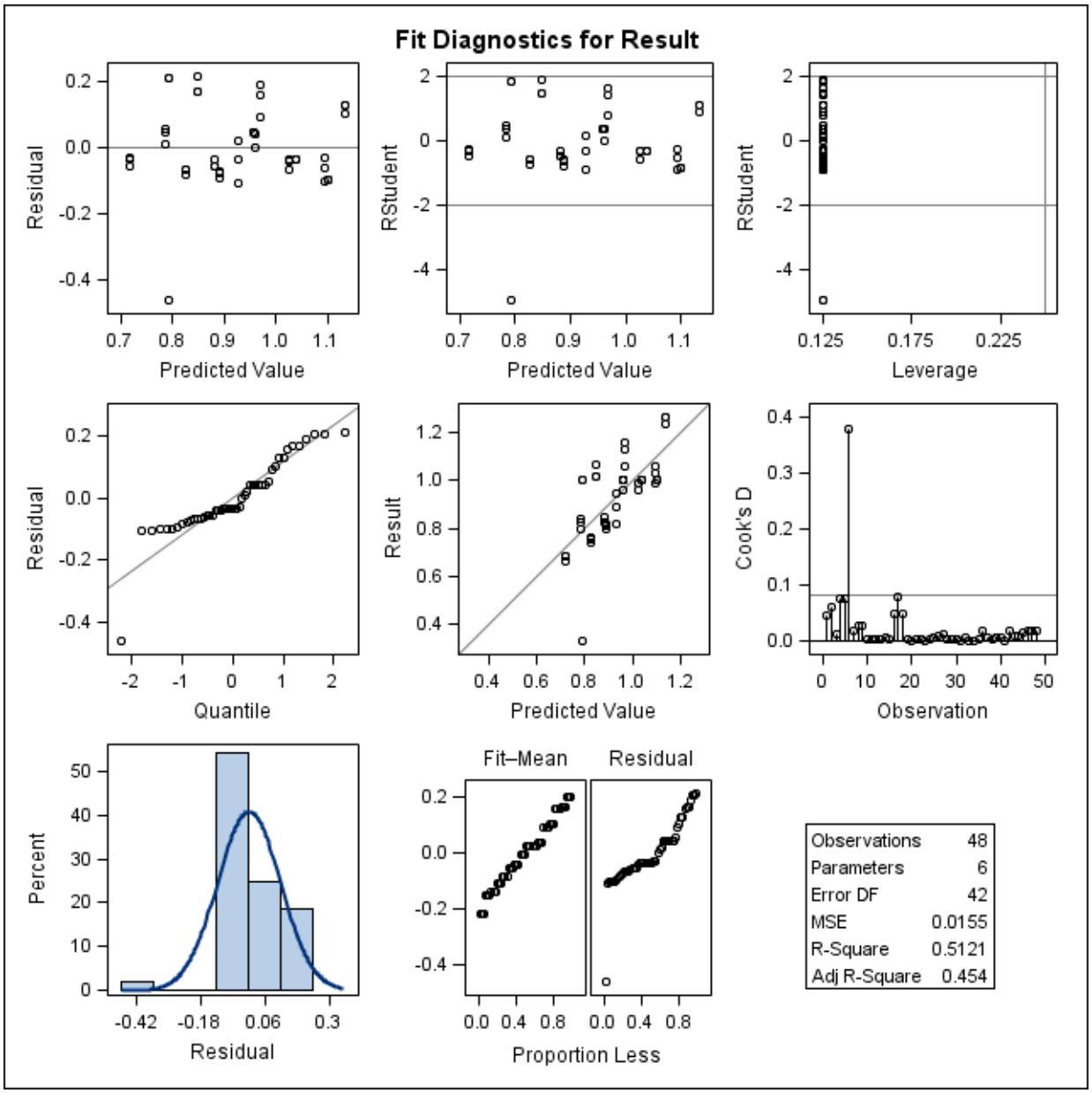
Radiello - n-Hexane



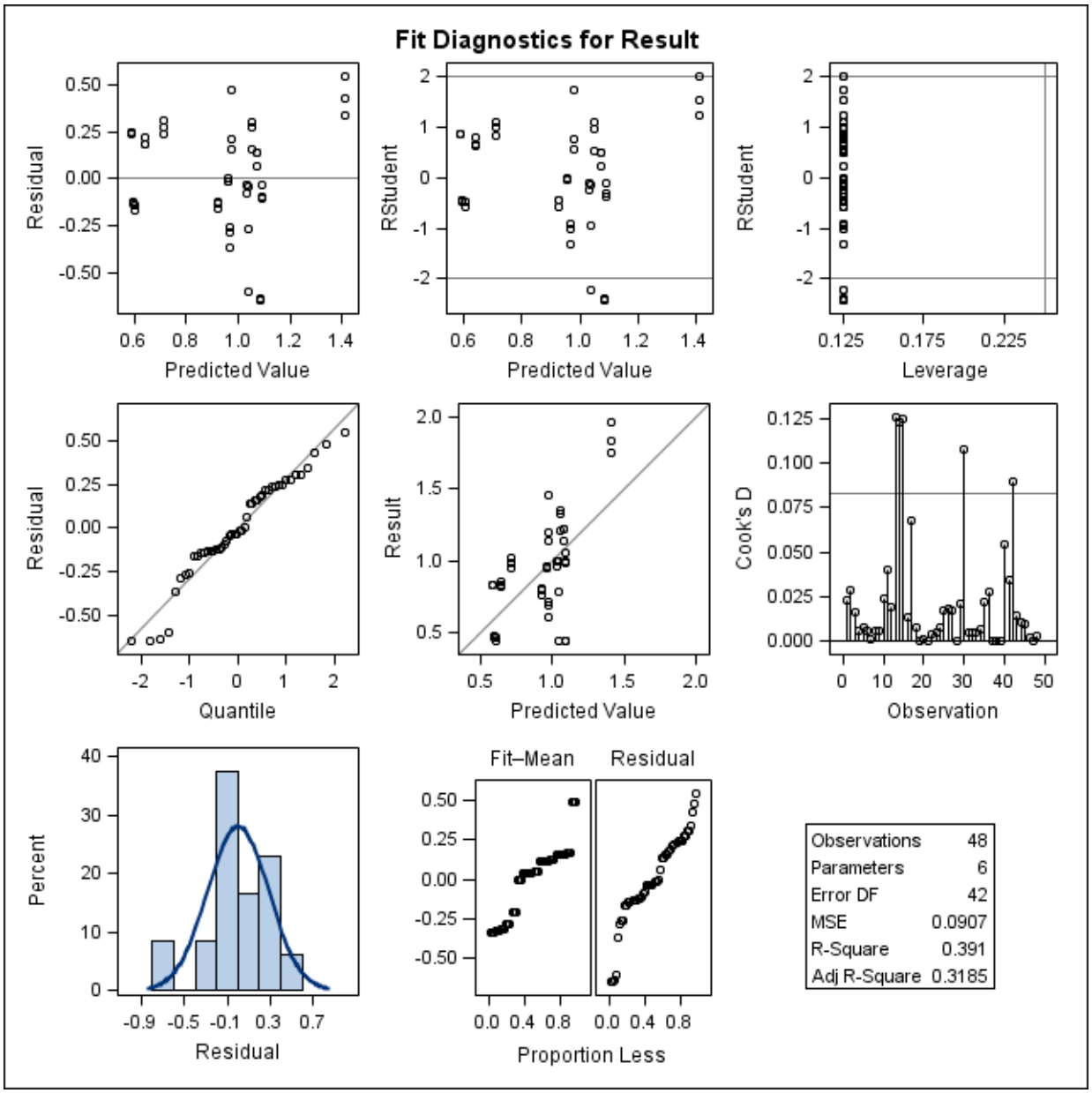
Radiello - Methylethyl Ketone



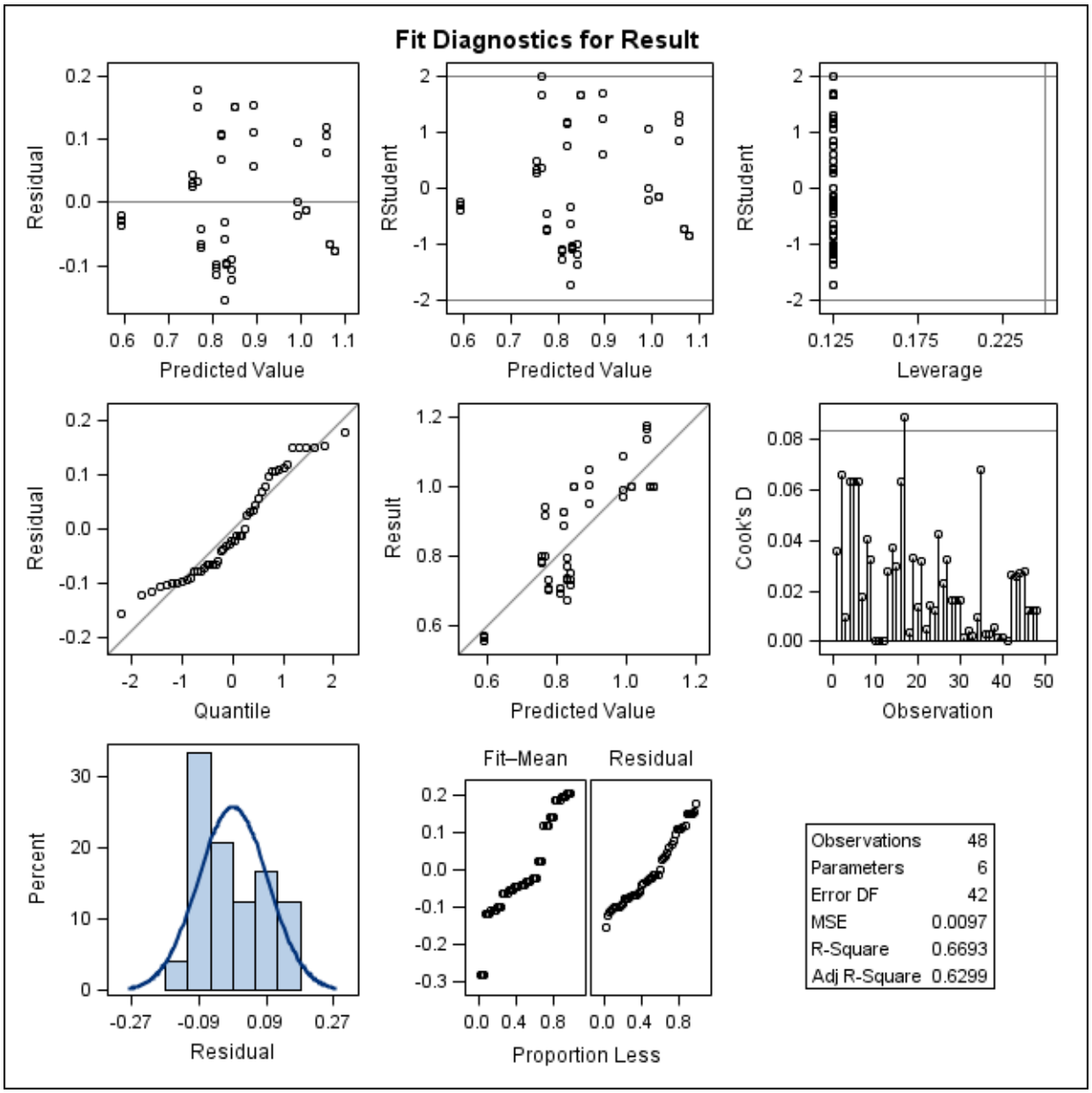
Radiello - Naphthalene



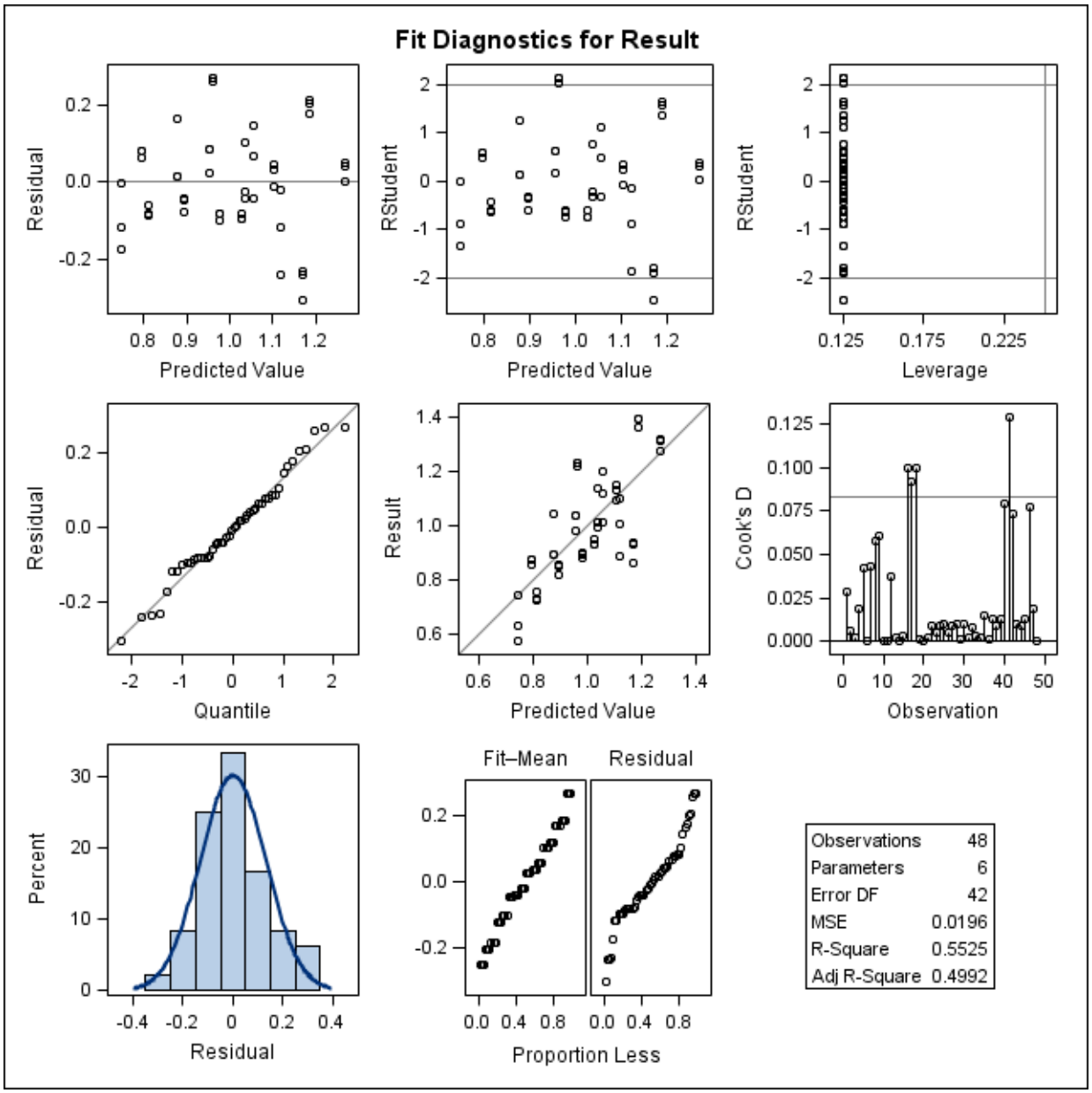
Radiello - Tetrachloroethene



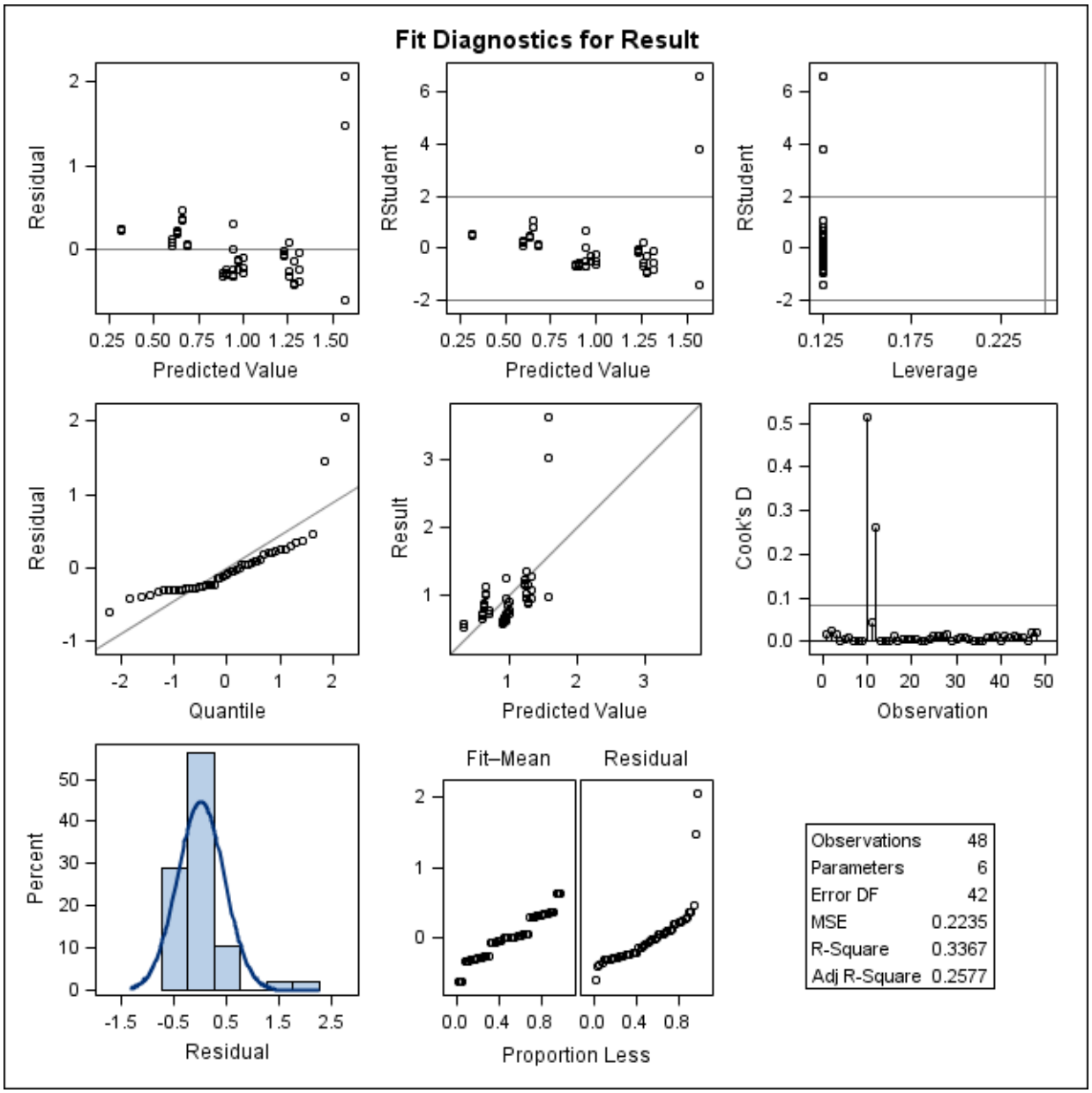
Radiello - 1,1,1-Trichloroethane



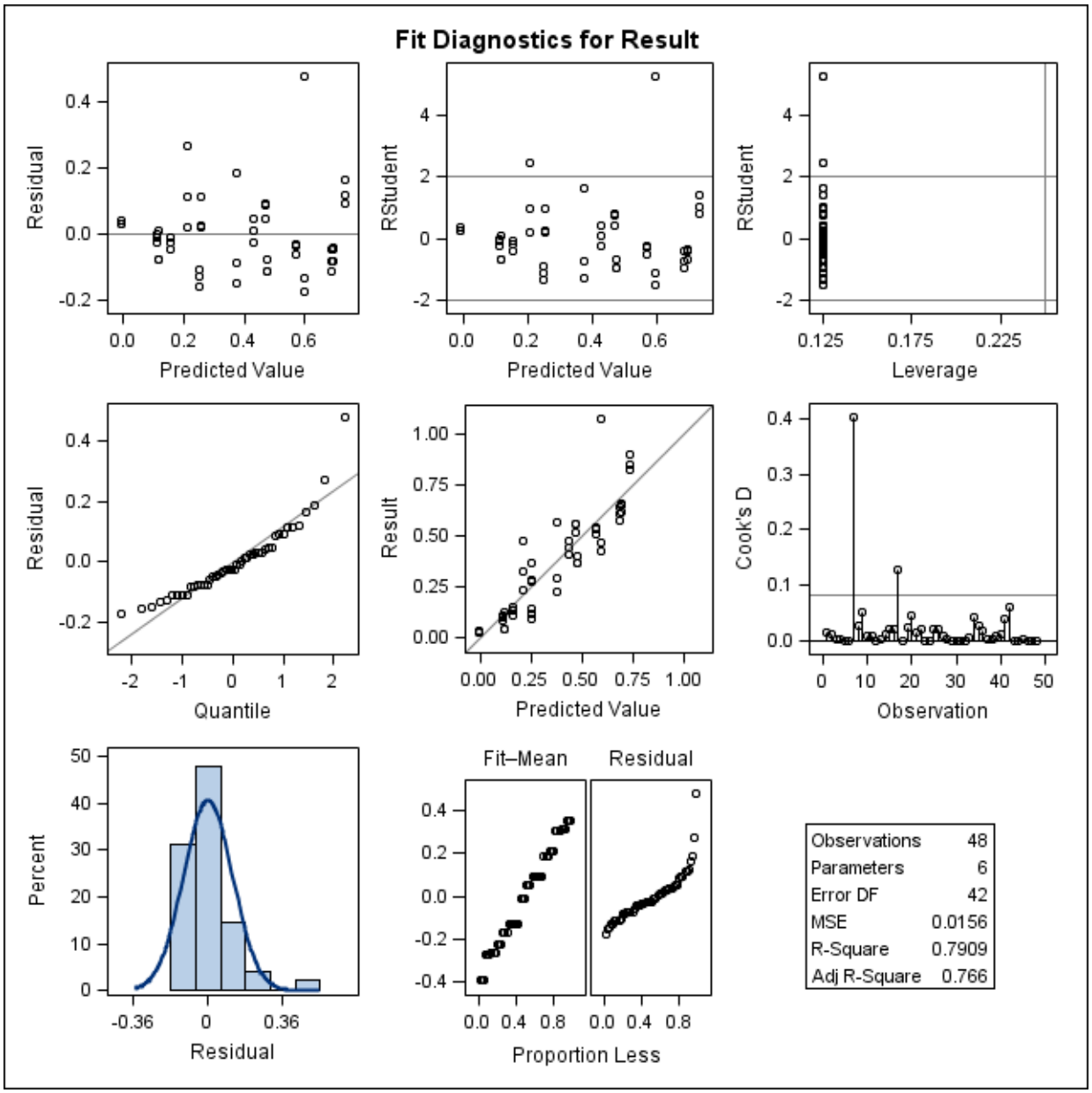
Radiello - Trichloroethene



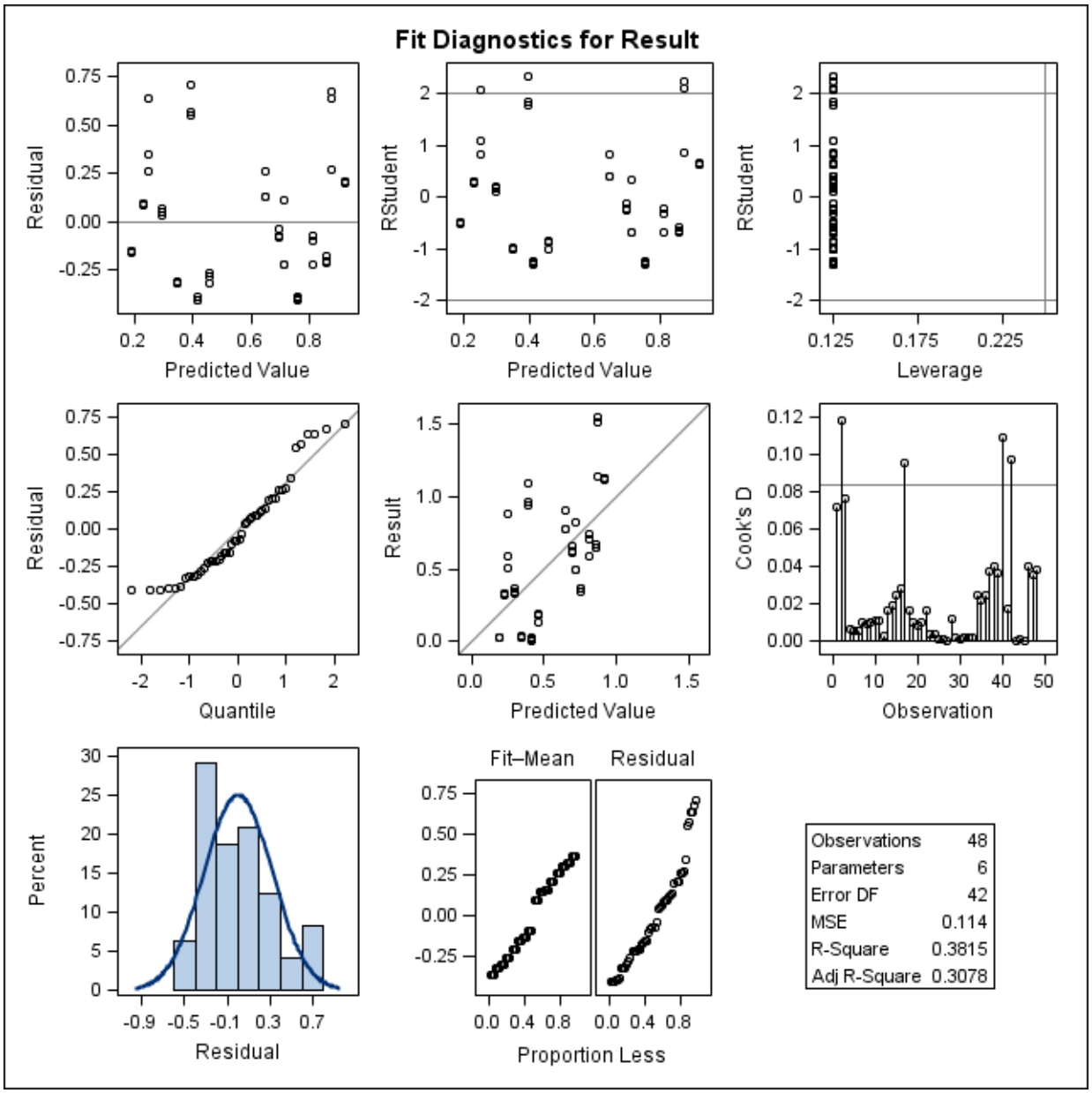
Radiello - 1,2,4-Trimethylbenzene



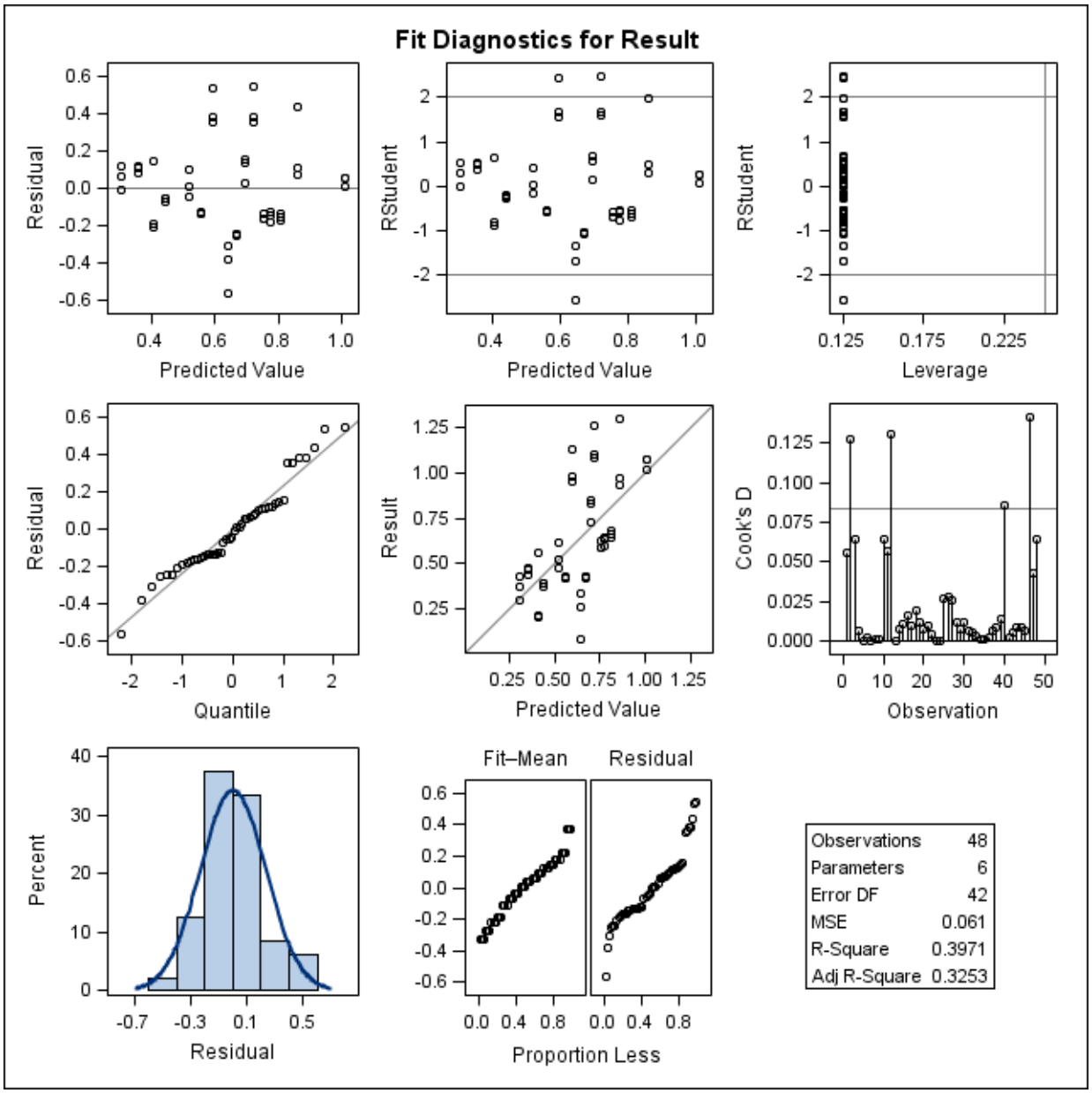
SKC Ultra - Benzene



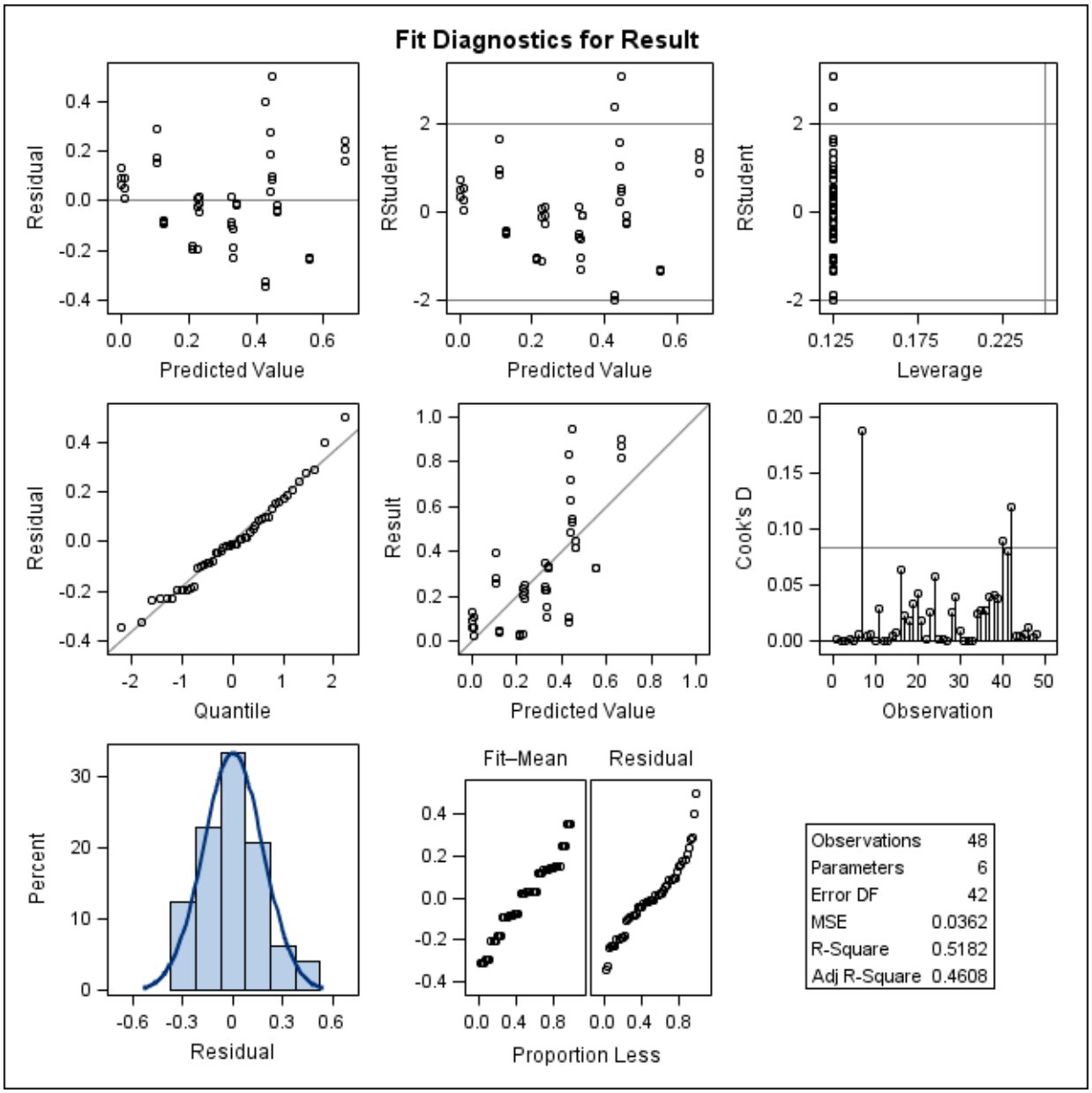
SKC Ultra - Carbon Tetrachloride



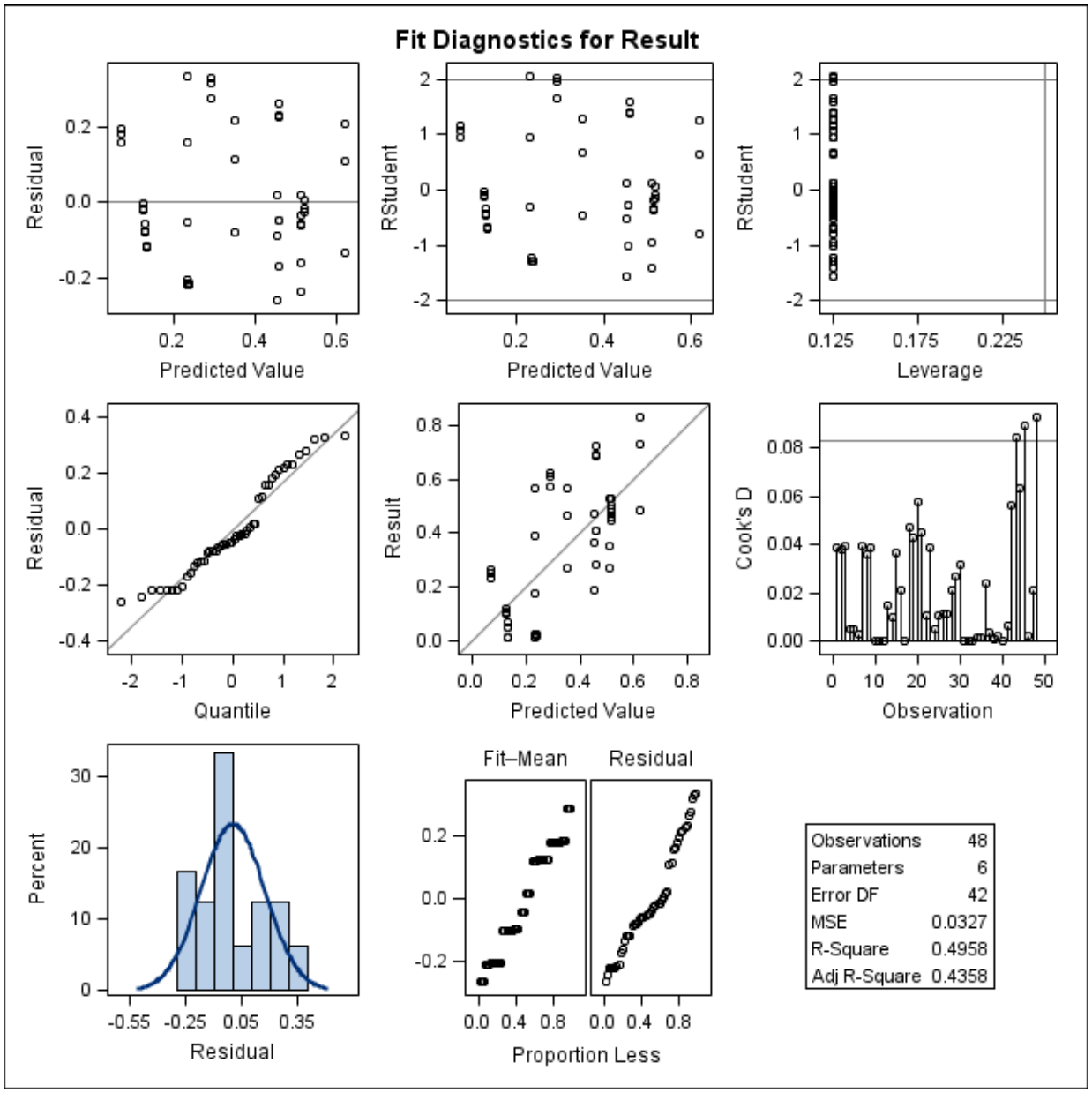
SKC Ultra - 1,2-Dichloroethane



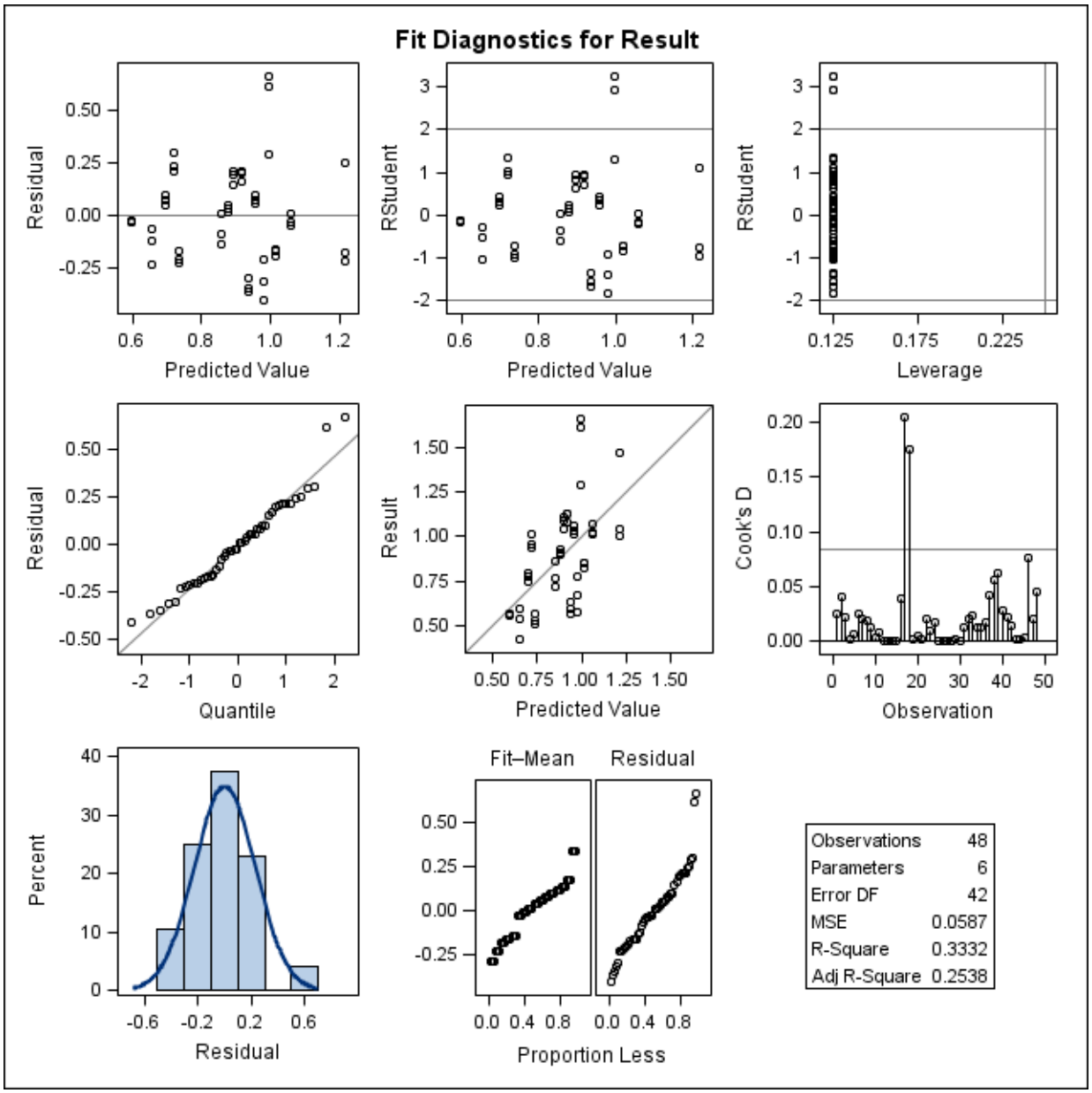
SKC Ultra - n-Hexane



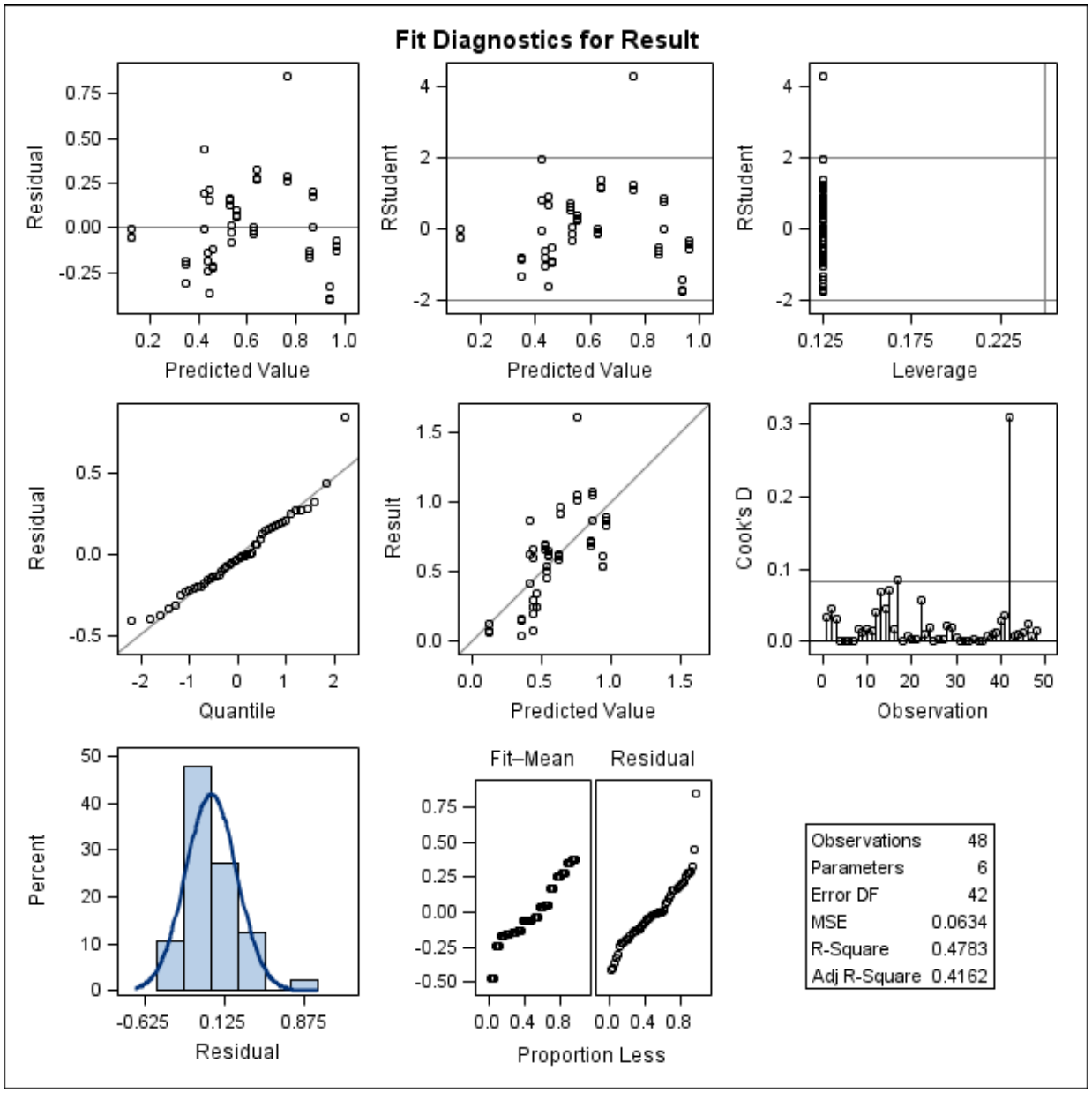
SKC Ultra - Methylethyl Ketone



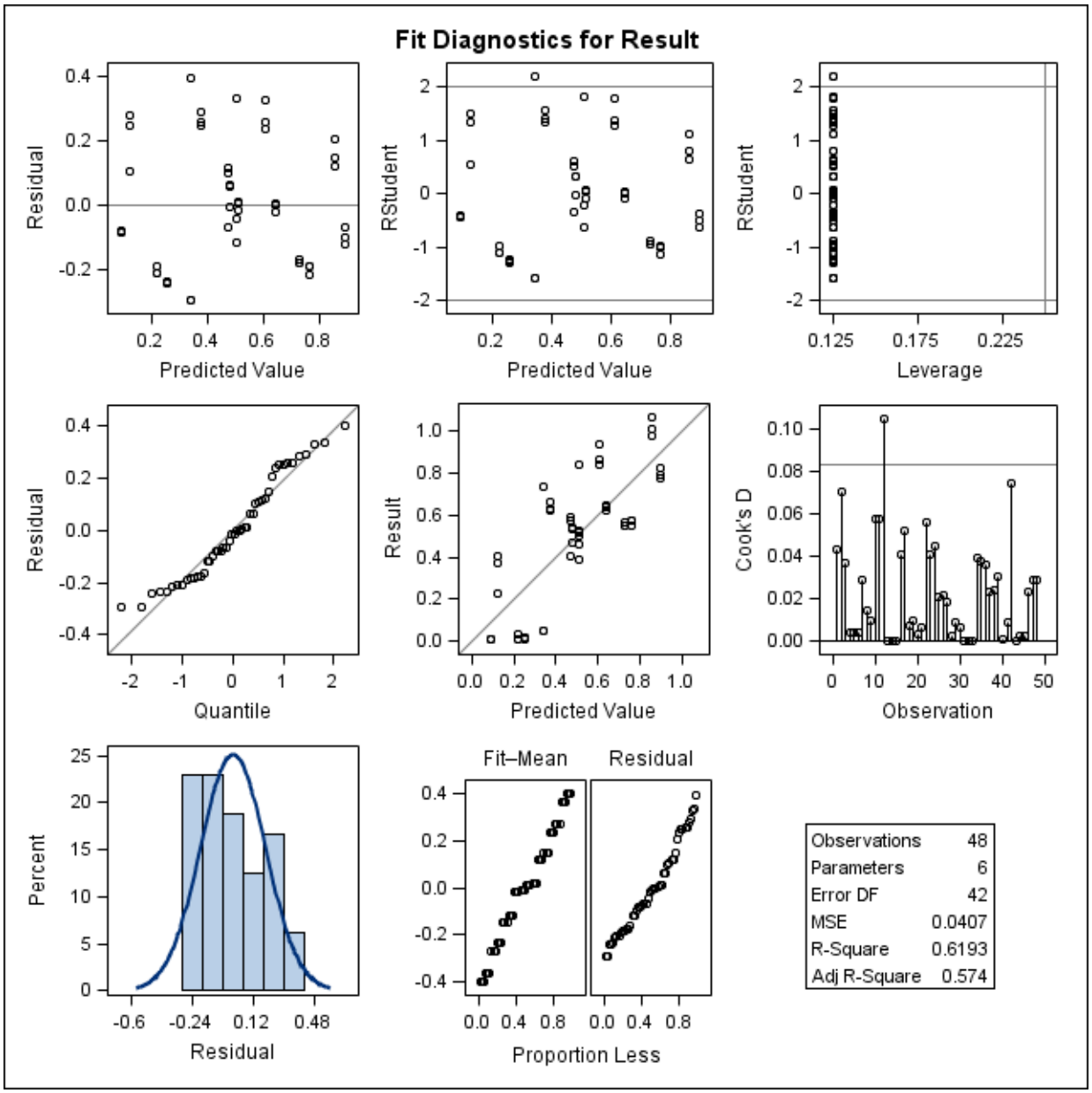
SKC Ultra - Naphthalene



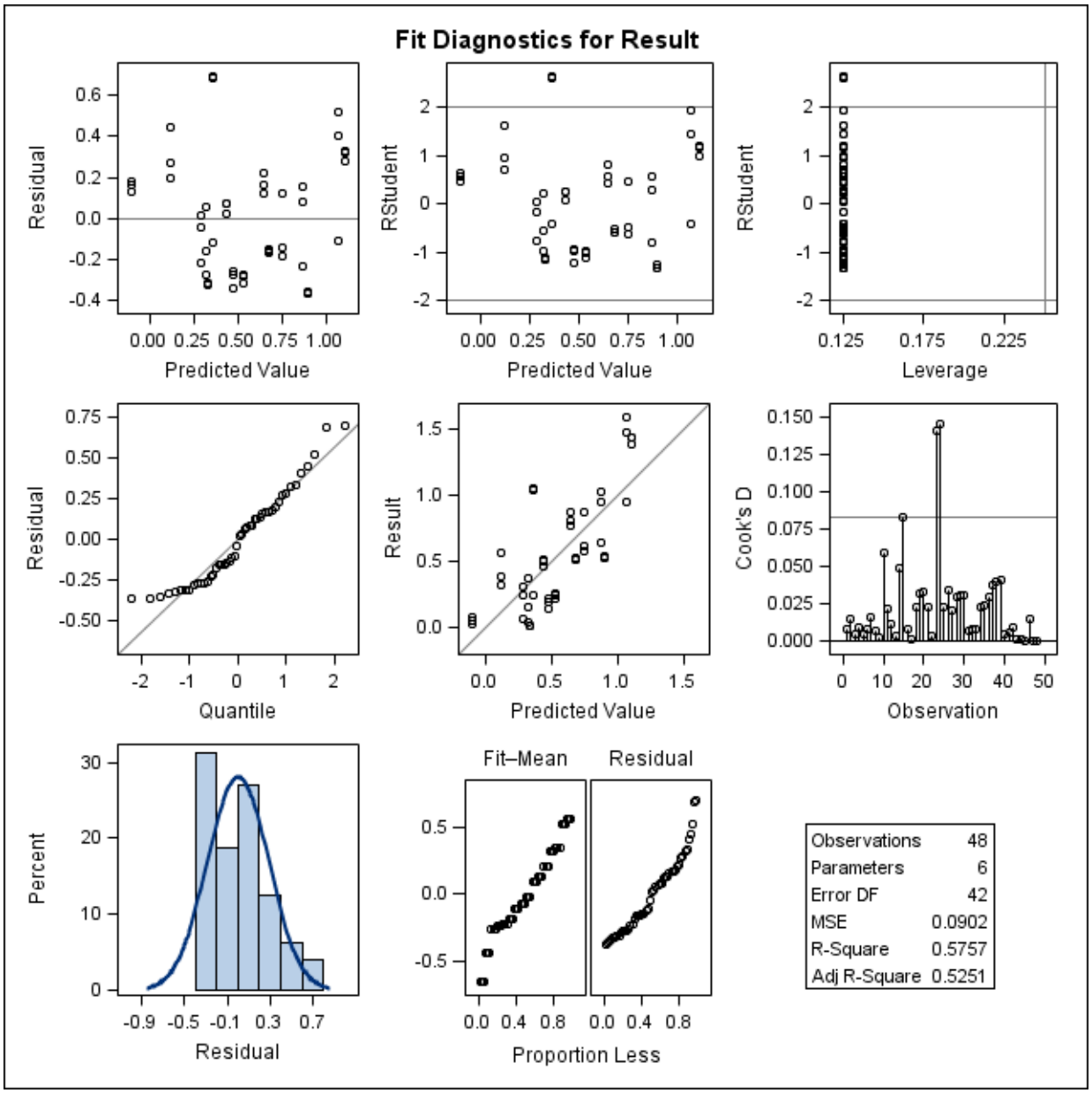
SKC Ultra - Tetrachloroethene



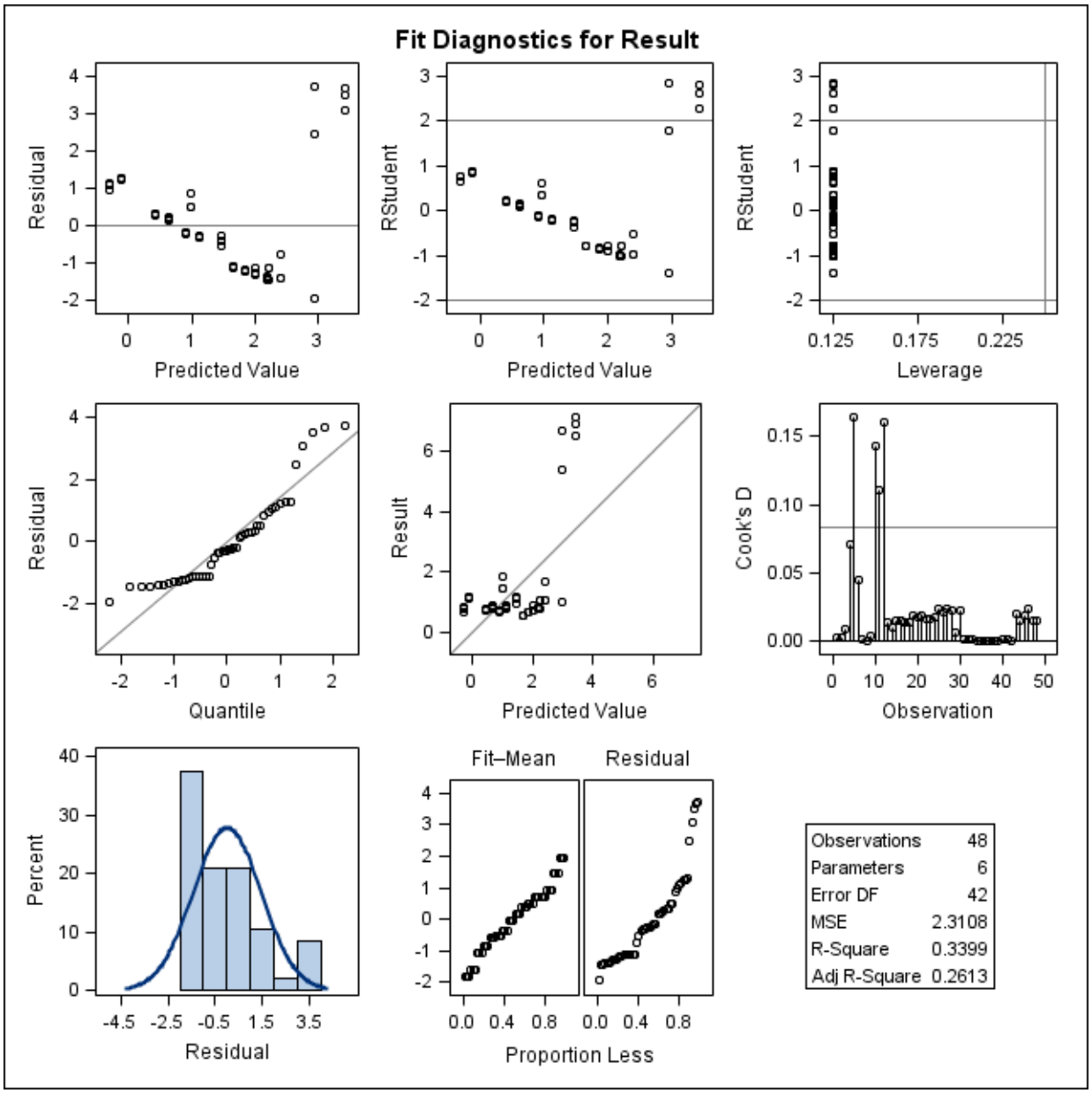
SKC Ultra - 1,1,1-Trichloroethane



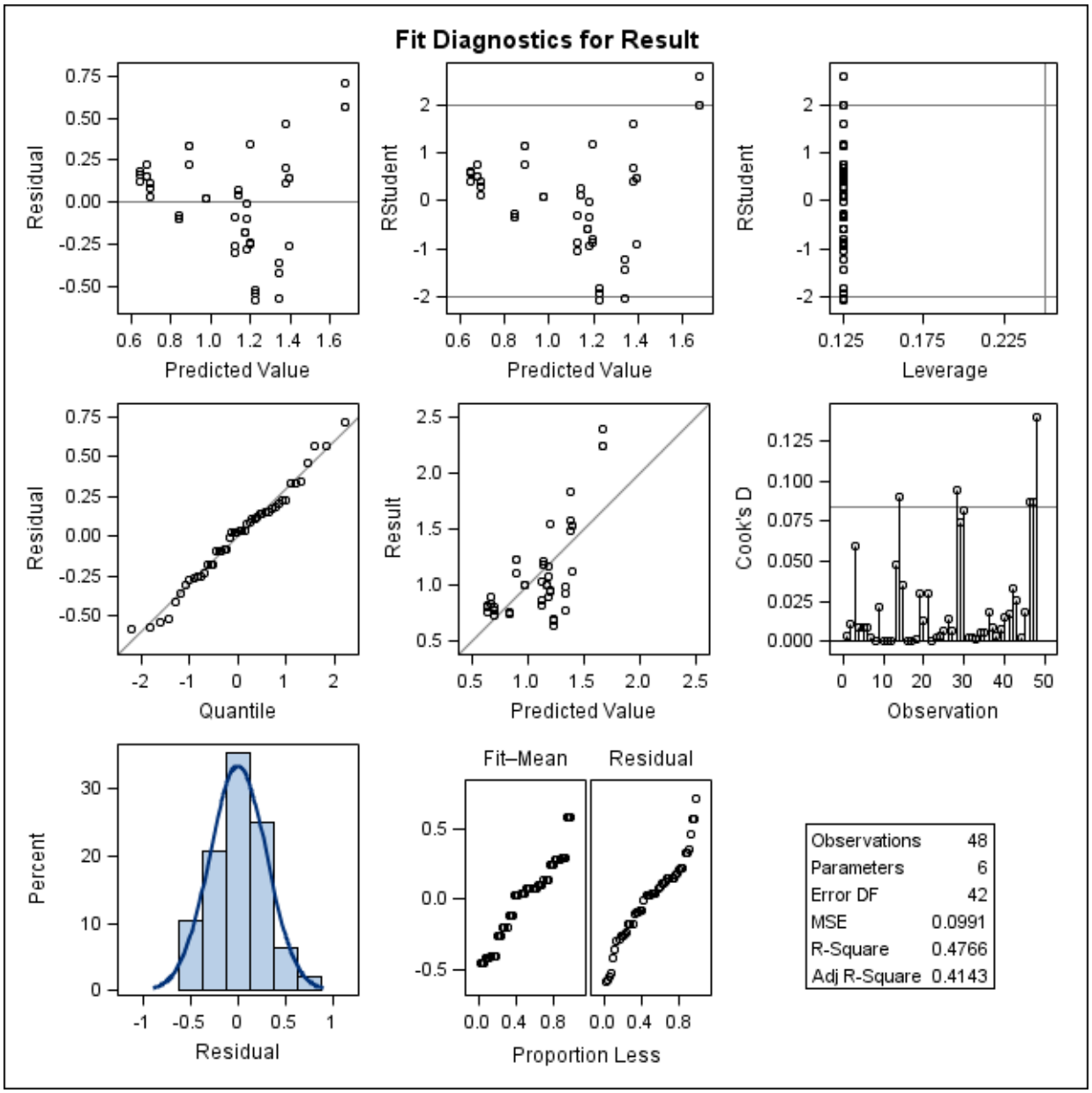
SKC Ultra - Trichloroethene



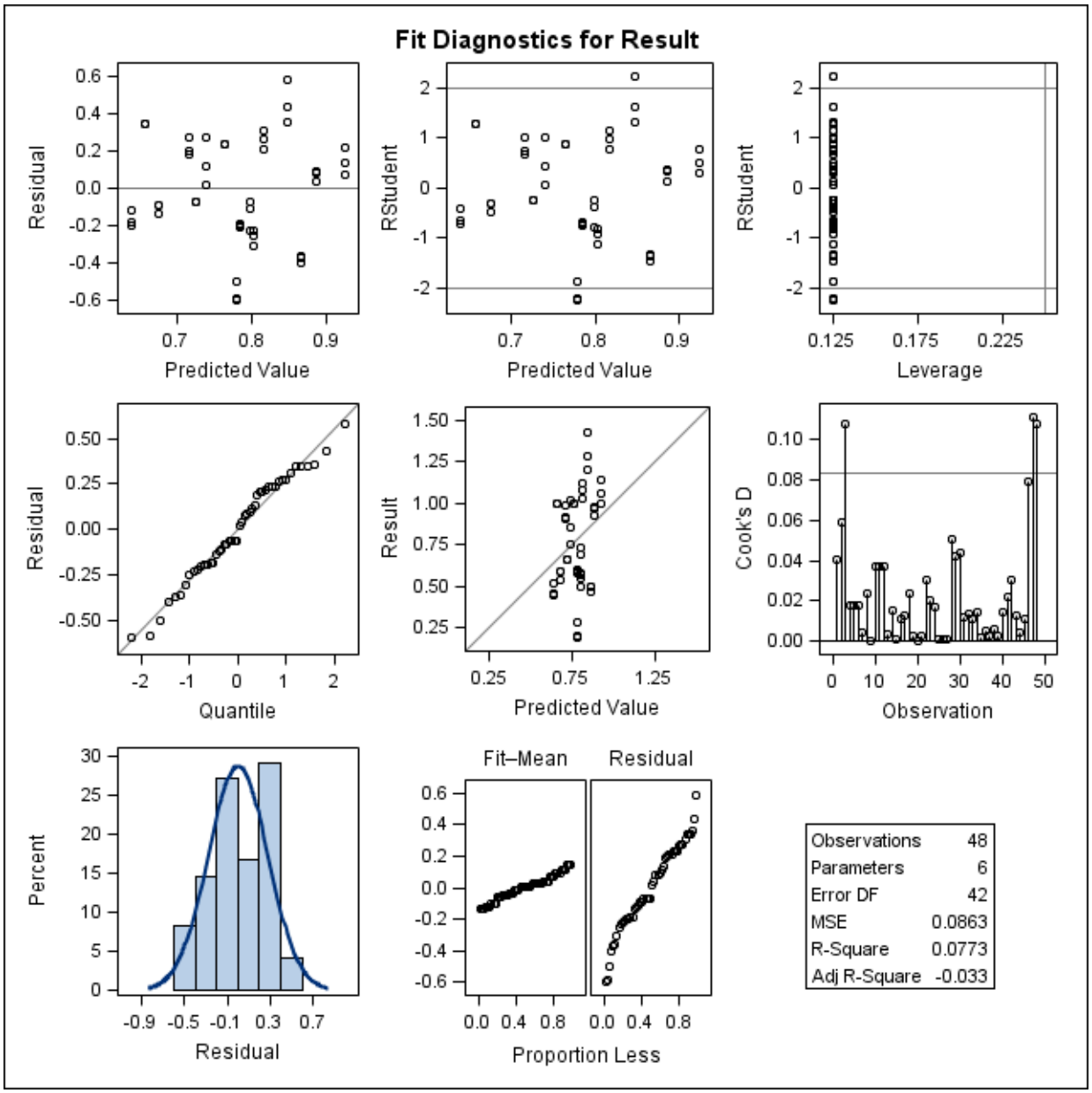
SKC Ultra - 1,2,4-Trimethylbenzene


Fit Diagnostics for Result
Residual
Predicted Value
RStudent
Predicted Value
RStudent
Leverage
Residual
Quantile
Result
Predicted Value
Cook's D
Observation
Percent
Residual
Fit–Mean
Residual
Proportion Less
Observations 48
Parameters 6
Error DF 42
MSE 2.3108
R-Square 0.3399
Adj R-Square 0.2613

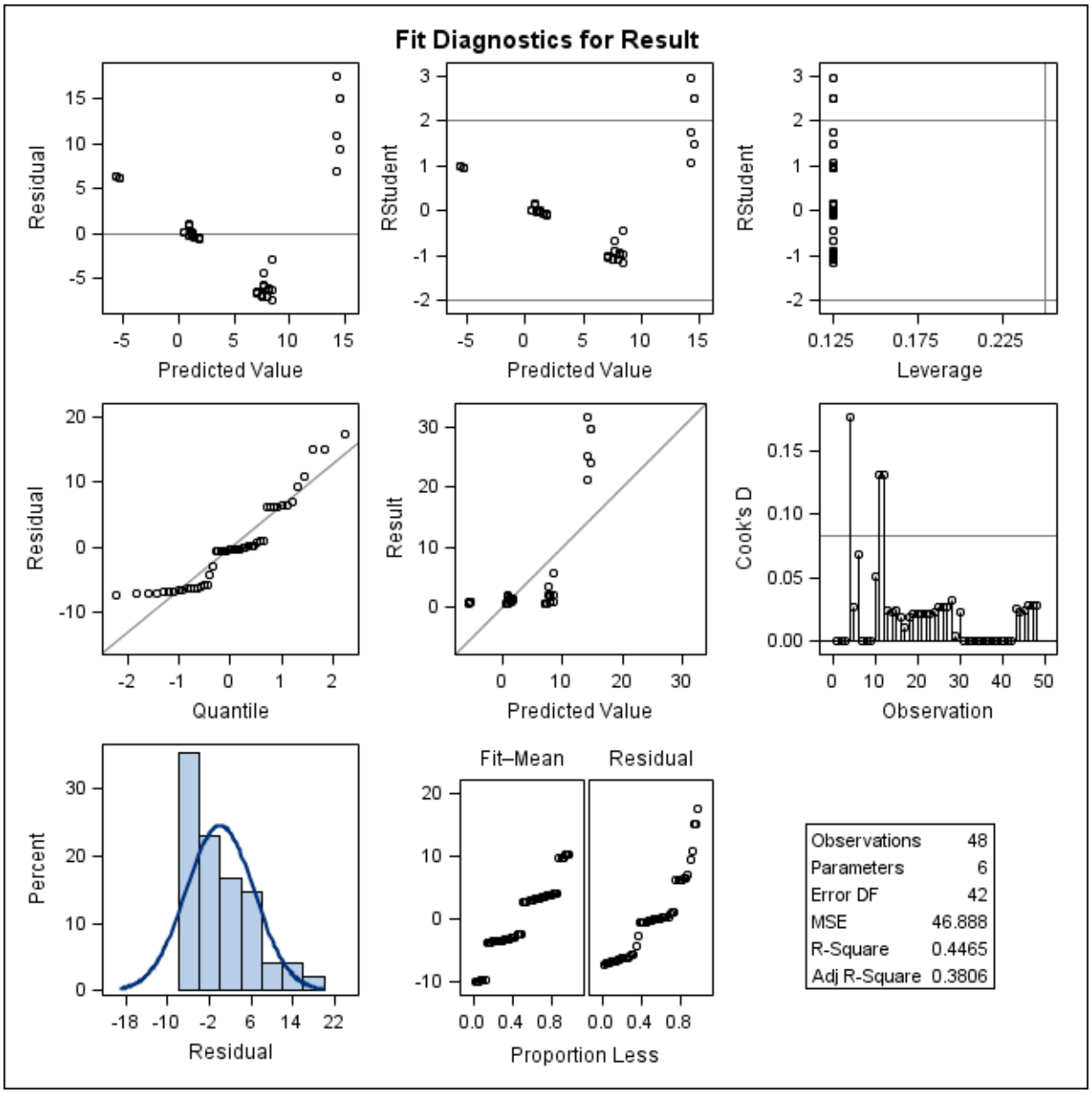
WMS - Benzene



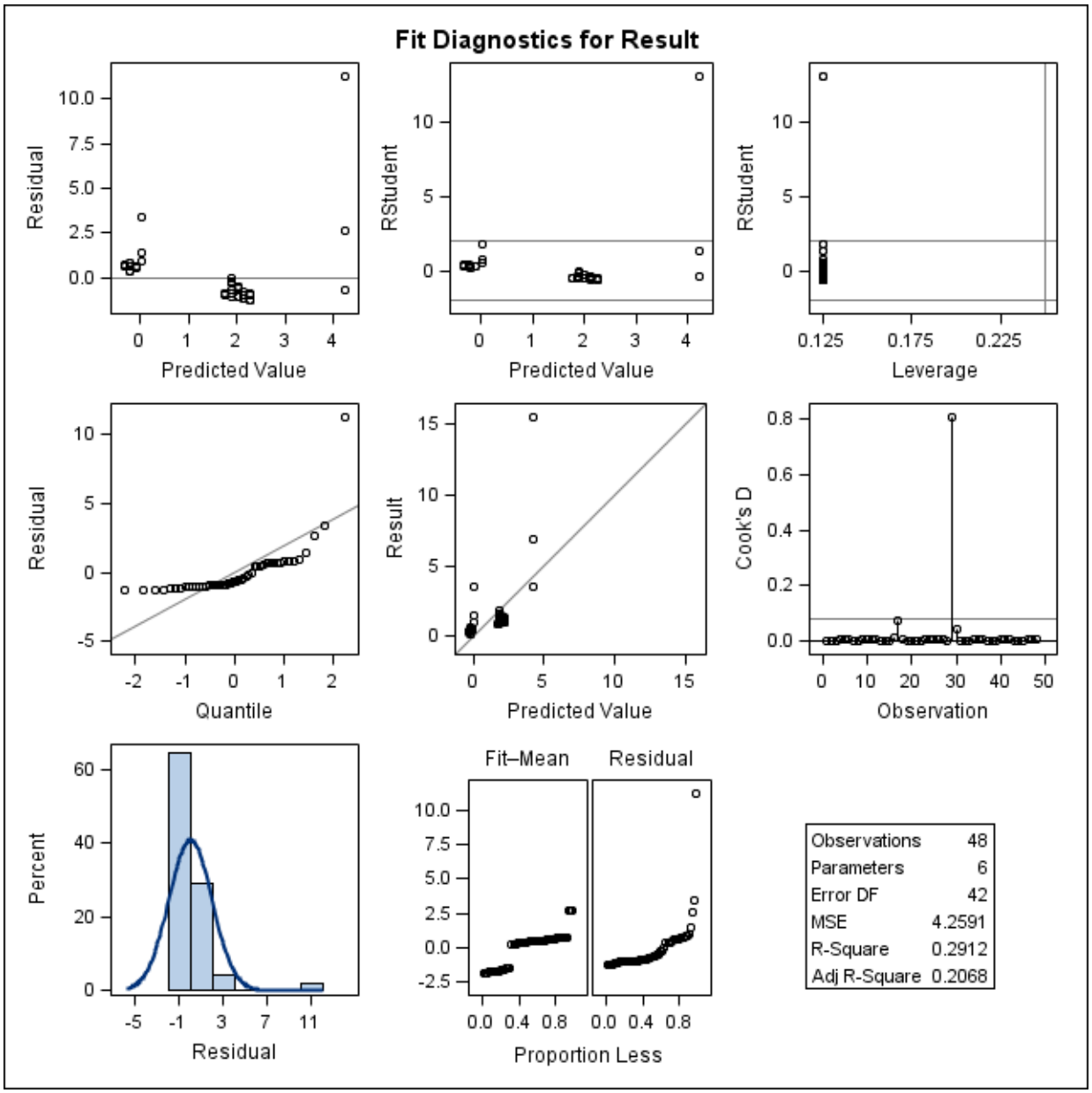
WMS - Carbon Tetrachloride



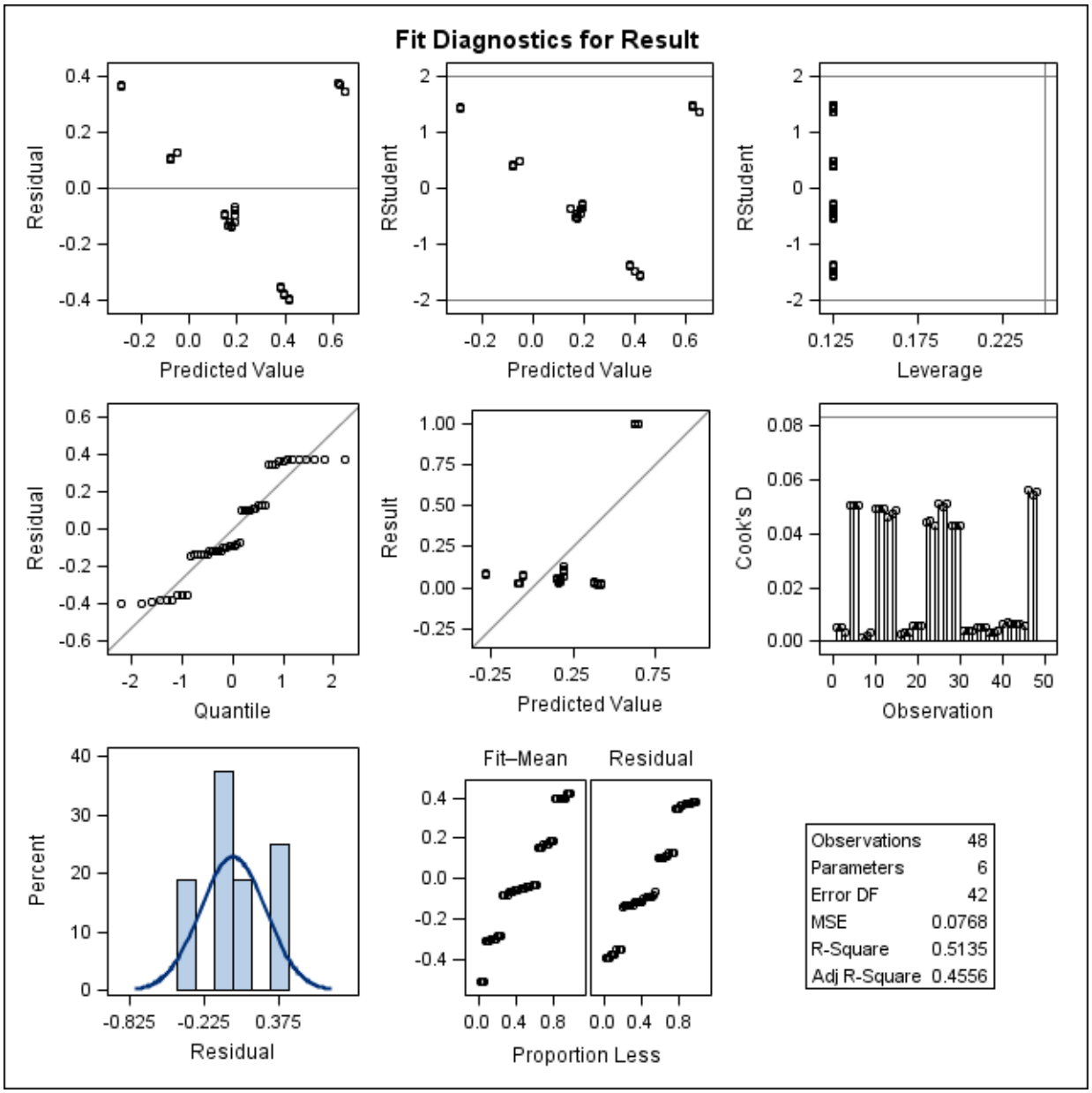
WMS - 1,2-Dichloroethane


Fit Diagnostics for Result
Residual
Predicted Value
RStudent
Predicted Value
RStudent
Leverage
Residual
Quantile
Result
Predicted Value
Cook's D
Observation
Percent
Residual
Fit–Mean
Residual
Proportion Less
Observations 48
Parameters 6
Error DF 42
MSE 46.888
R-Square 0.4465
Adj R-Square 0.3806

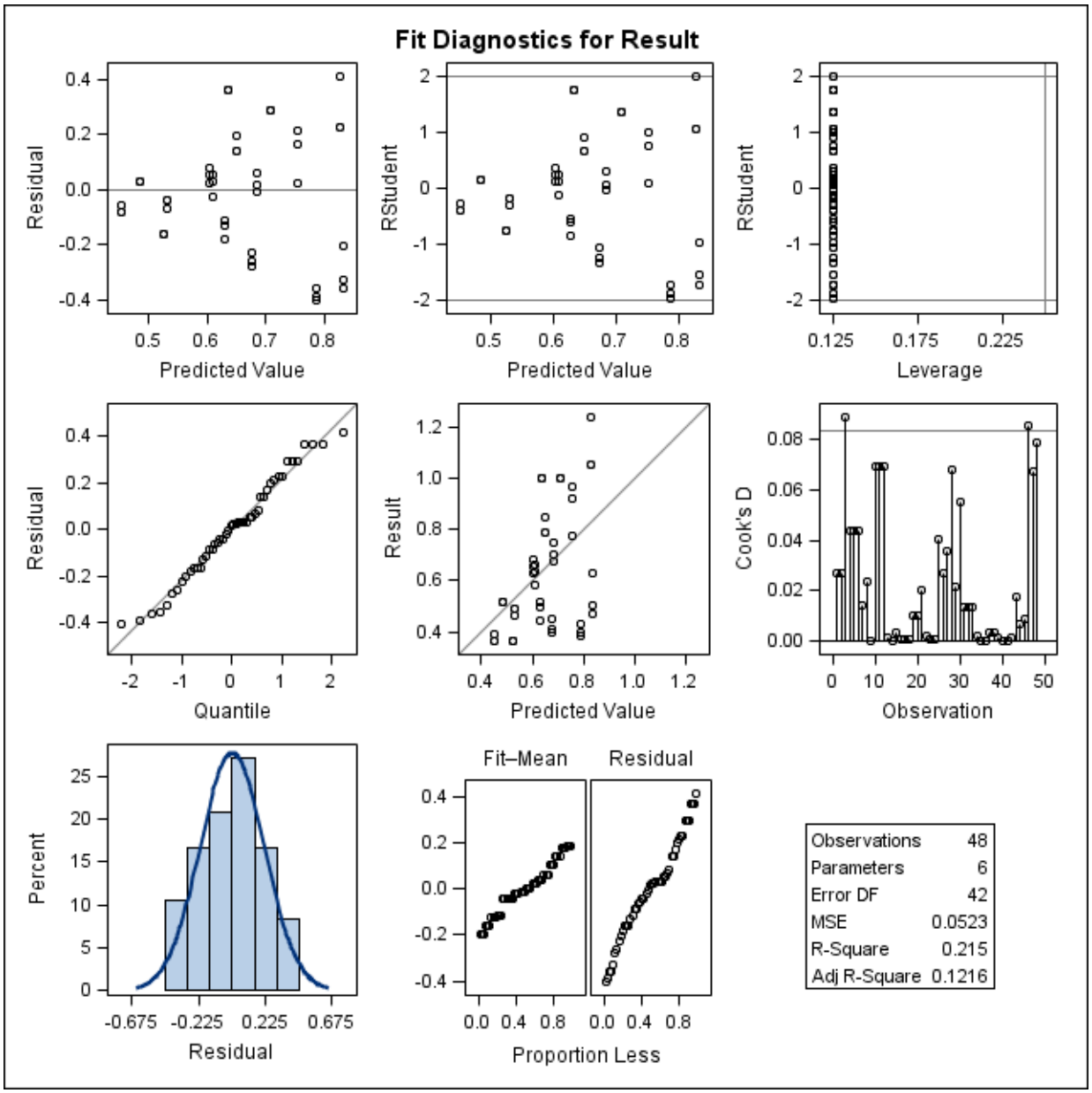
WMS - n-Hexane



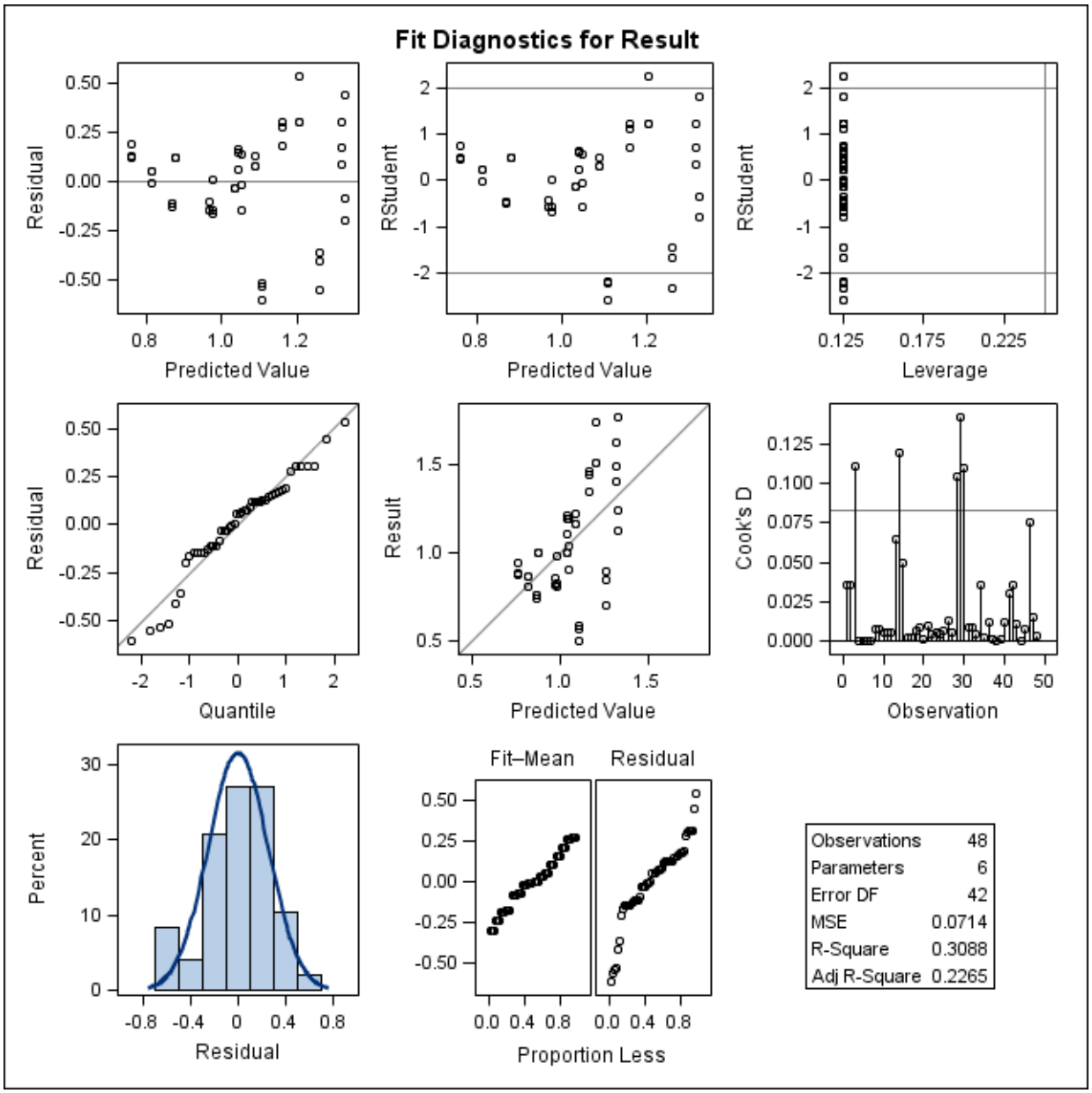
WMS - Methylethyl Ketone



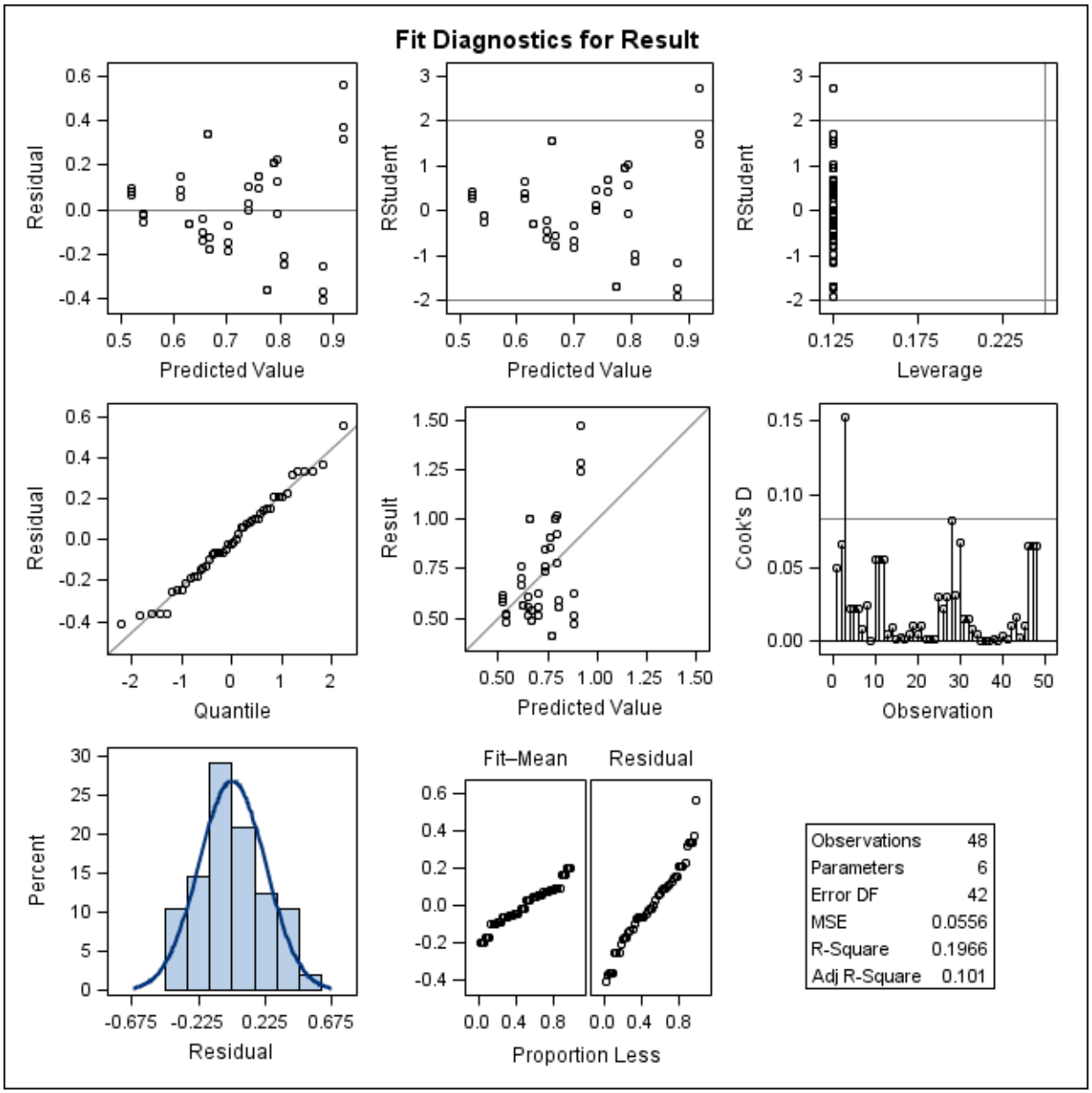
WMS - Naphthalene



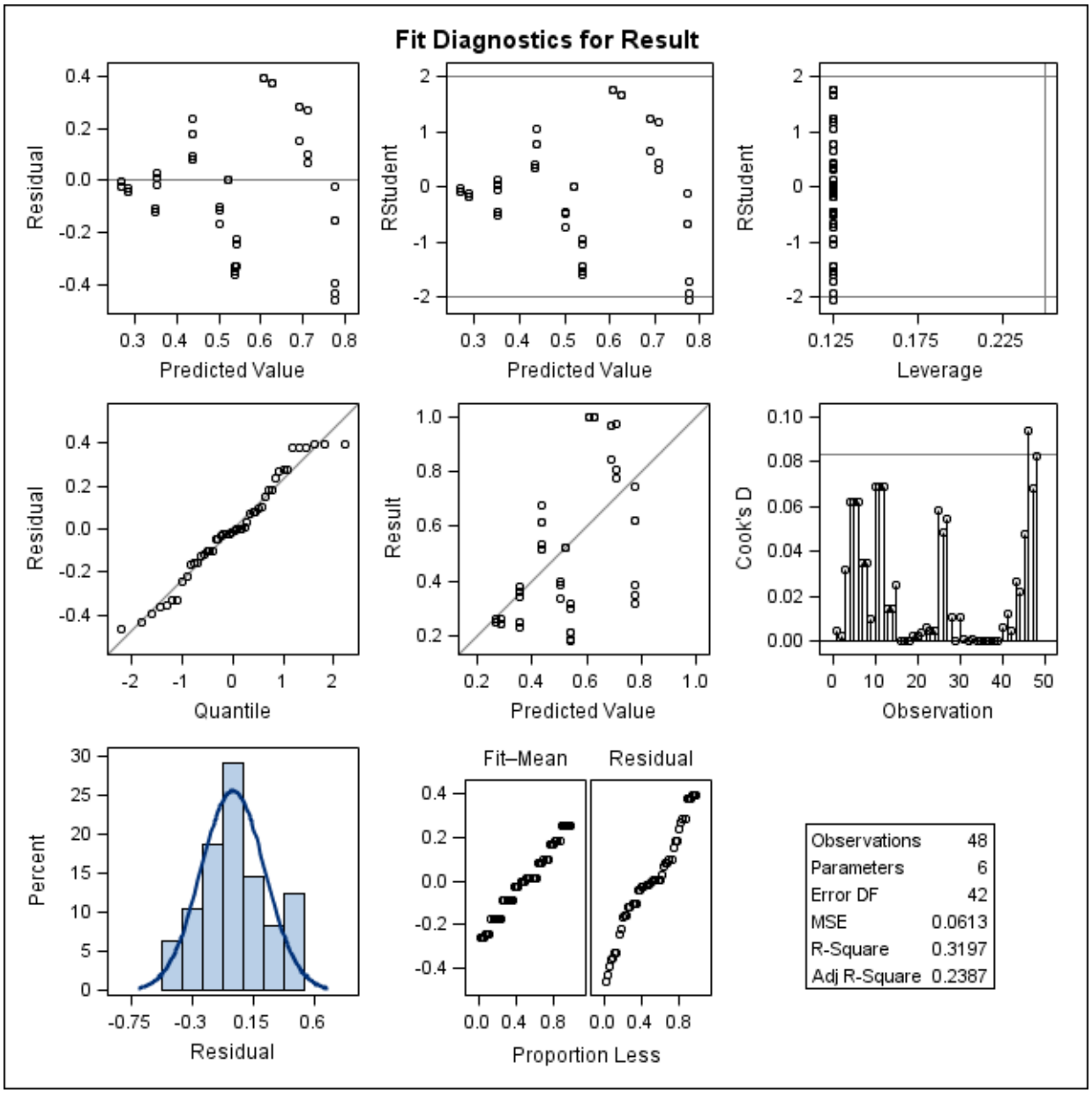
WMS - Tetrachloroethene



WMS - 1,1,1-Trichloroethane



WMS - Trichloroethene



WMS - 1,2,4-Trimethylbenzene