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A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites

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14. ABSTRACT

This project developed a quantitative decision framework to improve decision making and site-management practices for Navy industrial/commercial vapor intrusion (VI) sites. A multidimensional data base was first developed and populated with Navy Environmental Restoration Program VI site data from a diverse range of geologic, geographic, building types and other site conditions. The decision framework was then designed based on statistical and non-statistical analyses of both analytical and non-analytical data in the database. The project focused on chlorinated hydrocarbon sources which represent the largest potential Navy VI source.

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NAVFAC
Naval Facilities Engineering Command

Navy Environmental Sustainability Development to Integration Program

FINAL REPORT
A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites
NESDI #476
TR-NAVFAC-EXWC-EV-1603

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NESDI Program
Final Report

A Quantitative Framework for Assessing Navy Vapor Intrusion Sites
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Acronyms and Abbreviations

µg/L	micrograms per liter
µg/m^3	micrograms per cubic meter
AF	attenuation factor
AF$_{bldg}$	AF describing processes across the building envelope (indoor air concentration/sub-slab soil gas concentration)
AF$_{soil}$	AF describing processes that occur in the vadose zone (sub-slab soil gas concentration/groundwater vapor concentration)
AF$_{vi}$	AF for vapor intrusion from groundwater to indoor air (indoor air concentration/groundwater vapor concentration)
AFCEE	Air Force Center for Environmental Excellence
ANOVA	analysis of variance
BASE	Building Assessment Survey and Evaluation
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CSM	conceptual site model
CVOC	chlorinated volatile organic compound
DCE	dichloroethene
DNAPL	dense non-aqueous phase liquid
DoD	Department of Defense
EDA	exploratory data analysis
EDD	electronic data deliverable
ESTCP	Environmental Security Technology Certification Program
EXWC	Expeditionary Warfare Center
GC	gas chromatography
gw	groundwater
HVAC	heating, ventilation, air conditioning
INFADS	Internet Naval Facilities Assets Data Store
ITRC	Interstate Technology and Regulatory Council
LNAPL	light non-aqueous phase liquids
NAVFAC	Naval Facilities Engineering Command
ND	non-detect
NESDI	Navy's Environmental Sustainability Development to Integration
NIRIS	Navy Installation Restoration Information Solution
NIST	National Institute for Standards and Technology
NYSDOH	New York State Department of Health
PCE	tetrachloroethene
QA	quality assurance
QC	quality control

RPM	remedial project manager
SDS	Safety Data Sheet
SERDP	Strategic Environmental Research and Development Program
TCA	trichloroethane
TCE	trichloroethene
TM	Technical Memorandum
TPH	total petroleum hydrocarbon
USEPA	U.S. Environmental Protection Agency
VI	vapor intrusion
VI NEDD	Vapor Intrusion Navy Electronic Data Deliverable
VISL	Vapor Intrusion Screening Level
VOC	volatile organic compound

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- Andrew Madsen and Alex Liu: extensive data analysis and graphing
- Jennifer Baer and Lynn Miller: graphical support to decision framework

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Executive Summary

The Naval Facilities Engineering Command (NAVFAC) Expeditionary Warfare Center (EXWC), NAVFAC Atlantic, and CH2M HILL conducted a research project titled, "*A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites - NESDI Project #476*." The work was funded through the Navy's Environmental Sustainability Development to Integration (NESDI) program. The primary project objective was to develop a quantitative decision framework which can be incorporated into Navy VI guidance documents, training, and other evaluation tools. The project involved developing and analyzing a database of empirical data from Navy sites where the potential for subsurface vapors related to historical releases of volatile organic compounds (VOCs) to migrate into industrial buildings (i.e., vapor intrusion) has been investigated.

Single and multivariate analysis of geological and building factors potentially influencing vapor intrusion (VI) was performed to identify the key factors and the relationships between them in support of a quantitative decision framework. The decision framework provides a prediction of VI potential, based on analysis of data collected at Department of Defense (DoD) industrial/commercial buildings, and can be utilized to prioritize initial VI investigations, evaluate whether detected indoor air concentrations are VI-related, and guide long-term stewardship decisions.

The project also conducted an analysis of normalized indoor concentrations (commonly called attenuation factors [AFs]) for industrial buildings using methods generally consistent with those of the United States Environmental Protection Agency (USEPA) residential database. AFs (which represent the reduction in vapor concentrations between the subsurface source and indoor air) underlie the risk-based groundwater and soil gas VI screening levels frequently used during the initial screening phase of VI investigations. The current USEPA dataset of AFs is based almost exclusively on data from small residential structures and is overly conservative when applied to industrial/commercial buildings at DoD facilities.

The following methods were used in development of the framework:

- Identified building data sets through a service-wide data call
- Developed and populated a structured database in Microsoft Access representing installations, sites, buildings and sample zones where indoor air samples had been collected within the building
- Considered the effects of nondetectable (ND) results on the dataset
- Conducted initial exploratory data analysis using all available data
- Paired data (indoor air with sub-slab soil gas and groundwater) by sample zones
- Implemented screening of indoor and AF data to minimize the impact of indoor sources and atypical preferential pathways on the analysis
- Conducted single and multivariate regression and other statistical analyses on the screened data sets

- Utilized the results of the analyses to develop and assign weight to lines of evidence in the framework scorecard.

The key conclusions of the data analysis were:

- DoD Commercial/Industrial buildings exhibit markedly different VI behavior than residential structures included in the USEPA residential database.
- Only very high sub-slab soil gas concentrations result in indoor air concentrations above conservative USEPA indoor air screening levels (e.g., tetrachloroethene > 100,000 $\mu g/m^3$ and trichloroethene > 2,000 $\mu g/m^3$).
- Indoor air concentrations above USEPA screening levels were only observed when the groundwater vapor concentration (soil gas concentration calculated using Henry's Law) exceeds 10,000x the indoor air screening level (rather than the 1000x USEPA assumes in residential cases).
- An increase in the sample zone area was significantly correlated with decreasing indoor concentration on a log-log plot.
- A significantly higher concentration of trichloroethene was observed in sample zones with exterior walls.

The conclusions were used to develop a quantitative decision framework. The main elements of the decision framework are:

- A flow chart showing the overall process step-by-step and providing "off ramps" for clear-cut cases of very low VI potential and leading to a scorecard for other cases.
- The scorecard allows a more in-depth evaluation of "grey zone" cases using multiple lines of evidence leading to a "VI prioritization score." The range of weights in the scoring system are tailored to emphasize the importance of certain predictor variables identified in the data analysis; sample zone area, average sub-slab concentration, average groundwater concentration, soil type, presence of atypical preferential pathways and distance to the point at which the chemicals were originally released.
- Graphical keys for the interpretation of the VI prioritization score were provided that can be used at several different stages in site management:
  - In initial site investigations, to prioritize the need for further evaluations, such as determining when indoor air samples are necessary.
  - In site investigations that have progressed to include indoor air sampling, to evaluate if the observed indoor air concentrations are likely the result of vapor intrusion or indoor sources.
  - In planning for long-term stewardship of VI sites.

Field validation of the VI Decision Framework will require efforts outside the scope of this study and will involve application/assessment at a variety of Navy vapor intrusion sites. This will require acceptance by Navy RPMs and other stakeholders vested in improving site management decision making. It is expected that implementation of this quantitative decision framework will improve decision making and reduce costs at DoD VI sites.

1.0 INTRODUCTION

1.1 BACKGROUND

Vapor Intrusion (VI) is an increasing concern at Navy Environmental Restoration Program industrial/commercial sites. A 2012 NAVFAC survey identified 144 Navy sites (each site included anywhere from 1-50 buildings) needing Vapor Intrusion Assessments, up from 116 Navy VI sites in 2010 and 75 Navy VI sites in 2008. (Lund, 2013) A VI Assessment can run from $100K-$400K for a site with 2-10 buildings.

Most VI research to date has been focused on residential buildings. Ninety percent of the Navy buildings with potential VI issues are industrial/commercial buildings. (Lund, 2013) As the Navy has collected more and more Navy specific VI data, it has become evident that the existing generalizations, empirical relationships, and subsurface-to-indoor air attenuation factors developed for VI in residential buildings do not always accurately reflect what is occurring at Navy industrial sites or military settings. Attenuation factors and other relationships developed for residential buildings are much more conservative than expected and observed for industrial/commercial buildings. USEPA has not incorporated industrial data into their guidance or default assumptions based on the lack of available specific industrial data; therefore, EPA often recommends use of the overly conservative residential attenuation assumptions when assessing industrial/commercial buildings which results in expensive and unnecessary sampling and characterization of potential industrial VI sites.

Navy Remedial Project Managers (RPMs), contractors and regulators need direction and tools to more effectively and efficiently assess the VI pathway at Navy industrial/commercial sites. Overly conservative or unfocused VI investigations take time and cost money and could potentially lead to implementation of costly mitigation measures not actually needed.

A Microsoft Office Access database was developed to collect and store Navy VI site specific data from previous VI investigations at chlorinated hydrocarbon contaminated sites. The project examined the site specific factors which affect vapor intrusion (e.g., composition, concentration, and distribution of volatiles in soil, groundwater, soil gas, and/or indoor air, vertical and horizontal distances between vapor sources and buildings, lithology/hydrology, building characteristics such as building height, zone volume, mechanical and natural ventilation, and preferential pathways) and identified and quantified relationships between them in order to develop a data-driven decision framework for evaluating vapor intrusion. A more data-driven, systematic decision framework will limit the number of buildings investigated and result in optimizing investigation strategies for specific types of conceptual site models and increasing the strength of the evidence for the strategy selected.

1.2 REGULATORY DRIVERS

USEPA has focused most of its VI efforts on residential buildings which can behave very differently than industrial buildings with respect to VI. The final USEPA VI guidance was issued in June 2015. Also, many States have developed VI guidance or related technical memoranda. However, there is significant variability among State VI guidance; and there is no consistent approach to assessing VI for industrial/commercial buildings. The January 2009 DOD VI Handbook parallels the draft EPA guidance and provides no definitive approach to assessing VI for industrial/commercial buildings.

1.3 OBJECTIVE OF THE PROJECT

The two objectives of the project were to develop a quantitative framework to improve decision making and site-management practices for Navy industrial/commercial VI sites and to develop and populate a multidimensional database to collect Navy Environmental Restoration Program VI site data. The decision framework was based on statistical and non-statistical analyses of both analytical and non-analytical data in the database from Navy VI industrial/commercial sites representing a diverse range of geologic, geographic, building types and other site conditions. The project focused on chlorinated hydrocarbon sources (petroleum hydrocarbon information was included in the database only when they are co-mingled with chlorinated hydrocarbons) since chlorinated hydrocarbons represent the largest potential Navy VI source, and therefore the largest data set.

The **primary goals** for the project included:

1. Perform multivariate analysis of VI factors and investigation outcomes and determining key factors and relationships between them. The following are some examples of the types of questions that were asked:
    1. Is there a quantifiable relationship between the strength of a subsurface VOC source, the location of the building relative to that source, and the likelihood and magnitude of VI?
    2. Are there relationships between VI factors that support development of VI exclusion criteria?
    3. Can buildings be categorized with respect to quantifiable characteristics (e.g., size and compartmentalization) and descriptive characteristic (e.g., condition, operation, and use) and the potential for VI?
    4. To what extent do geological characteristics, such as vadose zone thickness and soil texture, influence the potential (and magnitude) of VI at Navy industrial facilities?

2. Conduct an analysis of attenuation factors (AFs) for industrial buildings using paired indoor/subsurface data and methods generally consistent with those of the United

States Environmental Protection Agency (USEPA, 2012a). AFs (which represent the reduction in vapor concentrations between the subsurface source and indoor air) underlie the risk-based groundwater and soil gas VI screening levels frequently used during the initial screening phase of VI investigations. The current USEPA dataset of AFs (USEPA, 2012a) is based almost exclusively on data from residential structures and is believed to be conservative when applied to industrial buildings. The data incorporated into the NESDI VI database and corresponding AFs will be made available to Navy remedial project managers (RPMs) to provide support for use of more realistic (i.e., less conservative) industrial-based attenuations factors.

3. Provide data and understanding to support the development of a quantitative VI decision framework. The decision framework should be designed to be accessible to RPMs within the Department of Defense (DoD) and to State and Federal regulatory staff. The decision framework should make the findings of this project accessible and useful at various stages in the VI site management life cycle.

In addition to the above primary goals, the following **secondary or supporting goals** and questions were considered:

1. Does the aerobic degradation of vinyl chloride minimize its significance as a potential VI contaminant of concern?

2. Can the building prioritization process be improved and placed on a more scientific and defensible footing? Building prioritization has played a key role in optimizing the allocation of investigation resources at sites with large numbers of buildings. At one major naval facility, for example, more than 1,000 building are within the regulatory site boundaries for sites with VOC contamination. A much reduced number of buildings were selected for data collection based on a prioritization process that considered factors such as subsurface VOC source strength, building size, occupancy and use, and distances between sources and buildings. The relative importance of these factors (i.e., their numerical weight) was further refined during a Phase 2 VI investigation at NAS Jacksonville (Lund et al., 2012). The VI data incorporated into the NESDI VI database was evaluated to assess the extent to which this quantitative prioritization process can be further refined and justified, thereby improving the site screening and building prioritization process.

3. Can additional "*exclusion criteria*" be developed for industrial sites? For example, are there some subsurface VOC concentrations or site/building characteristics for which significant VI has never been detected or has less than 95% probability of detection?

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The decision framework is based on a multidimensional database developed as part of this project. The database includes categorical information (e.g., VOC release characteristics, including source, strength, and distance from the building; size and characteristics of the building and zones within the building; media sampled; lithologic characteristics). Identifying these detailed categories was critical for successfully exploring the data, since ignoring or mistreating such categorical information could have resulted in flawed conclusions. Results and hypothesis developed by USEPA and others using numerical modeling were used to identify and rank the likely significance of these categories for affecting the fate and transport of vapors and ultimate vapor intrusion impacts.

The database was populated with existing empirical data from Navy VI sites which was then examined using exploratory data analysis (EDA) to identify patterns and correlations. Protocols for conducting further statistical/correlation analyses were refined by the EDA results and took into consideration common performance criteria for statistical hypothesis testing. Analyses included graphical EDA, multivariate statistical analysis for simultaneous analysis of several variables, parametric/non-parametric analysis of variance to determine statistically significant difference in data sets, and Bayesian statistics.

Results of the statistical analyses were used to develop a VI decision framework consisting of flowcharts, a scoring table, keys for interpreting scores, and recommendations which can be incorporated into Navy VI guidance documents, training, and other VI evaluation tools. The decision framework will help Navy RPMs expedite site management decisions and will be used to screen sites for further assessment, develop sampling approaches to optimize types and numbers of samples based on conceptual site model conditions, and evaluate data to assess the cumulative strength of individual lines of evidence.

2.2 TECHNOLOGY DEVELOPMENT

Beginning in 2002 and more recently in 2008, USEPA has undertaken an effort to collect and analyze a database of vapor intrusion data to conduct nonparametric statistical analysis of attenuation factors. (*U.S. EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors, March 4, 2008, Office of Solid Waste, U.S. EPA*) This NESDI effort builds upon USEPA's previous work and accounts for factors specific to Navy industrial and commercial buildings and settings.

The exploratory data analysis techniques used have been applied for many years (even before the creation of the environmental laws and regulations in the late 1980s) when analyzing data sets. They are used to summarize the data sets' main characteristics in an easy-to-understand format (e.g., commonly using visual graphics) and without using statistical models.

The parametric/non-parametric individual and multivariate statistical methods used in this project have been used in the environmental practice for many years and consist of procedures for comparing chemical concentrations or properties (measured or estimated) in various locations within the investigated media, including indoor and outdoor air, subsurface soil gas, and groundwater. The appropriate type and scope of the statistical procedure depends on the objective of the intended comparison. Detailed discussions on the most common individual and multivariate statistical techniques are included in the Department of the Navy's *Guidance for Environmental Background Analysis* (Vol. 1 – *Soil* [2002]; Vol. II – *Sediment* [2003]; Vol. III – *Surface and Groundwater* [2004]; and Vol. IV – *Vapor Intrusion Pathway* [2011]). Gilbert's 1987 book titled, "*Statistical Methods for Environmental Pollution Monitoring*" is also commonly cited and provides sampling plans, statistical tests, parameter estimation procedures, and references to other pertinent publications.

Application of decision analysis theory and procedures in various fields (e.g., environmental, energy, strategy, natural resources, and sustainability) has grown exponentially over the last two decades as discussed in Linkov and Moberg's recent (2012) book titled, "*Multi-Criteria Decision Analysis – Environmental Applications and Case Studies.*" Elements of decision analysis have been used in developing the decision framework in this project.

Leveraged Projects

The NIRIS (Naval Installation Restoration Information Solution) database is maintained and funded under the Environmental Restoration (ER) Program and currently stores a limited amount of VI data. Results from this project will be used to develop a VI NIRIS Electronic Data Deliverable (NEDD), funded by NAVFAC HQ, to collect additional key parameters influencing VI.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The current lack of an established decision framework for evaluation of VI sites can result in expensive and unnecessary sampling and characterization of potential VI sites. Application of the quantitative decision rules developed for this project will result in more efficient and accurate VI assessment at 144+ Navy sites. The number of Navy VI sites is increasing and many of the sites in the database are rapidly approaching a stage where final decisions have to be made regarding VI investigations, mitigation, and monitoring. The framework from this project will systematically weigh the various lines of evidence of vapor intrusion based on developed relationships between source strength, building characteristics and geologic conditions. This is a significant improvement over the current practice which is mostly based on assumptions that might not be entirely valid for industrial buildings.

With the products from this project, the Navy can implement more cost effective and scientifically defensible vapor intrusion evaluation strategies. Sampling approaches can be developed to optimize types and numbers of samples needed for maximum strength of the most critical lines of evidence enhancing our ability to evaluate vapor intrusion. These approaches will also ensure that the resources are directed toward obtaining only the essential data needed for VI investigations and mitigation measures.

The decision framework and the Navy VI database can provide a better understanding of the relationships and correlations between vapor source strength, building characteristics, and geologic conditions command-wide. The final USEPA guidance (2015) is based primarily on residential scenarios which often do not reflect the industrial scenarios of Navy sites. As no specific industrial data are available, USEPA often recommends use of the overly conservative residential parameters, even when assessing industrial buildings and scenarios. Providing specific input for Navy industrial settings will advance the science and understanding of VI and will allow the Navy to influence the regulatory approach for Navy specific VI evaluations.

As another benefit from this effort, the database and the NIRIS Electronic Data Deliverables (NEDD) developed from this project will enable Navy RPMs and contractors to update the VI database, share lessons learned from VI investigations, and thus enhance the VI related decision making process.

Findings from this report will be incorporated into future updates of Navy/DoD VI guidance documents, training, or site evaluation tools.

3.0 PERFORMANCE OBJECTIVES

3.1 PERFORMANCE CRITERIA

The project included development of a multidimensional database of Navy VI sites and a quantitative decision framework which could be used for decision making and management of Navy industrial/commercial VI sites. The project team concludes that a follow-on field validation of the decision framework is necessary. Field validation will involve application/assessment at a variety of Navy vapor intrusion sites. The measures of success during field validation can be demonstrated by the strength of the patterns and relationships identified during the data analysis phase, and the degree of acceptance by Navy RPMs and other stakeholders vested in improving site management decision making.

3.2 PERFORMANCE OBJECTIVES

Two products were developed under this project for which performance objectives can be measured: the Microsoft Access VI Database, and the VI Decision Framework. As field validation of the decision framework was not part of this effort, all performance objectives were qualitative.

Performance Objective	Data Requirements	Success Criteria	Criteria Met
QUALITATIVE			
Ease of data input to Microsoft Access Database	User feedback	First time user would be able to learn to add additional site data in 1-2 days	Yes
Ease of use of Decision Framework	User feedback	First time user familiar with a VI site investigation can apply the framework to their site in 1-2 days	Yes

4.0 FACILITY/SITE DESCRIPTION

This project focused primarily on industrial sites with chlorinated hydrocarbon sources (petroleum hydrocarbons were only included in the database when co-mingled with chlorinated hydrocarbons) since chlorinated hydrocarbons represent the most significant potential Navy VI source, and therefore the largest data set.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

Existing Navy and Air Force VI data from industrial sites was identified and collected. This included data collected under the Environmental Restoration Program as well as VI data collected at Navy industrial sites under ESTCP, or other projects. Data gathering was prioritized to emphasize sites with:

- Chlorinated volatile organic compound (CVOC) analytes that are less likely to be present in background sources
- Highest subsurface source strengths (some lower source strength data were included to support exclusion of data in the end)
- Other lines of evidence that indicate VI is likely occurring

A subset (13) of Navy and Air Force VI sites (49 buildings) that had the best/most usable data for thorough assessment was selected. The buildings included in the database contain the following general characteristics:

1. With the exception of two installations, the selected sites were located in coastal geographies as shown on **Figure 4-1**. Therefore, coastal geologies are predominating in the dataset.
2. Many of the buildings in the database were originally constructed during the World War II era. Eighteen (38%) of the buildings included in the database were constructed between 1940 and 1945. For comparison, 11% of commercial buildings in the U.S. commercial building inventory (SMR Research, 2011) were constructed in the time period from 1920 to 1945.
3. The average age of buildings in the database is 55 years. For comparison, the average age of all military and commercial industrial buildings in the U.S. is approximately 50 years (SMR Research, 2011). The Energy Information Agency survey of commercial buildings indicates an average age of 30 years (U.S. Energy Information Agency, 2003).
4. Buildings included in the database were primarily constructed by or under oversight from the U.S. government. Thus they would be expected to have been constructed with more uniform construction practices then those employed in the civilian sector (R. Christopher Goodwin and Associates, 1997).
5. The database includes a group of very large buildings. Five of the 49 buildings (~10%) are over 100,000 ft^2 and 12 of the 49 buildings (~24%) are between 50,000 and 100,000 ft^2.

In comparison, Koomey (1990) reports that approximately 5% of U.S. commercial buildings are greater than 50,000 ft^2. The database includes most of the industrial/commercial building uses commonly found at DoD sites (**Table 4-1**). In contrast, the buildings included in USEPA's database are primarily single family residences.

6. The majority of the sites included in the database are located in the southern states (below 40 degrees north latitude), with Virginia, North Carolina, and Florida heavily represented. In contrast, the USEPA (2012a) database is predominantly composed of data collected in buildings located in northern states (New York, Colorado, and Massachusetts).
7. The buildings included in the database are constructed almost entirely slab on grade, while the USEPA (2012a) database includes a significant number of slab-on-grade, crawlspace, and basement structures.
8. The depth to water at the sites included in the database is typically shallow (consistent with the coastal geography), with the majority of sites having depths to water of 3.0 meters (m) (9.8 feet) or less. In comparison, USEPA's residential database had majorities of both sites and data points from depths greater than 9.8 feet (USEPA, 2012a).

Information collected from each site for inclusion into the database included:

- Subsurface characteristics – soil type, groundwater depth, distance to CVOC source, groundwater flow/direction, and bioattenuation capacity/parameters
- Building characteristics – usage history, construction date, size/compartmentalization, volume, air handling/ventilation, chemical usage/release history, subsurface structures, and occupancy
- Analytical data – groundwater, sub-slab, indoor, and outdoor air CVOC data (analytes, concentrations, and sample location)

Environmental concerns for each selected site included: vapor source, strength and distance from buildings; building characteristics, and geologic conditions. Background sources of Vapor Intrusion were also of concern and considered.

5.0 TEST DESIGN

This project began with the assembly of a suitable database of the characteristics of DoD industrial, commercial and institutional buildings where VI had been studied. Data on groundwater concentrations, sub-slab soil gas and indoor air concentrations was assembled for these buildings. An initial qualitative exploratory data analysis (EDA) was conducted and included:

- Addressing the effects of non-detectable results on the dataset
- Analyzing individual media data first before calculating AFs or screening out data suspected of background (indoor source) influence
- Evaluating the relationship between source strength and distance and VI potential
- Exploring the relationship between building characteristics (e.g., area and height) and VI potential
- Addressing uncertainties associated with spatial and temporal variability
- Assessing the significance of background influences on indoor air concentrations

Results of the initial exploratory data analysis were used to define the following focus areas for more in depth analysis:

1. Relationship between building or sample zone size to indoor air concentrations
2. Relationship between sub-slab soil gas and indoor air concentrations
3. Relationship between groundwater and indoor air concentrations
4. Soil type effects on VI
5. Exterior wall effects on VI
6. Relationship between source strength and distance to indoor air concentrations
7. Seasonal effects

The more quantitative analysis included screening the dataset using approaches parallel to those used in USEPA's (2012a) residential database analysis to minimize the effect of background (indoor) sources. The dataset was also subdivided to focus on points not influenced by atypical preferential pathways. Relationships between predictor and outcome variables were then explored graphically, through single variable statistical analyses and finally through multivariate statistical analysis. The results of the qualitative and quantitative analysis conducted as part of this project were used to develop a decision framework consisting of a flowchart and scoring system, presented in Section 7.

5.1 Site and Building Selection

This section summarizes the process used to select the DoD Sites and buildings included in the database. Additional details regarding site selection are included in **Appendix A**.

NAVFAC Headquarters issued a data call to RPMs in the winter of 2012/2013. The data call resulted in 144 sites reported where subsurface VOCs exist and the potential for VI had been considered to varying degrees. Two additional sites, administered by the U.S. Air Force, were identified for inclusion in the NESDI VI project after the data call was completed to provide additional representation of noncoastal geographies. The current database includes 12 installations, 13 sites, and 49 buildings. **Appendix A** contains the results of the recent data call, as well as worksheets related to the site and building selection process. **Appendix B** contains the results of the data gap analysis conducted after the initial database population effort.

The data used to populate the Navy VI database were selected using the structured process described below.

- Step 1: Sites containing industrial/commercial buildings where chlorinated VOCs were the primary contaminants of concern and where indoor air data had been collected were retained for further consideration. Two large barracks buildings were also retained (15,000 and 91,000 square feet), which generally had similar sub-slab soil gas and indoor concentrations to the commercial buildings in the dataset. Although these barracks buildings have a style of construction not typical for single-family residences, they do differ from commercial buildings in the density of their plumbing fixtures.
- Step 2: Sites with buildings where sub-slab soil gas data were available were given preference. However, sites where groundwater was the only vapor source and no sub-slab soil gas data were available were not eliminated if there were other relevant and influencing VI factors.
- Step 3: Professional judgments were made about prioritization following Steps 1 and 2 and were based on detailed site characteristics. The team selected buildings that had sufficient data for analysis, and, in aggregate, demonstrated diversity in site and building characteristics and VI outcomes.

Electronic data were requested from the U.S. Navy and U.S. Air Force to populate the database upon completion of building selection. The types of data requested regarding buildings and environmental contamination are described in more detail in **Section 5.2**. VI data collected after installation of mitigation systems were not included in the database.

5.2 Database Description

The following sections describe the database structure and the data sources used to populate the database. The quality control (QC) procedures implemented during database population are also described.

5.2.1 Structure

The database structure is discussed using the following terms and definitions:

- Objects – An object has structure or state (variables) and methods (behavior/operations). An object is described by four characteristics:
  - Identifier: a system-wide unique ID for an object

  - Name: an object may also have a unique name in database (optional)
  - Lifetime: determines whether the object is persistent or transient
  - Structure: construction of objects using type constructors (Metz et al., 2015)
- Field – A field is a space allocated for a particular item of information. In database systems, fields are the smallest units of information that can be accessed. Most fields have certain attributes associated with them. For example, some fields are numeric whereas others are textual, some are long, while others are short. A field can be required, optional, or calculated in database management systems.
- Record – A collection of fields.

The basic structure of the database is shown in **Figure 5-1**. A detailed discussion of each field in the database is provided in **Appendix C**. Brief descriptions of each major heading in the schema are provided below.

5.2.2 Installation

Installation is the highest level object in the database. It represents a single military installation. An example of an installation is "Naval Air Station Anytown."

5.2.3 Site

Each installation can have one or more sites within the database, which are physical locations at which environmental contaminant releases are managed, and are represented as objects in the database. Sites are typically geographical subsets of the installation and are numbered.

5.2.4 Building

Each site may have one or more buildings (buildings are another example of an object within the database). Buildings are generally defined as structures with a roof and walls; separate buildings were defined for this project as they were in the NIRIS database or published reports. In some cases, separate building numbers are assigned in that database to additions that share common walls. The characteristics associated with each of the buildings included:

- Building Name
- Building Number
- Building Height Maximum
- Building Height Minimum
- Building Construction Date
- Building Footprint Area
- Building Use
- Number of Floors
- Building Volume

5.2.4.1 Sample Zone

One or more sample zones are defined within each building. The sample zone object represents an enclosed location within a building where at least one indoor air sample has been collected. The conceptual idea that best represents sample zone is a box. Ideally, a sample zone would have limited air mixing with other sample zones.

5.2.4.2 Sample Zone Characteristics

The sample zone characteristics table of the database includes:

- Sample Zone Name
- Sample Zone Number
- Sample Zone Footprint Area
- Sample Zone Interior Ceiling Height Maximum
- Sample Zone Interior Ceiling Height Minimum
- Sample Zone Depth to Groundwater
- Sample Zone Exterior Wall
- Sample Zone Flooring Type
- Sample Zone HVAC (heating, ventilation, air conditioning) Type
- Sample Zone Preferential Pathway (yes/no with notes)
- Sample Zone Use
- Sample Zone Volume
- Sample Zone Soil Type
- Sample Zone Subgrade Structures (yes/no with notes)
- Sample Zone Background Source
- Floor Drain Present?
- Vault/Pit Present?

The fields for preferential pathway within the sample zone characteristics table require particular discussion because there is a lack of consensus in the field for the definition of that term. A preferential pathway is one by which vapor may move into the Sample Zone in a less inhibited manner than the traditional pathway (migration through floor cracks, expansion joints, etc.). Examples include utility vaults and conduits and elevator shafts. The Navy VI Tool provided the following guidance concerning what types of features to consider as preferential pathways and should be used to determine whether potential significant preferential pathways exist:

> *Preferential pathways are natural or anthropogenic subsurface features of higher permeability or air filled porosity than the surrounding matrix. Preferential pathways may transport vapors farther or faster than what would be predicted by vapor transport models or assumptions (i.e., the Johnson and Ettinger model or attenuation factors). Because of this, preferential pathways may create an atypical connection/pathway between a vapor source and a building. Identifying significant preferential pathways is a critical component of the CSM. In order for a pathway to be "preferential" it must contribute to significantly different vapor transport compared to the expected transport through the surrounding matrix. Per ITRC (2007) VI Guidance:*
>
> > *"Most buildings have subsurface utility penetrations, so their presence alone is not considered preferential ... some increased component of soil gas flow into the building is usually required to consider the pathway to be preferential."*

> *Since the pathways are in the subsurface, they may not be obvious, and a careful inspection is often required to identify their presence or absence. Detailed building surveys/inspections, blueprints/as-built drawings, and geological investigations are some resources to help identify potential significant preferential pathways. Examples of Anthropogenic Preferential Pathways include:*
>
> - *Subsurface utility conduits (e.g., a sewer line intersecting contaminated groundwater)*
> - *Floor drains (e.g., around the gravel pack of the drain pipe where it enters the building or inside the pipe if contaminated groundwater has entered a sewer line and the trap is not maintained)*
> - *Building sumps or dry wells*
> - *Drainage pits*
> - *Large, unsealed penetrations through otherwise solid concrete floors*
> - *Unsealed saw-cut expansion joints in concrete floors, or floors where seals have desiccated or deteriorated over time*
> - *Utility conduits and surrounding granular fill, but only where there is a pressure gradient driving flow or the surrounding soil is too moist to allow appreciable vapor diffusion*
> - *Unlined crawlspaces, especially where the vadose zone is enough to make pumping important*
> - *Elevator pits and shafts*
> - *Examples of Natural Preferential Pathways*
> - *High permeability soils (e.g., gravel)*
> - *Heterogeneous sediments*
> - *Fractured bedrock*
> - *Animal burrows"*

This discussion from the Navy VI tool is much more extensive than the information on the subject in the DoD Handbook (Tri-service Environmental Risk Assessment Working Group, 2009) and generally agrees with the discussion in USEPA (2013). USEPA does attempt to define a subset of preferential pathways "significant":

> *"Furthermore, the CSM should identify known or suspected preferential pathways that could facilitate vapor migration to greater distances and at higher concentrations than otherwise expected. USEPA recommends that buildings with significant preferential pathways be evaluated closely. For the purposes of this guidance, a "significant" preferential pathway is a naturally occurring or anthropogenic (human made) subsurface conduit that is expected to exhibit little resistance to vapor flow in the vadose zone (i.e., exhibits a relatively high gas permeability) or groundwater flow (i.e., exhibits a relatively high hydraulic conductivity) and be of sufficient volume and proximity to a building so that it may be reasonably anticipated to influence vapor intrusion into the building. Significant vertical preferential pathways may result in higher than anticipated concentrations in the overlying near surface soils, whereas significant horizontal preferential pathways may result in elevated concentrations in areas on the periphery of subsurface contamination. Naturally occurring examples include fractures and macropores, which may serve as preferential pathways for either the vertical or horizontal migration of source materials and/or vapors. Anthropogenic examples include utility vaults and conduits, elevator shafts, subsurface drains, and permeable fill that intersect vapor sources or vapor migration pathways. In highly developed residential areas, extensive networks of subsurface utility conduits may be present, which can significantly influence the migration of contaminants"*

During EDA, additional classes of preferential pathways were defined. First using the notes information, binary variables were defined and populated for specific common types of preferential pathways: sumps/pits and floor drains. A narrow category "strict preferential pathway" was defined and was populated as "true" only when there was a clear record of a visually observable and a clearly atypical preferential pathway was present. After discussion among the project team, it was determined that features such as floor drains were too common in buildings included in the database to be considered atypical.

Examples of features that merited a "true" for a strict preferential pathway were:

- A tunnel that was clearly determined to be a vapor transport pathway.
- An underground utility trench that runs from the source area to the building.
- A sample location directly over a floor grate covering a drainage ditch.
- A zone where false wall utility conduits connected to dirt foundations and serve as preferential pathway.

5.2.4.3 Sample Zone Groundwater

A table describing the groundwater beneath or near each associated sample zone is included in the database. The Sample Zone Groundwater object represents the groundwater under a Sample Zone. Only analytical data that represent concentrations at or near (up to 10 feet below) the water table was considered in this table. Fields within this table included:

- Analyte
- Interpolated Maximum under Sample Zone
- Interpolated Minimum under Sample Zone
- Measured Maximum
- Measured Minimum
- Measured Max Location ID
- Measured Minimum Distance

5.2.4.4 Sample Zone Background Sources

The Sample Zone Background Source object represents potential background sources of an analyte that may cause indoor air or sub-slab soil gas concentrations to be elevated. If not identified, background sources can lead to a false conclusion that VI is occurring and/or significant. Sample Zone Background Sources will typically be due to outdoor air VOC sources or chemicals used or stored in the building; however, situations where outdoor air concentrations are elevated due to subsurface impacts would not be considered background.

5.2.4.5 Sample Zone Primary Release

The Sample Zone Primary Release object is associated with each sample zone and represents the release point/area of contaminants in the vicinity (e.g., within 100 feet) of the Sample Zone. It does not represent the resulting plume from the migration of the contaminants to groundwater. The objective of the Sample Zone Primary Release field is to provide as much relevant information as possible about how close a vadose zone source may be to a Sample Zone. An example of a primary release would be a "historical chlorinated solvent surface disposal site." The fields in the sample zone primary release table are:

- Distance to Primary Release
- Primary Release Source Name
- Sample Zone Locations

5.2.4.6 Sample Locations

One or more tables describing specific sample locations are associated with each sample zone. Sample matrices may be collocated but are designated with separate Sample Zone Location entries due to the database construction.

5.2.5 Analytical Data

Sub-slab soil gas and indoor air analytical data from specific sampling events are linked to the sample zone.

5.2.6 Data Sources

Data sources that were used to develop the VI database are described in Table 1 of **Appendix A**. In general, these include:

- Analytical data
    - Data published in the NIRIS database. Additional information about the NIRIS database can be found in Sadorra and Fortenberry (2009) and at http://www.navfac.navy.mil/navfac_worldwide/specialty_centers/exwc/products_and_services/ev/erb/niris.html
    - Data provided in electronic data deliverable (EDD) format in the case of non-Navy sites or Navy sites where analytical data were not yet loaded into NIRIS.
- Site/building/sample zone characteristics data:
    - Information contained in project documents.
    - Building characteristic information contained in DoD documents such as the Energy Audit Reports or the Internet Naval Facilities Assets Data Store (INFADS) database.
    - Data developed specifically for the NESDI project through additional interviews or site reconnaissance.

The database includes 12 installations, 13 sites, 49 buildings, and 150 sample zones.

5.2.7 Quality Control

To mitigate potential data entry errors in data that reside in the VI database, data population underwent a thorough quality assurance/quality control (QA/QC) process, as outlined in the *Vapor Intrusion Database Guidance: Population, Quality Assurance/Quality Control TM* (QA/QC Guidance) (**Appendix C**).

Figure 5-2 is a flowchart for the QA/QC process, where the term “User” refers to the team or individual responsible for manually collecting the data and entering those data into the Data Entry Form for the initial population of the VI Database. The “Reviewer” then reviewed the database entry and worked with the User to correct any data quality issues.

Once the data were verified or corrected within the workbook for each site, it was then provided back to the Data Entry Manager for re-uploading into the VI database. This process was conducted for each site until the VI database entry and verification were complete.

5.3 Data Processing

This section describes the data processing methods used to prepare the data for the EDA.

5.3.1 Selection of Target Compounds

The entire VOC dataset available for each sample in either NIRIS or EDDs was uploaded to the database. Upon evaluation of the available data and frequency of detection (**Tables 5-1** and **5-2**), a subset of VOCs were selected for detailed analysis. The following VOCs were selected as those most likely to result in meaningful EDA based on the size of the dataset and because of their common presence at DoD facilities:

- 1,1,1-Trichloroethane (1,1,1-TCA)
- Cis-1,2-dichloroethene (Cis-1,2-DCE)
- Tetrachloroethene (PCE)
- Trichloroethene (TCE)
- Vinyl Chloride (VC)
- 1,1-Dichloroethane (1,1-DCA)
- 1,1-Dichloroethene (1,1-DCE)
- 1,2-Dichloroethane (1,2-DCA)

5.3.2 Handling Non-detects

The usability of sampling and analytical data to perform EDA and to develop indoor air to sub-slab soil gas concentration ratios (used to estimate AFs) is influenced by the proportion of results that are not detected ("ND" or "U"-qualified) or below analytical reporting limits provided by the laboratories. Each of the target compounds considered in the EDA have various proportions of results below reporting limits. This section discusses how ND results affect the overall distributions of the data, and provides a recommendation for the proxy values that were used in place of ND or U-qualified values for purposes of EDA and in some aspects of the quantitative analysis discussed further in **Section 6**.

The frequencies of detection for indoor air and sub-slab soil gas samples for the target compounds, the minimum and maximum detections, and the minimum and maximum reporting limits are provided in **Tables 5-1** and **5-2**.

PCE and TCE had the highest frequency of detection in both the indoor air and sub-slab soil gas samples, with 85% or higher detection frequencies in the sub-slab soil gas samples and approximately 50% detection frequencies in the indoor air samples. Detection frequencies for the other VOCs ranged from 3 to 50% in the indoor or sub-slab soil gas samples. Data sets containing increasing amounts of ND values are said to be "censored," which must be considered and accounted for in the analysis (Gilbert, 1987). USEPA (2009b and 2013) guidance provides various options for consideration when analyzing censored datasets, depending on the degree of censoring. There was overlap between the reporting limits for ND results and detected concentrations for some analytes (**Tables 5-1** and **5-2**).

The potential for bias in the exploratory data analysis and indoor air to sub-slab soil gas ratio calculations introduced by ND results was explored through graphical sensitivity analysis and evaluation using two of the three standard approaches for assessing ND data: 1) substitution (assigning a proxy value such as the reporting limit or one-half the reporting limit); 2) maximum likelihood estimation; and 3) non-parametric methods (Helsel, 2005). Maximum likelihood estimation is not included in this analysis because it assumes that data fit theoretical statistical distributions. Goodness of fit tests were not performed on these datasets.

The sensitivity analysis described in the previous paragraph focused on indoor air results for the target compounds and included the following steps:

- Preparation of graphical plots (box and whisker plots and standard normal probability plots) for:
  - All indoor air results that include detected results and reporting limit values for ND results
  - Concentrations detected only in indoor air
  - ND results only using reporting limits
- Preparation of order statistics for all indoor air results (detect and ND) using the Kaplan-Meier method. This is a non-parametric method derived from right-censored survival analyses in medical research which is "flipped" to develop statistics for left-censored environmental datasets with multiple results below reporting limits (USEPA, 2013). The Kaplan-Meier method was used to calculate order statistics in USEPA's VI attenuation factors database (USEPA, 2012a). The Kaplan-Meier order statistics were compared with the order statistics based on all indoor air results and detected indoor air results to determine whether including ND values created a bias in overall indoor air statistics.

The analyses of the effects of data censoring were prepared for four selected analytes: TCE, PCE, cis-1,2- DCE, and 1,1,1- TCA. These were selected to reflect a range of frequency of detection: TCE and PCE were detected in approximately 50% of the indoor air samples, cis-1,2-DCE was detected in 27% of the indoor air samples, while 1,1,1-TCA was detected in 11% of indoor air samples. These selected analytes were evaluated to provide examples of how censoring potentially affects usability of the data and are presented in **Figures 5-3** through **5-6**.

A comparison of the box and whisker plots (in **Figures 5-3** through **5-6**) indicated that, as expected, including ND values at the reporting limits shift the distributions to the left, decrease the median, and lower variability of the "all results" dataset as seen by the smaller interquartile range (the "box") between the "all results" and "detects" populations. The probability plots (**Figures 5-3** through **5-6**) for the "all results" and "detects" populations generally look similar, both with inflection points at approximately the same points in the distributions. This suggests that the ND results have limited influence on the overall shape or distribution of the data. Comparison of the order statistics calculated with the Kaplan-Meier method and order statistics for all results shows that a small (approximately two-fold) increase in values at the lower percentiles, but that the statistics between the two methods for the upper percentiles (90th and 95th) generally are indistinguishable. The notable exception is cis-1,2-DCE, where a large proportion of ND results had a reporting limit of 10 $\mu g/m^3$, which would be reflected prominently in order statistics of the "all results" dataset.

The results from this analysis indicate that ND reporting limits can be used as the "result" value in the EDA. Including ND results with reporting limits substituted as values for ND results provides a larger dataset and allows calculation of more ratio pairs. While including NDs at detection limit values slightly decreases the overall distribution of indoor air concentrations, the individual reporting limit values will provide more conservative indoor air to sub-slab soil gas concentration ratios. This is because indoor air concentrations with ND results are lower than the concentration represented by the reporting limit values. In addition, a comparison of "all results" with a method that formally estimates statistics accounting for censored values shows that censoring does not affect the upper percentile values in indoor air, and therefore does not affect the reliability of ratios based on upper percentile values. There will be some analytes, such as cis-1,2-DCE, where this approach will produce a high bias to indoor air concentrations, although a high bias to indoor air concentrations generally will result in more conservative indoor-to-subsurface concentration ratios.

5.3.3 Pairing Data

In order to make comparisons between results measured in different media such as groundwater, sub-slab soil gas, and indoor air, the following process of associating or pairing the data was conducted:

- Normalized indoor-to-sub-slab soil gas concentration ratio calculations were based on data pairs located within a given sample zone where both samples were collected within 14 days. Where multiple data pairs were available within the given timeframe, the analysis included only the most contemporaneous sub-slab or groundwater point for a given indoor air observation.
- Where more than one sub-slab soil gas or indoor air sample was present within a sample zone, normalized concentrations were calculated using one of the two following procedures:
  - The mean indoor and sub-slab soil gas concentrations within the zone were used, which results in a single normalized indoor air-to-subsurface concentration ratio per sample zone.
  - Indoor air sample results were paired with every other sub-slab soil gas sample in a zone. For example, six normalized concentrations would be calculated if a zone had two indoor and three sub-slab soil gas sample locations.

5.3.4 Normalizing Data

Vapor intrusion data are frequently normalized by dividing the indoor air concentration by the sub-slab soil gas concentration or deep soil gas concentration; the same practice was used for normalizing this projects' data. This normalized concentration is conventionally referred to as an attenuation factor (AF). The terminology used in this section was selected to be consistent with USEPA terminology for AFs, but also in the event that the results from this analysis are compared with the results from the USEPA residential database.

Consistent with the USEPA database analysis, the following AFs were calculated:

- The attenuation factor describing processes across the building envelope (known as AF_{bldg}) was calculated for each pair of data points as: AF_{bldg} = indoor air concentration/sub-slab soil gas concentration.
- The attenuation factor describing processes that occur in the vadose zone (AF_{soil}) was calculated as: AF_{soil} = sub-slab soil gas concentration/groundwater vapor concentration. The groundwater vapor concentration is the concentration calculated to be in deep soil gas at equilibrium with the groundwater analyzed, using Henry's law.
- The overall attenuation factor for vapor intrusion from groundwater to indoor air (AF_{VI}) was calculated and reflects both soil column and building envelope effects: AF_{VI}= indoor air concentration/groundwater vapor concentration.

Thus: $AF_{VI} = AF_{bldg} \times AF_{soil}$

5.3.5 Accounting for Background

The procedures for accounting for background sources in the database were modeled closely on those used by USEPA (2012a). The following screening/filtering steps were applied to the dataset:

- Data pairs with sub-slab soil gas or groundwater concentration below detection limits were excluded (termed the "subsurface concentration screen" by USEPA). This is the first step to reduce the influence of indoor sources on the dataset. However, ND reporting limits were used when calculating mean sub-slab soil gas concentrations, whereas one-to-one pairs with ND sub-slab soil gas concentrations were excluded.
- Information about a background source(s) provided in site reports was reviewed. The "Background" table in the database was a repository for this type of information. There were few entries, with most of these pertaining to outdoor/indoor results comparisons. This likely reflects the content of the referenced reports, as few of them explicitly addressed background sources. The reports often contain survey information, but the information in the database was available only if a specific source was identified as being important in the report narrative.
- Indoor-to-sub-slab ratios were calculated for different analytes. Analytes with ratios one order of magnitude or more different than the other analytes indicate the potential influence of a background source (USEPA, 2012a). Graphs summarizing the indoor and sub-slab soil gas results by sample zones and dates expedited the review of this information. This step is the equivalent of the USEPA (2012a) data consistency screen. Data were also compared with site-specific ambient concentrations where available to assess the potential for outdoor air background sources to influence measured indoor air concentrations. Data pairs where the indoor concentrations were less than two times the measured outdoor concentration(s) were excluded from the AF calculations; given the likelihood that outdoor air is the primary source of the measured indoor concentrations. Steps 1 through 3 define what USEPA (2012a) calls the "Baseline Screen**.**"
- Consistent with USEPA (2012a), a sub-slab source strength screen was implemented to determine whether there is a subsurface source concentration below which the influence of VI could not be reliably assessed. The USEPA (2012a) source strengths of 50x for sub-slab soil gas and 1000x for groundwater vapor were used. This involved calculating values 50x the indoor air background concentrations. Sub-slab locations with concentrations < 50x background levels were excluded. Groundwater concentrations were converted to a deep soil gas equilibrium concentration using Henry's Law at an assumed temperature of 20^{o} Celsius and then "groundwater vapor" locations with concentrations <1000x the indoor air background were excluded. The source strength screen was implemented at a building level, not at sample zone level because VI that occurred in a room adjacent to the sample zone could influence the sample zone indoor air concentration.
- The background screening step was implemented by excluding all indoor air data less than the 90th percentile of the Building Assessment Survey and Evaluation (BASE) study indoor

air distribution (Appendix C-2; NYSDOH, 2006). This is consistent with how background was defined in USEPA (2012a). Although the BASE study was the best available public and commercial dataset, it used methods less sensitive than those currently employed, as the data were collected in 1994-1996. Thus if the BASE study reported a 90th percentile is a less-than value, indicating detectable indoor air concentrations were rarely found in that study at its elevated detection limits, then the median of 90th percentile concentrations from multiple residential studies was used instead, as done by USEPA (2012a). If both studies had a 90th percentile less-than value, no data were screened out for background for that compound.

The background value selected for quantitative analysis in data screening was the 90th percentile of the BASE study indoor air distribution (Appendix C-2; NYSDOH, 2006). The BASE study database was derived from intensive sampling of 100 randomly selected public and commercial office buildings in the United States with sampling from 1994-1996. The use of the 90th percentile value is consistent with how background was defined in the USEPA database study (2012a). If the BASE study 90th percentile was a less-than value, indicating detectable indoor air concentrations were rarely found in office buildings at the elevated detection limits that were common in the 1990s, then the median of 90th percentile concentration from multiple residential studies (USEPA, 2011) was used instead, as done in the USEPA (2012a) residential database report. If both studies had a less-than value for the 90th percentile, then background sources were considered unlikely and no data were screened out on the basis of background for that compound. No other North American commercial building background studies were readily available in a suitable format at the time this study was conducted. The utilized background information is summarized in **Table 5-3**. The comparison of data from industrial/commercial buildings to residential background is not ideal in cases where background industrial/commercial data are not available, but provide useful information because:

- Many products for cleaning, pest control, etc. are purchased from the same sources for both residential and commercial uses. Cosmetics, cooking, building materials, furniture, and human exhalation are all examples of VOC sources that are present to varying extents in many residential and commercial environments. However, air exchange rates and building volumes are often different for residential and commercial structures.
- Other than office buildings, it is difficult to find industrial/commercial buildings with no possibility of previous industrial use of VOCs that are geographically separated from other industrial users of VOCs, and thus are certain to be representative of “background” conditions.

The choice made to use the multiple residential background data when the BASE study was ND has relatively limited influence, because there were only three compounds for which it was needed: vinyl chloride; 1,1-DCE; and 1,2-DCA. Those three compounds are not featured extensively in this report, although they are discussed in places. In each case, the residential 90% result was less than the BASE study ND.

An additional table was created within the database to capture the various reasons that analytical results might be flagged relative to the potential presence of background sources. The fields in this table captured whether the following conditions existed:

- Groundwater concentrations (measured or interpolated) were ND under or near a building.

- Indoor air concentrations were greater than two times the measured outdoor concentration for a given sampling event.[1]
- Sub-slab soil gas concentrations were greater than 50 times[2] the literature background value for indoor air.
- The calculated groundwater vapor source concentrations were greater than 1000 times[3] the literature background value for indoor air.
- Indoor results were greater than the literature background value for indoor air.
- Analysis of site-specific data, specifically the indoor-to-sub-slab soil gas concentration ratio for multiple analytes, suggested the presence of a background source.

The following seven screened subsets of the dataset were constructed using the combination of background screening information and the strict (atypical) preferential pathway definition discussed in **Section 5.2.4.2**:

- Screening Indoor Sources
    - No screen
    - Baseline screen only applied
    - Both baseline and source strength screens applied
    - Both baseline and background screens applied
- Then additionally screen for strict (atypical) preferential pathways
    - Without any background screens but with data pairs for which "preferential pathway strict = yes" excluded
    - With baseline screen + source strength screen as well as "preferential pathway strict = yes" excluded
    - With baseline screens + background screen as well as "preferential pathway strict = yes" excluded

5.3.6 Additional Calculated Variables

Certain additional variables were derived from the fields in the database and used for data analysis in an Excel "flat file":

- Building_volume_calc = building area x building height max
- Sample_Zone_Volume_Calc = sample zone area x sample zone height max

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[1] 2x factor was selected on the basis of professional judgment that values less than 2x above ambient concentrations were almost certainly heavily influenced by ambient concentrations. While some ambient influence is undoubtedly present in concentration values where indoor air is, for example, 4x ambient concentration, as the multiple increases the likely contribution of ambient concentrations decreases.

[2] After considering multiple values for this factor, USEPA, in their residential database report (EPA-530-R-10-002), the agency selected 50x. This value was considered reasonable based on the authors' professional judgment and was used to allow consistent comparison to the USEPA report.

[3] After considering multiple values for this factor, USEPA, in their residential database report (EPA-530-R-10-002), selected 1000x. This value was considered reasonable based on the authors' professional judgment and was used to allow consistent comparison to the USEPA report.

- The variable AF_Data contained either the concentration or the AF across the building envelope, depending on whether the field "type" was set to indoor air, sub-slab soil gas or AF.
- Variables with names beginning with "Range" were used to bin certain fields into logical groups which were used in the box and whisker plots.
- Variables with names beginning "Flag" were used to implement the logic of the screening for background as discussed in **Section 5.3.5**.
- The variables "Minofsubslab" and "Maxofsubslab" contained the minimum and maximum sub-slab soil gas concentrations for the sample zone in question.

5.3.7 Grouping Data by Vapor Intrusion Conceptual Site Model

Vapor intrusion can conceptually originate primarily from groundwater, primarily from vadose zone sources, or from a mixture of these two cases. Thus, at the suggestion of the Navy, the sample zones were reviewed to designate sample zones as primarily influenced by vadose zone, groundwater, or mixed sources and classified as fitting a particular conceptual site model (CSM). Professional judgment was used to make these designations on a zone- and VOC-specific basis, considering the records available for the following four fields:

- Distance to primary release
- Primary release notes
- Ratio of maximum sub-slab soil gas concentration in a sampling zone to the maximum interpolated groundwater concentration
- Ratio of maximum sub-slab soil gas concentration in a sampling zone to the maximum measured groundwater concentration

Cases where the primary release was within 50 feet of the sample zone were given more weight relative to the potential for a vadose zone source. Cases with primary release distances of 10 feet or less were considered to be strongly indicative of a vadose zone source. Cases with ratios of sub-slab soil gas to groundwater concentrations close to or above unity were considered highly likely to reflect vadose zone sources. Cases with ratios below 0.1 were considered highly likely to reflect groundwater sources (USEPA, 2012b). Cases where these database records did not provide a clear answer to the person performing the classification were discussed with personnel familiar with the site-specific investigation work before a judgment was made.

5.3.8 Exploratory Data Analysis

According to USEPA (www.epa.gov/caddis/da_exploratory_0.html), an EDA is "an analysis approach that focuses on identifying general patterns in the data, and identifying outliers and features of the data that might not have been anticipated. EDA is an important first step in any data analysis. Understanding where outliers occur and how different environmental variables are related can help one design statistical analyses that yield meaningful results." According to Seltman (2009), EDAs are mainly used to detect mistakes, check assumptions, help preliminarily select appropriate models, determine relationships among explanatory variables, and assess the relationships between exploratory and outcome variables.

This report and its appendices will describe the dataset as a whole and then subsets of the dataset are sorted according to potential predictor variables using descriptive statistics such as:

- Minimum, maximum, mean, median, standard deviation
- Frequency of detection by analyte
- 5th, 25th, 50th, 75th, 95th percentiles

The primary graphical tool used in the EDA was a box and whisker plot (see **Figure 3-6** for example), which is a way of graphically describing the distribution of the data. For example, if the quartile marks are grouped closely at one end, but have greater spacing at the other end, the distribution is skewed toward the end with more spacing. At the top of the box and whisker plots, the number of ND samples in each category is given as "N(N)" as well as the number of detectable samples, "N(Y)". Data were plotted and analyzed using JMP® Software and the quartile box plot function are used to show quartiles of continuous distributions for data subset. As shown in the box plots, the ends of the box are the 25th and 75th quartiles, and the line across the middle of the box identifies the median sample value of dataset. The hollow circles represent the outliers of the dataset. The whiskers outside of the boxes located at the two ends of the box plots identify the maximum and minimum of the dataset.

The term "outlier" as used by JMP follows a standard statistical definition (Tukey's Method [Seo, 2006]). According to the Engineering Statistics Handbook:

> *"If the lower quartile is Q1 and the upper quartile is Q3, then the difference (Q3 - Q1) is called the interquartile range or IQ. A box plot is constructed by drawing a box between the upper and lower quartiles with a solid line drawn across the box to locate the median. The following quantities (called fences) are needed for identifying extreme values in the tails of the distribution:*
>
> - *Lower inner fence: Q1 - 1.5*IQ*
> - *Upper inner fence: Q3 + 1.5*IQ*
> - *Lower outer fence: Q1 - 3*IQ*
> - *Upper outer fence: Q3 + 3*IQ*
>
> *A point beyond an inner fence on either side is considered a mild outlier. A point beyond an outer fence is considered an extreme outlier."* (NIST/SEMATECH, 2013)

One way to evaluate the number of outliers is to consider the rule of thumb that "Less than 5% of the data should fall beyond the inner fences, even for very skewed distributions" (Dienes, 2011).[4] According to Kirkman (1996), "*Outliers are not necessarily 'bad' data-points; indeed they may well be the most important, most information rich, part of the dataset. Under no circumstances should they be automatically removed from the dataset. Outliers may deserve special consideration: they may be the key to the phenomenon under study or the result of human blunders.*"

The detected concentrations (in red) are graphed separately from ND concentrations (shown in blue at the reporting limit). In order to create the box and whisker plots, ranges of values for individual independent variables were selected. Ranges were selected to provide a tractable number of groups, to include a significant number of data points in most groups, and (when possible) to use familiar round values. In some cases where this presentation as box and

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[4] See also http://www.sinclair.edu/centers/mathlab/pub/findyourcourse/worksheets/Statistics/ConstructingBoxPlots.pdf.

whiskers for particular data ranges left unanswered questions, the data were also presented as XY graphs.

Descriptive statistics for filtered data groupings of soil gas and indoor air were prepared and reviewed for the following groupings by facility.

- By facility and building
- By building use (shop/industrial, office, warehouse, mixed, etc.)
- By sample zone use
- By building size
- By sample zone volume
- By HVAC type
- By sample zone interior ceiling height maximum
- By sample zone interior ceiling height minimum
- By flooring type
- By presence/absence of exterior wall
- By sample zone exterior wall
- By sample zone preferential pathway
- By sample zone subgrade structures (type such as vault, utility trench)
- By groundwater concentration
- By distance to primary release
- By sample zone soil type
- By building footprint area and groundwater concentration

Subsets of these data groupings for which analysis was conducted but were not selected as focus areas for the main body of the report are included in **Appendix D,** Exploratory Data Analysis, and **Appendix E,** Additional Results from Exploratory and Statistical Data Analysis.

5.4 Statistical Analysis

Statistical analysis was conducted to add mathematical rigor to the analysis begun in the EDA. Statistical methods were used to determine whether the apparent relationships were meaningful or "significant." The statistical analysis was used to evaluate the "outcome variable" (i.e., indoor air or sub-slab soil gas VOC concentration) using information about one or more "predictor variables." The predictor variables were based on characteristics of the buildings studied or the releases of VOCs to soil and groundwater that may contribute to vapor intrusion. Therefore, the predictor variable is defined as, "*the presumed 'cause' on a nonexperimental study*[5]." The outcome variable is also known as the dependent variable and is the effect being observed in this survey-based analysis.

Indoor air concentration was selected as the primary outcome variable because of the emphasis placed on it in regulatory management of VI sites. However, it is well known that indoor air concentration is an outcome that can be heavily influenced both by VI and background sources. Therefore, the datasets were reviewed after the various screening approaches discussed in **Section 5.3.5** were applied in order to assess the potential influence of background sources.

Sub-slab soil gas concentration was evaluated as a secondary outcome variable because:

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[5] http://www.indiana.edu/~educy520/sec5982/week_2/variable_types.pdf http://www.indiana.edu/~educy520/sec5982/week_2/variable_types.pdf

- The risk of future VI may exist at buildings with high sub-slab soil gas concentrations even if indoor air concentrations do not currently exceed risk-based target levels.
- It may provide some insight into potentially understanding factors controlling transport from a source through the vadose zone to the sub-slab.
- In this mechanistic context, sub-slab soil gas concentration would be considered by statisticians as an intervening variable, defined as *"A variable that explains a relation or provides a causal link between other variables."*[6]
- Sub-slab soil gas concentration is typically orders of magnitude higher than indoor air concentrations in cases of actual VI.
- Sub-slab soil gas concentrations are likely to be less vulnerable to confounding by indoor sources in situations where both indoor sources and sub-slab sources contribute to the observed indoor air concentration.

It is expected that no single predictor variable will fully explain the outcome variables such as indoor air concentration. VOC VI is generally believed to be at least as complex as radon VI, which has been the subject of hundreds of research papers. Lewis and Houle (2009) summarize the radon literature stating:

> *"This paper identified about thirteen factors that can affect radon variation…The thirteen factors being soil moisture content, soil permeability, wind, temperature, barometric pressure, rainfall, frozen ground, snow cover, earth tides, atmospheric tides, occupancy factors, season and time of day. One can see the complexity of understanding and studying radon variability in homes….. Four factors that influence radon concentrations indoors are properties of the building material and ground; building construction; meteorological conditions; and occupant activities"* (Lewis and Houle, 2009).

Lutes et al. (2013) found that temperature, snowfall, snow and ice accumulation, barometric pressure, and winds were factors explaining the temporal variability of PCE and chloroform VI in an Indianapolis duplex. Johnston and Gibson (2013a) performed an analysis of USEPA's VI database and reported that normalized indoor air concentration was a function of soil type, depth to groundwater, season, household foundation type, and contaminant molecular weight. Johnston and Gibson (2013b) also reported on a field study of a group of homes in San Antonio, Texas, that:

> *"We found that within any given home, indoor concentrations increase with the magnitude of the barometric pressure drop (P= .048)*[7] *and humidity (P<0.001), while concentrations decrease as wind speed increases (P<0.001) and also during winter (P= 0.001). In a second analysis to examine sources of spatial variability, we found that indoor air PCE concentrations between homes increase with groundwater concentration (P= 0.030) and a slab-on-grade (as compared with a crawl space) foundation (P= 0.028), whereas concentrations decrease in homes without air conditioners (P=0.015)"* (Johnston and Gibson, 2013b).

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[6] Miller, Robert S. http://www.indiana.edu/~educy520/sec5982/week_2/variable_types.pdf Course materials for Education 520, Indiana University "Strategies for Educational Inquiry" accessed 2015

[7] Here and throughout the report the p value is the probability of obtaining a result at least as extreme as the one observed assuming that the null hypothesis is true. It can also be seen as the probability that the observation is due to random variability alone.

Thus, while there is no consensus yet between studies as to which factors control VI, all studies concur that it is a complex process influenced by numerous climatic and building variables.

5.4.1 Linear Regression, Goodness of Fit and Significance of Slope

Linear regression analysis is one of the most widely used of all statistical techniques. In linear regression, the prediction of the outcome (Y) is a straight-line function of each of the X variables assessed independently. The slopes of the straight-line relationships with Y are constants, the coefficients of the variables. The constant is the change in the predicted value of Y per unit of change in X, all other things being equal.

R-squared is a measure of the goodness of fit of the regression, the "percent of variance explained" by the model. That is, R-squared is the fraction by which the variance of the errors is less than the variance of the dependent variable**.** Generally it is better to look at **adjusted R-squared** rather than R-squared. The adjusted R-squared is the R-squared, adjusted for the number of coefficients in the model relative to the sample size in order to correct it for bias. Despite the fact that adjusted R-squared is a unitless statistic, there is no absolute standard for what is a "good" value (Nau, 2015a).

A statistical test called a t-test can also be used to determine the significance of the slope of a linear regression fit. The null hypothesis in this hypothesis test could be stated as H0: slope = 0. If one does not reject the null hypothesis (i.e., the slope of the line is 0), then no further analysis is necessary, as one would then conclude that the linear relationship is not significant. The t-test concerning whether or not a linear relationship is significant (i.e., the test concerning a slope) is based on the assumptions that the relationship between two quantitative variables is indeed linear and that the variable Y has a normal distribution for each given value of X (Sprechini, 2015).

5.4.2 Mann-Whitney Test for Categorical Variables

In the NESDI database, many of the variables are categorical, observations that can be sorted into groups or categories rather than being described by a numeric value. Categorical variables have non-intrinsic ordering to the categories. Examples include soil type and presence/absence of and exterior wall in a sample zone.

To test the significance of these categorical variables, the Mann-Whitney test was used. The Mann-Whitney test is a nonparametric test that allows two groups or conditions or treatments to be compared without making the assumption that values are normally distributed[8]. The null hypothesis is that the distributions of the two groups are identical. The output of the Mann-Whitney test is a test statistic U, which is compared to tabulated critical values of U to determine whether the two different groups being compared are significantly different from each other. The likelihood that the observed difference between the two groups could be due to chance is expressed as the p value.

5.4.3 Multivariate Analysis Methods

After detailed discussion of the nature of this dataset with a statistician, it was decided to use multiple linear regression as the primary tool to explore interrelationships between multiple

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[8] Social Science Statistics, Mann-Whitney U-value Calculator http://www.socscistatistics.com/tests/mannwhitney/

predictor variables in this study (rather than using analysis of variance [ANOVA] for example). This analysis was performed using the "Real Statistics" add-in for Excel 2013. Categorical variables were represented in this analysis as indicator parameters. For example, the presence or absence of an exterior wall in the sample zone was conveyed with a 1 or 0. Season represented by winter = 1 was coded if a sample was collected during the 4 months from November through February. The analysis used the screened dataset – baseline + source strength + strict preferential pathway.

Analyses were performed separately for these high-priority outcome variables, which had large datasets available:

- TCE and PCE in indoor air (with and without a log transformation for indoor air)
- TCE attenuation factor
- TCE in sub-slab soil gas

A manual stepwise multiple regression was performed – narrowing in on the most important parameters (reduced model) based on a combination of reviewing p values, correlation analyses, and professional judgment. It is important to find reduced models that have strong predictive value for the outcome variable because models with large numbers of variables compared to the number of data points run the risk of "over fitting" the data. Over fitting is when the model fits the noise and not just the underlying relationship. When a model is over fitted to the dataset, the training dataset used to make the model may be well described, but the model may not correctly predict other related situations (Ye, 2010).

Literature indicates that there is no one best way to select the reduced model and that automated methods are not necessarily superior (Nau, 2015b). The multiple regression could only be performed on the data points that contained all of the predictor variables, so judgment was required to select an optimal combination that comprehensively considered the potential predictor variables but included the most extensive a dataset as possible. The analysis in this project began with numerous individual predictor variables. Variables were then added to account for interaction/cross terms describing how groundwater concentration interacted with depth to groundwater and groundwater concentration. The results of the Abreu/Johnson 3D model were used as an approximate guide for selecting the form of these terms to test (USEPA, 2012b). Figure 8 in the USEPA (2012a) document (not reprinted here) shows the effect of groundwater source depth on soil vapor distribution in a case with the source located directly under the building. In those cases, the soil vapor concentration under the building, as fraction of groundwater (gw) vapor, were as follows:

- 3 m (9.8 feet) below slab: 0.5 to 0.9
- 8 m (26.2 feet) below slab: 0.3 to 0.5
- 18 m (59.0 feet) below slab: 0.1 to 0.3

Therefore, this study tested variables for [gw]/depth and [gw]/(depth)$^{0.5}$ in an attempt to approximately fit this modeled relationship. Similarly, based on an examination of the trends in **Figure 5-7**, the study tested the variables of forms to describe the effect of lateral separation between the building and the plume:

- [max gw]/(max well distance)
- [max gw]/(max well distance2)

- [max gw]/(max well distance3)

Linear regression models can only be run if the number of variables is less than the number of data points (model is not saturated). Ideally, a multiple regression should have at least 10 observations per predictor variables (Ye, 2010); thus, larger vapor intrusion datasets than the one collected for this project will likely be needed.

5.5 Refining the VI Decision Framework

A decision framework is an "evidence based, practical" structure to guide the making of decisions (Ottawa Hospital Research Institute, 2014). It describes the information gathered as inputs to the decision and how the inputs are evaluated or weighted to arrive at the decision. In order to prepare a quantitative decision framework based on the results of this research, several possible technology transfer formats were considered.

A combination of a flowchart with an embedded scoring approach was ultimately selected and is described in **Section 7**. The flowchart and embedded scoring system that is similar to the format used in the Interstate Technology and Regulatory Council (ITRC) Petroleum VI document (ITRC, 2014). This format was selected because:

- The flowchart shows the overall process step-by-step and provides "off ramps" for clear-cut cases. Harder cases requiring a more nuanced analysis would lead the reader to a scoring box.
- The scoring scheme allows a more in-depth evaluation of "grey zone" cases using multiple lines of evidence leading to a "vapor intrusion prioritization score."
- The range of weights in the scoring system are tailored to emphasize the importance of certain predictor variables.
- The vapor intrusion prioritization scoring system was designed to be centered on zero points. In general, zero points is assigned either to the presence of information that suggests average risk OR the absence of information. Thus, the same scorecard can be used with different amounts of data.
- Point totals are used to prioritize sites for further vapor intrusion investigation or pre-emptive mitigation.
- A separate, additional uncertainty score is then computed based on the number of missing lines of evidence.

The unit of analysis chosen for the scoring system was the sample zone, because that was the primary unit of analysis in our project. However, the scoring system can be used to prioritize buildings by considering the highest scoring regularly occupied zone within each building. Similarly, sites could be prioritized by evaluating the buildings proximate to that site individually and considering the number of high-priority buildings in each site.

In this database, the size of some of the enclosed areas (sample zones) [9] is quite large. For example 56 of the 151 sample zones with data in the database are between 1,001 and 10,000 feet^2 and 20 are greater than 10,000 feet^2.

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[9] The Sample Zone concept in the database represents an enclosed location within a building where at least one indoor air sample has been collected. The conceptual idea that best represents Sample Zone is a box. A Sample Zone should have limited air mixing with other Sample Zones.

6.0 RESULTS

This section provides a summary of the EDA, quantitative data analysis, and multivariate analysis conducted as part of this study. Additional analysis, not specifically discussed in the text below, is included in **Appendix E**.

6.1 Exploratory Data Analysis

The EDA conducted as part of this study included a wide range of variables and was used to identify the general trends in the dataset and prioritize variables for quantitative analysis. The EDA was conducted using the total dataset collected, prior to conducting data screening/filtering intended to separate cases where vapor intrusion is the predominant cause of the indoor air concentrations observed from cases where indoor sources are the predominant cause. The EDA was conducted after the analysis of the impact of nondetectable results described in **section 5.3.2**. This approach was selected because the available screens are inevitably imperfect, potentially eliminating some true cases of vapor intrusion and/or retaining in the datasets some data potentially influenced by indoor sources.

The most significant findings and insights from the EDA (presented in detail in **Appendix D**) that were carried through for additional evaluation included:

- <u>Relationship between Sampling Zone (and Building) Size to Indoor Air Concentrations:</u> Plots of the normalized indoor air concentration vs. sampling zone size (**Appendix D**, page 9) suggested that PCE indoor concentrations decreased significantly (by up to orders of magnitude) with increasing building size. This was consistent with the hypothesis that larger buildings provide more volume for dilution in cases where VI occurs in only a portion of the building. For example, the same mass of volatiles would result in higher concentrations in a small versus large building because of dilution and mixing. A similar pattern was observed for PCE with sample zone footprint. However, the same pattern was not immediately apparent with the other VOCs.
- <u>Relationship of Sub-slab Soil Gas to Indoor Air Concentrations:</u> Plots of indoor air concentration vs. sub-slab soil gas concentration (**Appendix D**, page 14) before screening generally displayed a “hockey stick” shape with an inflection point. These plots indicated that sub-slab soil gas concentrations in the lower range (below the inflection point) have no apparent effect on indoor air concentrations, and suggested that in this range the measured indoor air concentrations are background-related. Sub-slab soil gas and indoor air concentrations at or above the inflection points appear to be correlated. The inflection point for commercial/industrial/institutional buildings is generally higher than would be implied by current regulatory approaches, such as the USEPA Vapor Intrusion Screening Levels (VISLs) (USEPA, 2014) or in various state guidance or screening levels. In this document, all reference to VISLs are calculated based on a commercial exposure scenario, with a target risk for carcinogens of 1E-06 and a target hazard quotient for non-carcinogens of 1.
- <u>Relationship of Groundwater to Indoor Air Concentrations:</u> Plots of indoor air concentration vs. groundwater (**Appendix D**, page 14) concentration before screening showed indoor concentrations as usually relatively constant until an inflection point is reached. This pattern appeared to be present even before completing the background screening steps or fully considering the proximity of vadose zone sources. Similar to the pattern observed with sub-

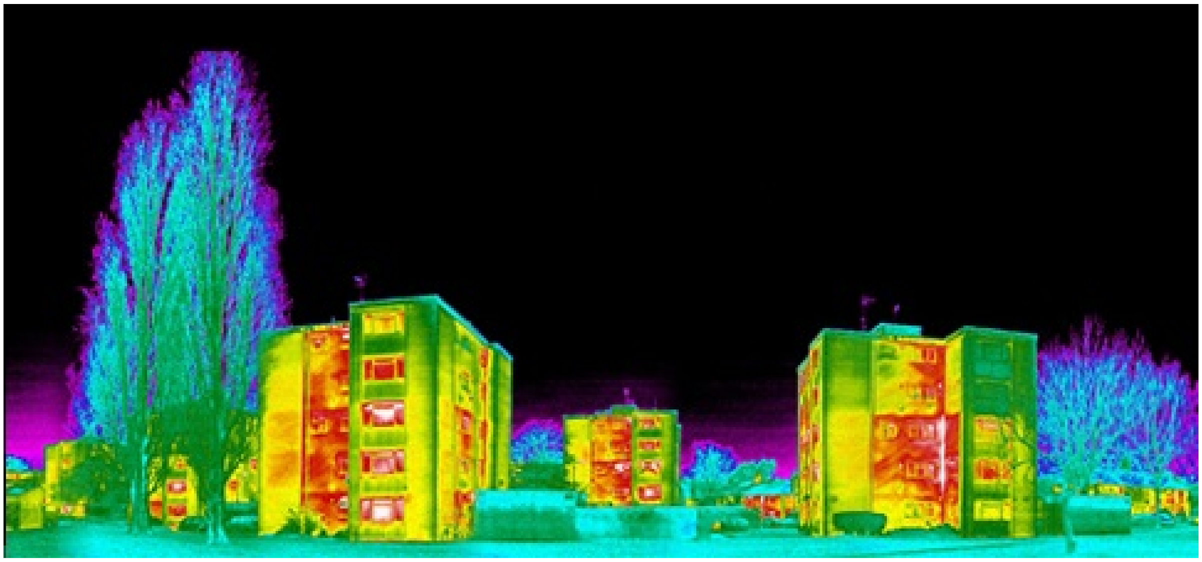
slab soil gas vs. indoor air concentrations: (1) groundwater concentrations below the inflection points appear to have no apparent effect on indoor air concentrations; (2) it is conceivable that concentrations at or above the inflection points may be correlated; and (3) the inflection point for commercial/industrial/institutional buildings is generally considerably higher than would be implied by current regulatory screening approaches.

- Soil Type: Plots of indoor air concentration vs. soil type suggested that indoor air concentrations may be higher for buildings with fine soils than coarse soils (**Appendix D**, page 13).
- Exterior Wall: Plots of indoor air concentrations in the presence or absence of an exterior wall suggested that higher indoor concentrations may be more frequent in sample zones with an exterior wall. Higher sub-slab soil gas concentrations were also observed in sample zones with an exterior wall (**Appendix D**, page 10).
- Source Strength and Distance vs. Indoor Concentration: Plots of indoor air concentration vs. sub-slab soil gas concentration suggested source strength and distance correlate with the potential for significant indoor air impacts (**Appendix D**, page 14).

Predicting VI due to a distant soil gas or groundwater source is a complex multi-step process. Therefore, it is not surprising that some of the single variables explored in the EDA did not in and of themselves appear to be good predictors of indoor air concentrations from VI. Additionally, because the EDA was conducted utilizing existing data rather than collection of new data with a specifically designed protocol, there are inherent uncertainties for some variables in the individual site reports that were used to populate the NESDI database.
In many cases, there is such a multiplicity of types and conditions present in the field that simple classification into a small number of bins was challenging and further evaluation is not warranted under this project. These variables would require a more extensive and nuanced data collection process. Examples include variables such as the HVAC type and flooring material. For completeness, **Appendix E** includes additional exploratory and statistical level analyses performed that were not discussed in the EDA technical memorandum (**Appendix D**) or in the main body of this report. These analyses can be used to plan future studies.

Further analysis of preferential pathway influence was conducted as suggested in the Preliminary EDA Technical Memorandum that is included in **Appendix D**. The presence or absence of a significant preferential pathways is a widely discussed subject in VI guidance documents. As discussed in **Section 5**, preferential pathways were originally categorized in the database with a somewhat inclusive definition and a "strict" definition was added during data analysis. Regardless of definition, the presence of observable, atypical preferential pathways was not consistently associated with higher indoor air concentrations in this dataset (**Appendix E,** although there were individual cases where preferential pathways were associated with high indoor TCE concentrations), nor did the presence of atypical preferential pathways have a consistent or substantial effect on the distribution of concentrations in sub-slab soil gas (**Appendix E**). Therefore, preferential pathways are not discussed further in this section. However, this does not mean that at an individual building scale preferential pathways are not an important contributor to mass transport. As shown in thermal images, such as **Photographs 6-1 and 6-2** all building envelopes have a continuum of air gaps of differing sizes, so that portions of the envelope are more important than others in transmitting flow. The finding of this database analysis likely suggests that current visual means of assessing the building envelope to determine how "leaky" a floor system is based on the observation of discrete macroscale features is inadequate. It is possible that improved methods to find or define preferential pathways could be developed in the future.

The EDA conducted and summarized in **Appendix D** also suggests the possibility of focusing VI evaluations on a number of key compounds. For example, TCE and PCE were the most commonly detected chlorinated VOCs in the indoor air data set (50 and 49%, respectively). The other chlorinated VOCs/biodegradation products that were detected included cis- and trans-DCE, 1,1-DCE, 1,1-DCA, 1,2-DCA, 1,1,1-TCA, and vinyl chloride. The EDA suggested that subsurface sources of vinyl chloride do not generally result in significant VI impacts, which may be related to its aerobic biodegradation potential. 1,1,1-TCA concentrations, while somewhat more frequently detected, were well below risk-based screening levels, so discriminating VI from background sources may not be needed. However, it was determined that the available dataset was not sufficient to fully explore topics such as the occurrence of 1,1,1-TCA and vinyl chloride.



Photograph 6-1:
Thermal Camera Image of Multiple Buildings, Showing a Continuum of Thermal Heat Loss Reprinted from http://energy.mae.cornell.edu/images/hvac.jpg

Photograph 6-2:
Thermal Camera Image Taken within a Building, Showing how Preferential Heat Flow Occurs at Locations that Appear Visually Well Sealed
Reprinted from http://homeenergypros.lbl.gov/profiles/blogs/infrared-imaging-uncovers-many

6.2 Quantitative Analysis

The EDA was used to choose a limited number of predictor variables in the database on which to focus a more quantitative analysis. As discussed in **Section 5** and although statistical tests were used to evaluate the significance of the slope, correlation coefficients were computed, and probability values (e.g., p-values) were reported to provide a sense of the strength of the observed correlations, these values must be used with caution, since this is an observational and not an experimental study. The sample buildings and locations in this study were not randomly selected.

6.2.1 Factors Affecting Sub-slab Soil Gas Concentrations

Sub-slab soil gas concentrations were analyzed as an outcome variable because of the importance of these concentrations in management of future risk at vapor intrusion sites. Sub-slab soil gas concentration is also an intermediate variable that allows isolation of the geological processes involved in vapor intrusion and separates them from the building envelope processes. Since sub-slab soil gas concentrations are less vulnerable to being dominated by indoor sources, the unscreened datasets are used for most of the analyses of sub-slab soil gas data presented.

6.2.1.1 Groundwater Concentration

Groundwater concentrations were recorded in the database in four fields:

- Measured maximum concentration within 100 feet of the sample zone
- Measured minimum concentration within 100 feet of the sample zone
- Interpolated maximum concentration under sample zone
- Interpolated minimum concentration under sample zone

Those concentrations were then converted into "groundwater vapor" concentrations expected directly above the water table based on Henry's Law.

Interpolation of groundwater concentrations under the sample zone was almost always based on monitoring wells located exterior to the building. Therefore, it would not generally take into account any potential increase of groundwater concentration beneath the building that may occur if there is a capping effect associated with the building (Schumacher et al., 2010). Interpolation procedures generally relied on existing site isoconcentration maps (see detailed discussion in **Appendix C**).

As expected and where there were sufficient data to provide an adequate sample size for analysis, sub-slab PCE and TCE soil gas concentrations increased with increasing groundwater concentrations (**Figures 6-1** and **6-2**). This observation does not, however, provide information on whether the vadose zone soils or groundwater are currently serving as the primary source of contaminant mass, nor does it provide information on whether leaching from soil to groundwater or volatilization from groundwater to soil gas, dominate the mass transfer at the time of sampling. The observation does show that the two lines of evidence, groundwater and sub-slab soil gas, will generally be correlated. In general, the trends are clearer for the maximum measured groundwater concentration at wells within 100 feet of a sampling zone perimeter as compared to the maximum interpolated groundwater concentration beneath the zone, so the maximum measured concentrations were used to prepare the graphs.

The correlation between groundwater vapor concentration and sub-slab soil gas concentration for PCE appears approximately linear on a log-log plot, suggesting a power law relationship between the two variables (**Figure 6-1**; log-log plot $r^2=0.43$; $p < 0.001$). The correlation between measured maximum groundwater vapor concentration (the predicted soil vapor concentration at the water table based on Henry's Law) to sub-slab soil gas concentration for TCE (**Figure 6-2**; log-log plot $r^2 = 0.082$; $p<0.001$) and for cis-1,2-DCE (log-log plot $r^2=0.077$, $p=0.169$) were weaker. This weaker correlation for the lower chlorinated compounds TCE and cis-1,2-DCE compared with PCE may be due to their greater aerobic biodegradability (AFCEE, 2004).
In **Figures 6-1** and **6-2**, the current USEPA (2014) sub-slab soil gas VISL for industrial buildings are represented with purple dotted horizontal lines (470 micrograms per cubic meter [$\mu g/m^3$] for PCE and 30 $\mu g/m^3$ for TCE). The current USEPA groundwater VISLs for industrial buildings are represented with purple dashed vertical lines (64 micrograms per liter [µg/L] PCE in groundwater = 47,000 $\mu g/m^3$ groundwater vapor; 7.4 µg/L TCE = 3,115 $\mu g/m^3$). The green dotted line represents an "Empirical sub-slab soil gas screening level" derived from the analysis of sub-slab soil gas to indoor concentrations for DoD commercial/industrial buildings presented in **Section 6.2.2**. A red line on the figures shows a 1:1 correspondence between sub-slab soil gas and groundwater vapor concentrations. The limited number of cases above the red line where the sub-slab soil gas concentration exceeds the groundwater vapor concentration strongly suggests a predominant vadose zone source near the building. Based on the data from this project, a green dashed line was plotted to show the approximate empirical screening levels in groundwater for DoD commercial/industrial buildings. This empirical screening level in groundwater represents a concentration sub-slab soil gas attributable to groundwater that would be expected to be sufficient to lead to exceedances of the VISL in indoor air in DoD

commercial/industrial buildings (PCE 650 μg/L in groundwater = 470,000 μg/m^3 groundwater vapor; TCE 72 μg/L = 30,000 μg/m^3).

In selecting these approximate empirical screening levels in groundwater for DoD commercial/industrial buildings, data points were not considered where the sub-slab soil gas concentrations exceeded the groundwater vapor concentration because they likely result from vadose zone sources. A number of points were included that fall just below that line and therefore may be influenced by vadose zone mass storage. Results in the USEPA (2012b) VI Conceptual Model Scenarios document suggest that groundwater vapor to sub-slab soil gas ratios of 0.1 to 0.8 are common especially with strong sources directly under buildings. For example, in **Figure 6-1** for PCE, a group of five data points clustered near the intersection of the two green lines, just below the red line. If those points had also been included even though they were due to vadose zone influence, the selected empirical screening level in groundwater would have been several times higher.

Thus, this analysis suggests that DoD industrial/commercial buildings could be evaluated using groundwater screening levels at least an order of magnitude less conservative than suggested by the current industrial/commercial USEPA (2014) VISLs while maintaining protectiveness. Note that there are likely fewer vadose zone sources in the USEPA (2012a) residential data set than in this DoD dataset given the location of the primary vadose zone releases at industrial/commercial compared with residential buildings. In many cases, primary vadose zone releases are much closer to industrial/commercial compared with residential buildings.

The majority of groundwater vapor concentrations (the predicted soil vapor concentration at the water table based on Henry's Law) were greater than the sub-slab soil gas concentrations; which would be the expected in a classic CSM scenario where groundwater is the primary source of vapors. In many cases the degree of concentration reduction in the soil column is higher than suggested in the USEPA VISL calculations (0.01). A reanalysis of the USEPA database (Yao et al., 2013a) shows most of the values in that database lie between 0.1 to 0.001 for this ratio (also known as the soil attenuation factor or AF_{soil}).

Yao's et al. (2013) study indicated considerable variability in sub-slab soil gas concentration corresponding to a given groundwater vapor concentration (**Figure 6-3**). The study indicated that depth-to-groundwater variation and building construction/operational factors are insufficient to explain this variation; rather, they point to low-diffusivity moist soil layers, and the lateral displacement of the source from the building as important explanations for high degrees of attenuation in the vadose zone.

6.2.1.2 Building Dimension Effects

The walls that define the sample zone in the building interior are not consistently reflected in sub-slab features. Therefore, a discussion of sub-slab soil gas concentrations is not included, as the concentrations may be influenced by sample zone; rather, the discussion is focused on building area.

The relationship between building height and sub-slab soil gas concentration, which appears to be confounded by building use is discussed in **Appendix E**.

6.2.1.3 Building Area

Several studies (USEPA, 2009a, 2012b; Shen et al., 2013) indicate that concentrations in soil gas and groundwater beneath a building slab or other lower permeability surface are increased by a capping effect that limits volatilization from groundwater to ambient air, especially below the center of a large building and suggesting higher sub-slab soil gas concentrations beneath large buildings, given a constant groundwater plume strength.

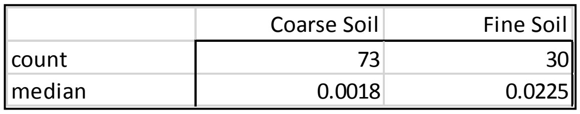
No consistent pattern was observed in the dataset relating sub-slab soil gas concentration to building area across most compounds (**Appendix E**). However, a trend was apparent that the intermediate biodegradation products cis-1,2-DCE and 1,1-DCA were unlikely to be present in high concentrations under small buildings, and more likely to be observed under large buildings. The spread of observed concentrations was very large beneath the largest buildings (**Figures 6-4** and **6-5**). This result is not statistically significant for cis-1,2-DCE, but was statistically significant for 1,1-DCA (r^2=0.14, p=0.003), and is potentially physically meaningful because in the presence of degradable organic material (e.g., petroleum hydrocarbons), the formation of degradation products are more likely (AFCEE, 2004; Abreu et al., 2013). This could be an important result for long-term site management because the current commercial building VISL at 1E-06 target risk level for 1,1-DCA is 77 $\mu g/m^3$, a concentration that was exceeded in many samples in the database. The amount of information in the database, however, was insufficient for the confident calculation of an alternate screening level for DoD buildings for this compound.

6.2.1.4 Soil Type Effects

Higher sub-slab soil gas concentrations associated with fine (i.e., silt or clay) soil types are apparent in the medians and 75th percentiles of the datasets for PCE; TCE; cis-1,2-DCE; trans-1,2-DCE; 1,1,1-TCA; 1,1-DCA; and 1,1-DCE as shown in box and whisker plots (**Figures 6-6** through **6-12**). The Mann-Whitney test establishes the statistical significance of this effect for PCE; TCE; trans-1,2-DCE; cis-1,2-DCE; 1,1,1-TCA; and 1,1-DCE. This effect appears quite strong, with the median concentration in fine soils exceeding the median concentration in coarse soils by 20 times for PCE and TCE.

Fine soils also appear to significantly increase the likelihood of detection of 1,1-DCE (two tailed p<0.001). The difference in detected sample distributions was not significant for 1,1-DCA by the Mann-Whitney test, but the odds of detecting 1,1-DCA beneath buildings overlying fine soils were significantly higher (**Figure 6-11**). Few detections of 1,2-DCA and VC were included in the database. Therefore, while the odds of detecting these compounds appeared somewhat higher for fine soils, the result did not quite reach statistical significance (two tailed p=0.12 for 1,1-DCA and two tailed p=0.065 for VC).

This effect was also tested on the normalized sub-slab soil gas concentration (AF_{soil}= Css/Cgw). For PCE, there was a statistically significant difference in the means by the Mann-Whitney test (two tailed p<0.001). As shown in the table below there were 73 coarse soil samples vs. 30 with fine soils. The median sub-slab concentration for coarse soil was 12.5 times lower than that for the fine soil cases.



	Coarse Soil	Fine Soil
count	73	30
median	0.0018	0.0225

For TCE the difference was also statistically significant by the Mann-Whitney test (two tailed $p<0.001$)

	Coarse Soil	Fine Soil
count	96	94
median	0.0009	0.0248

These results suggest a higher soil gas concentration in fine soils and may have a physical explanation. Fine soils can result in a more even soil moisture distribution from the water table to the surface, which some modeling studies suggest would result in significantly higher sub-slab soil gas concentrations in fine soils. Although fine soils are generally expected in the vapor intrusion literature to be protective by reducing the rate of contaminant migration through advection and diffusion from groundwater (USEPA, 2012a; Johnston and Gibson, 2013a) there are indications in the literature that an opposite effect may in fact occur. Shen et al. (2013) suggest that the Van Genuchten moisture curve for clay explains why moist soils are present up much closer to the foundation and, thus, that at equilibrium the concentrations from a groundwater source will be higher beneath the building (**Figure 6-13**) in the clay case. In sand, the moisture distribution curve is different, and thus there is a much sharper concentration drop off in VOCs that occurs just above the water table at the capillary fringe.

In cases where the point of release is in or near the building being sampled, the literature also suggests that fine soils would tend to trap contaminants in the vadose zone near the building and would diminish the effectiveness of natural attenuation processes such as volatilization attributable to barometric pumping and leaching (Clement et al., 2000; Suthersan, 1996; SERDP/ESTCP, 2006). In contrast to USEPA (2012a) residential database, it would be expected that many of the buildings in this dataset would be at or near the location of the primary release. Also, given the substantial presumed age of most of the contaminant releases in this study, the sites are most likely at quasi-equilibrium. Finally, note that high sub-slab soil gas concentrations do not necessarily correspond to high contaminant fluxes available for VI.

6.2.1.5 Distance to Primary Release

For most compounds and as expected, sub-slab soil gas concentrations were highest when distance from the sample zone to the primary release was low. This trend was observed for PCE (**Figure 6-14**; $r^2=0.20$ $p<0.001$), TCE (**Figure 6-15**; $r^2=0.37$ $p<0.001$), 1,1-DCA (**Figure 6-16**; $r^2=0.74$ $p<0.001$). The proportion of variability explained by this variable (r^2) was one of the highest for any variable evaluated in this project.

There was insufficient available information about distance to primary release and/or detectable sub-slab soil gas data to reach a reliable conclusion regarding cis-1,2-DCE; vinyl chloride; TCA; and 1,2-DCA (**Appendix E**). Trans-1,2-DCE appears to be an exception that does not fit this trend (**Figure 6-17**) although the number of data points this is based on is modest. It is possible that trans-1,2-DCE concentrations do not peak at the point of release because it is formed as an intermediate degradation product. The database does not include information about the direction of the groundwater flow.

6.2.2 Factors Affecting Indoor Air Concentrations

This section presents information about indoor air concentrations relative to concentrations in other environmental media through which vapor intrusion contaminants travel before entering indoor air:

- Sub-slab soil gas
- Groundwater

This section also includes a discussion of predictor variables prioritized for additional analysis based on the EDA:

- Building and sample zone dimensions
- Exterior wall (present in sample zone)
- Source strength and distance

The R-squared (r^2) coefficient of determination is used throughout this study as a measure of goodness of fit for models (linear equations) relating the indoor air concentrations to these variables. As noted in **Section 5**, r^2 values do not necessarily need to be high for the analysis to provide useful information. Most environmental sampling and analysis methods for trace concentrations in air (such as USEPA Method TO-15 [USEPA, 1999]) have substantial sampling and analysis uncertainty. Method TO-15 calls for replicate precision within 25% relative percent difference and audit accuracy of 30%; however, the results of inter-laboratory comparison studies of analysis of known standards suggest that even larger differences routinely occur between competent laboratories (Lutes et al., 2012). Therefore, a high r^2 will be very difficult to achieve for any set of variables used to predict observed trace indoor concentrations without over-fitting the particular dataset (Lehmann, 1975; Schunn and Wallach, 2005). Although beyond the scope of the current project, in future work more sophisticated measures of goodness of fit such as deviance, or the Akaike Information Criterion, could be employed. As a step in performing quantitative analyses on the indoor air data, screening/filtering was conducted to minimize the effects of indoor sources and strictly defined preferential flow pathways (**Section 5.3.5**). The numbers of detectable results in indoor air retained after each screening step are summarized in **Table 6-1**.

6.2.2.1 Indoor Air vs. Sub-slab Soil Gas Concentration

The relationship of indoor air concentration to sub-slab soil gas concentration is discussed in this section using the Baseline screen + Source strength screen + Preferential pathway=false dataset (this shortened nomenclature refers to a dataset in which the baseline and source strength screens have been applied, as well as the strict atypical preferential pathway screen). This dataset provides the best balance between adequately excluding data controlled by indoor sources, while retaining as many data points as possible for analysis.

As shown in **Table 6-2**, there was a wide range of detection limits associated with the non-detect (ND) results. Elevated detection limits are commonly caused by the interference of another target or non-target VOC that requires sample dilution. However, laboratories and sampling/analysis methods can differ substantially in detection limits even in the absence of an interference. Therefore, this dataset is presented two ways:

- With indoor air concentrations and sub-slab soil gas concentrations each averaged across the sample zone, including only detectable results.
- With indoor air concentrations and sub-slab soil gas concentrations each averaged across the sample zone, with ND results included at the detection limit.

Averaging across the sample zone was required because there is not a one-to-one physical correspondence between indoor air and the directly underlying sub-slab soil gas. Rather, soil gas anywhere within the sample zone can infiltrate into indoor air and then be rapidly mixed throughout the indoor air compartment. Examining the dataset with only detectable results was desirable because in some cases detection limits were elevated (**Table 6-3**). On the other hand, many ND results provide useful information that could indicate that contaminants are absent in indoor air despite substantial sub-slab soil gas concentrations. In cases where at least one sample within a sampling zone contained a detectable concentration and passed the source strength screen, inclusion of ND sub-slab soil gas concentrations in the zone average provides useful information to refine the sub-slab soil gas concentration average.

As shown in **Appendix D**, plots of indoor air concentrations vs. sub-slab soil gas concentration before screening generally displayed a "hockey stick" shape. These plots indicated that sub-slab soil gas concentrations in the lower range (below the inflection point) have no apparent effect on indoor air concentrations, suggesting that in this range the measured indoor air concentrations are background-related. Sub-slab soil gas and indoor air concentrations at or above the inflection points appear to be correlated. The inflection point for industrial buildings is generally considerably higher than would be implied by current regulatory approaches, such as the USEPA VISLs (2014) or in various state guidance or screening levels. The outcome of this analysis could be expressed either as industrial building sub-slab soil gas screening levels for PCE, TCE, and other compounds, or AFs that will be less conservative than those derived from residential datasets.

After screening/filtering (baseline, source strength, and preferential pathway) and averaging across sample zones, the lower portion of the "hockey stick" plots is no longer visible for PCE and TCE. Rather and as shown in **Figures 6-18** through **6-21**, plots of PCE and TCE show a correlation between sub-slab soil gas and indoor air, with only very high sub-slab soil gas concentrations causing indoor air concentrations in excess of conservative indoor air screening levels. As expected, the source strength screen removes the lower portion of the "hockey stick" plot – the region of lower sub-slab concentrations where there is no discernable relationship between sub-slab and indoor air concentrations. For example, PCE concentrations in sub-slab soil gas in excess of 100,000 µg/m^3 are required before concentrations in indoor air exceeded the USEPA (2014) industrial/commercial indoor VISL of 47 µg/m^3. TCE concentrations in excess of 2,000 µg/m^3 were needed in sub-slab soil gas before indoor concentrations exceeded the industrial/commercial indoor VISL of 3.0 µg/m^3. These empirical screening levels supported by the NESDI data set have been graphed with green lines and the current USEPA (2014) VISLs have been shown with purple lines on the figures.

Note that if TCE NDs are included in the dataset, then two data points marked by light blue crosses contradict the preceding conclusion. However, those points are a direct result of elevated detection limits in indoor air sampling due to laboratory performance limitations. If expressed as indoor-to-sub-slab soil gas ratios (i.e., attenuation factors; shown as the diagonal lines in the graphs), these PCE and TCE plots suggest that the use of an AF of 0.001 for military commercial/industrial buildings is appropriate in the absence of atypical preferential pathways. This value is 100 times less conservative and more representative than the value of 0.1 currently in use in the USEPA VISLs for both the residential and commercial scenarios (USEPA, 2014). However, it would only be 10x less conservative than 95th percentile value (0.01) for residences with slab-on-grade construction derived in USEPA 2012a. Olson and Alexander (2014) recently published an analysis of the nonresidential data in the USEPA database, along with a roughly equal number of nonresidential samples from North Carolina drycleaner sites. The Olson and Alexander study applied a similar set of screens derived from the USEPA residential screens and concluded that a sub-slab soil gas to indoor air attenuation factor of 0.01 would be "adequately protective 99% of the time."

It is also notable that these plots after screening do not have the puzzling characteristic that a recent reanalysis by Yao et.al. (2013a) pointed out in the unscreened USEPA residential database – a much greater degree of variation in concentration in sub-slab soil gas concentration than in the corresponding indoor air concentrations. Yao et al. (2013a) remarks that the USEPA database indoor concentrations generally span only three orders of magnitude, but that there are six orders of magnitude in sub-slab soil gas variability and hypothesizes that there may be a previously unidentified "physical restraint of some kind on indoor air data." The screened/filtered, zone averaged PCE and TCE plots in this industrial/commercial database show approximately an order of magnitude more variability along the sub-slab soil gas concentration axis compared to the indoor air concentration axis.

The plots for cis-1,2-DCE take on a different appearance (**Figures 6-22** and **6-23**) because, as discussed in **Section 5.3.5**, no background concentration was consistently observable in non-impacted buildings for that compound. Thus the source strength filter is moot for cis-1,2-DCE. Note that on the plot that does not include NDs, a single data point symbolized by a green triangle is observed that results from a situation in which one high concentration indoor air concentration occurred in the midst of a significant number of NDs for that zone. When plotted with NDs averaged in at the detection limit, that point is no longer an outlier from the pattern. The cis-1,2-DCE dataset as a whole suggests relatively little effect of sub-slab soil gas concentrations on indoor concentrations and that exceedances of the 186 $\mu g/m^3$ concentration level in indoor air are rare at DoD sites. This value is used as a basis for comparison, although it is recognized that the VISL has been rescinded for cis-1,2-DCE.

In order to understand how the sample zone averages were affected by variability within the sample zone (either temporally or spatially) the degree of variability expressed as maximum over minimum was tabulated (**Table 6-4**). Of the 93 sample zones with PCE data, only five contained observed sub-slab soil gas variability of more than one order of magnitude and only 20 contained observed sub-slab soil gas variability of greater than three times. High degrees of

sub-slab soil gas variability were observed in cases with both large (>10,000 ft^2) and small (<1,000 ft^2) sample zone areas. Only five sample zones had more than an order of magnitude of PCE indoor air variability (**Table 6-4**). However, the observed degrees of variability are not necessarily indicative of the total degree of potential variability because in many cases, only one or two sub-slab soil gas and indoor air samples were collected within a given sample zone.
For TCE, six out of 104 sample zones had more than three orders of magnitude of observed sub-slab soil gas variability, 14 had at least one order of magnitude of observed sub-slab soil gas variability, and 28 had more than 3x sub-slab soil gas variability (**Table 6-5**). As was seen with PCE, TCE sub-slab soil gas variability was high both in some very small and large sample zones by area. Indoor air variability was more than two orders of magnitude in two sample zones and more than one order of magnitude in 12 sample zones. Similar to PCE, the degree of observed variability in many cases is limited by the small number of samples collected.

In this dataset, the combined temporal and spatial variability in sub-slab soil gas was greater than that in indoor air. There is relatively little information in the database on temporal variability; there are less than a dozen buildings with useful examples of indoor air temporal variability data. The vast majority of the cases have about one order of magnitude or less temporal variability in either sub-slab or indoor air. No case has more than three rounds of indoor air data. Studies by McHugh et al. (2007) have generally found markedly less variability in indoor air concentrations than in sub-slab soil gas concentrations, likely due to the greater degree of mixing in the indoor environment. Sub-slab soil gas variability that has been observed in previous single building studies includes:

- Residential, Layton, Utah – 10-100 times spatial and 10 times temporal variability (Holton et al., 2013)
- Residential, Indianapolis, Indiana – 250 times spatial and 10-100 times temporal variability (Lutes et al., 2014)
- Six orders of magnitude in sub-slab soil gas concentration variability were reported by Eklund and Burrows (2009) for one building of 8,290 $feet^2$
- Schumacher et al. (2010) observed more than three orders of magnitude concentration variability in shallow soil gas below a slab near a military industrial building over a span of 50 lateral feet
- Lee et al. (2010) observed two orders of magnitude variability in sub-slab soil gas concentrations within a small military townhouse.

Thus, the observed degree of variability in the NESDI database cases appears typical of that reported by others.

6.2.2.2 Indoor Air vs. Groundwater Concentration

In the EDA (**Appendix D**), the dataset was examined using all of the four groundwater data fields (introduced in **Section 6.2.1**). Generally, the results of the analysis were similar. The dataset and results of the analyses are discussed below based on the maximum measured groundwater vapor concentration. USEPA presents its database analysis of residential vapor intrusion using groundwater depth bins, the shallowest of which is <1.5 m (4.9 feet) (USEPA, 2012a). That database is used to derive normalized indoor concentrations using ratios or attenuation factors (AF_{vi}) at each depth interval. The strongest break point in the USEPA (2012a) data analysis is generally assumed to occur where groundwater is 1.5 m (approximately 5 feet) below ground surface (bgs), and thus screening using groundwater-to-indoor air AFs is often only conducted with groundwater deeper than 5 feet. The NESDI dataset was also plotted after excluding data points with depth to groundwater of less than 5 feet (**Appendix E**); however, this did not meaningfully change the interpretation and therefore, a depth-to-groundwater screen/filter was not incorporated in the data screening/filtering process.

As shown in **Appendix D**, when indoor TCE concentration is plotted as a function of groundwater concentration without screening/filtering the data, increased measured maximum groundwater concentrations are generally associated with increased indoor air concentrations once aqueous TCE concentrations exceed approximately 100 µg/L (corresponding to a groundwater vapor concentration of 42,000 µg/m^3). However, there is considerable scatter in the data, so that any given groundwater concentration range above 100 µg/L corresponds to a wide range of indoor air concentrations. No clear relationship was observable between groundwater and indoor air concentrations for PCE without screening/filtering the data. Indoor air measurements were averaged across a sample zone after the baseline, source strength and preferential pathway screens were applied. With these screens applied, there was a relatively weak relationship of increasing PCE indoor air concentrations with increasing groundwater concentrations regardless of whether ND data were excluded (**Figure 6-24**) or included (**Figure 6-25**). Only one case exceeded the indoor VISL of 47 µg/m^3, which had a groundwater vapor concentration of >500,000 µg/m^3 (corresponding to a groundwater concentration of >1,200 µg/L). In contrast, it is common current practice to screen commercial buildings at vapor intrusion sites using the USEPA (2014) commercial/industrial groundwater VISL of 65 µg/L, which appears to be highly conservative when applied to DoD commercial/industrial buildings.

The TCE plots with the screens applied suggest that groundwater concentration is weakly correlated to indoor air concentration. With ND results excluded (**Figure 6-26**), only one sample zone shows a concentration slightly above the indoor air VISL of 3.0 µg/m^3 until the groundwater vapor concentration exceeds 1,000,000 µg/m^3 (approximately 2,400 µg/L in the aqueous phase). In contrast, it is common current practice to screen data for TCE in groundwater using the USEPA (2014) commercial/industrial VISL of 7.4 µg/L; which this analysis suggests is very conservative. With ND results included (**Figure 6-27**) two additional points are plotted above the indoor VISL (blue cross), which is the result of a series of samples with poor sensitivity (NDs in indoor air were reported in multiple samples between 13 to 54 µg/m^3).

There are less cis-1,2-DCE data available in the database, present at only three sites. After applying the screens to the cis-1,2-DCE dataset, there is no apparent relationship between groundwater vapor concentrations and indoor air concentrations regardless of whether NDs are included in the dataset (**Figures 6-28** and **6-29**). This result could suggest a predominance of indoor or vadose zone sources. It could also reflect that cis-1,2-DCE has a greater capacity for aerobic biodegradation in the vadose zone (AFCEE, 2004), which would tend to reduce the linkage between groundwater and indoor concentrations. No results in the dataset approached the previous USEPA indoor VISL of 186 µg/m^3; the maximum concentration was 40 times below the VISL (**Figure 6-28**). When reviewing **Figures 6-28** and **6-29,** be aware that in some cases including nondetectable data with high detection limits acts to elevate the average concentration.

The USEPA (2012a) residential database yields estimates of the 95th percentile for indoor air concentration normalized by groundwater concentration (AF_{vi}) of 0.001 for all soil types and water depths. That AF_{vi} value of 0.001 is currently incorporated into the groundwater vapor intrusion screening level calculator for both the residential and commercial scenarios and thus has a significant effect on site management decisions. For the screened datasets, calculated on a sample zone basis, only one result suggests a groundwater AF_{vi} of >0.0005 across all three compounds: PCE, TCE, and cis-1,2-DCE. Most of the data suggest a groundwater $AF_{vi} < 0.0001$. This suggests that a groundwater AF_{vi} of 0.0001 could be used for most DoD commercial/industrial buildings.

6.2.2.3 Building and Sample Zone Dimension Effects

In the EDA, the effects of building dimensions on indoor air concentrations were explored at two scales: sample zone and whole building. Floor area, height, and volume were investigated as predictor variables. In the main body of this report, the presentation focuses on the variable that had the most consistent and statistically significant results for PCE, TCE, and cis-DCE: sample zone area. Increasing sample zone area was associated with decreasing indoor concentration. The other five analyses: sample zone height, sample zone volume, building area, building height, and building volume did not yield consistent, statistically significant linear correlations even after screening to reduce the impacts of indoor sources and preferential pathways. The other variables are therefore discussed in **Appendix D** and **Appendix E**.

6.2.2.4 Indoor Air vs. Sample Zone Area

A working assumption about the definition of sample zone used in this project is that air is expected to be reasonably well and rapidly mixed throughout the zone (and perhaps over a larger volume, up to and including the full building in some cases). Conceptually, indoor air concentrations should decrease as sample zone area increases if all other variables are constant and if the source is due to a discrete activity or a preferential pathway. Indoor air concentrations should also decrease as sample zone area increases if vapors are intruding through only a portion of the floor in a large space. A special case of intruding through only a portion of the floor is the conventional conceptualization of vapor intrusion as having a major entry route through a slab perimeter crack of constant width (USEPA, 2012b). In that case, if the width of the crack is constant, the area of that crack would increase proportionally to the square root of the building area for a square building[10]. In other words, if a perimeter crack is the dominant entry point, then the area of the crack increases more slowly than the floor area (and thus more slowly than the volume of available dilution air) as the sample zone size is increased. It has been anecdotally reported that vapor intrusion mitigation systems in large buildings that focus on the edges of the building and have less coverage in the middle of the slab are still often effective,

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[10] For example for a square building the perimeter = 4*area$^{0.5}$. Thus the area of the crack = crack width*4* area$^{0.5}$.. For a rectangular building, if the aspect ratio is held constant at 2 (length is double width) then the Area = length^{2}/2; Perimeter = 3* length. Thus the building area increases as the square of the length and the perimeter (and crack area) increase directly proportionally to the length.

which supports the hypothesis that the perimeter crack is often a major entry route (Folkes, 2014).

However, there would not be expected to be a relationship between indoor concentration and sample zone area if:

- The contaminants are widely distributed below the whole sample zone (for example throughout a gravel layer)
- The "crack area" for vapor intrusion increased with sample zone area (such as might occur if regularly spaced, gridded, expansion joints were the primary entry path) or
- The amount of indoor source use increased with a larger sample zone

Plots of indoor air concentration versus sample zone area are provided as **Figures 6-30** through **6-32**. A statistically significant relationship was observed between increasing sample zone area and decreasing normalized indoor air concentration (AF_{bldg}) for TCE and cis-1,2-DCE (**Figures 6-31** and **6-32**). (Recall, as introduced in **Section 5.4.1**, a relationship can have considerable scatter but still be statistically significant (Nau, 2015a, 2015b). That would be the expected result in any case where the single predictor variable being studied only controls a portion of the variability in the outcome variable. That is expected here since certainly there are variables other than sample zone area that influence indoor air concentrations). For TCE, the log-log plot gave a statistically significant line fit ($r^2 = 0.078$, slope $p = 0.009$, $n = 85$) with an equation of:

$$\text{Log(AF)} = -0.488 * \text{Log (area)} - 0.77$$

For Cis-1,2-DCE, the log-log plot gave a statistically significant line fit ($r^2 = 0.059$, $n = 70$, slope $p=0.043$) with an equation of:

$$\text{Log(AF)} = -0.528 * \text{Log (area)} + 0.163$$

The relationship for PCE appears to show the same directionality, but is weaker and does not rise to statistical significance (**Figure 6-30**; $n=82$, $r^2=0.002$, $p=0.69$). A mechanistic reason for this difference in outcome between analogous compounds (PCE, TCE, and cis-1,2-DCE) has not been determined. A visual examination of the plots suggests that the outcome may be driven by higher normalized indoor air concentrations for PCE as compared to TCE or cis-1,2-DCE in the largest sample zones (>10,000 feet^2) with data in that size range being available for multiple compounds from many of the same facilities. One possible explanation would be that PCE indoor sources were not all eliminated by the screening procedures implemented – screening for indoor sources is likely to be difficult in these large rooms. For example, in such large spaces, interviewing all occupants to determine if dry cleaned clothing is being worn may not be feasible. DoD has largely phased out its use of TCE with an annual purchase of 11 gallons reported for 2005 (Vartabedian, 2006) as compared to a national total of 220 million pounds for 1944, of which the majority was for military and defense contractor uses (Swisdak, 2013). As of 2010, DoD's emerging contaminant program classified TCE as an "action list" substance and PCE as "watch list" (Yaroschak, 2010). As of November 2013, TCE was a watch list compound and PCE was delisted from the watch list (Yaroschak, 2013).

This relationship was not studied as quantitatively for the other compounds, because there were generally insufficient number of detectable samples to define a clear trend or a clear trend was not visible in the EDA (**Appendix E**).

6.2.2.5 Exterior Wall Effects

If the slab/foundation perimeter gap was the primary source of elevated indoor concentrations, then it would be reasonable to expect that higher concentrations would be observed in sample zones along exterior walls. Such gaps are a typical design feature of many slab-on-grade foundations systems, and are often referred to as perimeter cracks (US EPA, 2012b), capillary breaks (**Figure 6-33**), isolation joints, or expansion joints (Ching and Adams, 2001). As shown in **Figure 6-33**, these capillary breaks are often found in proximity to thickened footing elements and sometimes thickened gravel drainage layers (Wing, 1998). Gravel layers would be expected to be high-permeability zones facilitating soil gas movement. An alternate hypothesis was also considered wherein exterior walls would be associated with greater degrees of ventilation and thus lower concentrations.

As shown in **Figure 6-34** for PCE, there appears to be little difference in the median indoor concentrations, but the 75th percentile and 90/95th percentiles appear to be substantially higher in sample zones with exterior walls. The trend for higher concentrations in sample zones with exterior walls is more pronounced for TCE (**Figure 6-35**). For TCE a Mann-Whitney Test showed that the median detectable indoor air concentrations were statistically significantly higher (two tailed p=0.0005).

There was little observable difference in the median indoor concentrations for 1,2-DCA, cis-1,2-DCE and trans 1,2-DCE when analyzed according to the presence or absence of an exterior wall. Sufficient 1,1,1-TCA data were not available for an effective judgment about statistical significance and exhibits primarily very low concentrations. However, the limited dataset does suggest a similar difference in medians for 1,1,1-TCA, with exterior wall median 0.51 $\mu g/m^3$ vs. without 0.17 $\mu g/m^3$ (**Figure 6-36**).

There were an insufficient number of samples with detectable concentrations for many compounds in indoor air in sample zones without exterior walls for a meaningful comparison of distributions or medians. However, in some cases a significant difference was observed in the likelihood that a detectable indoor air concentration would be observed that is statistically correlated with the presence of an exterior wall in the sample zone. For example, for 1,1,-DCA, among sample zones with no exterior walls there were no detections (23 non-detects); while in sample zones with exterior walls there were 27 detections and 76 non-detects. According to the Fisher Exact Test, the corresponding odds ratio of detection of 1.5 is significant, with the two tailed p=0.004. The odds of detection on exterior walls were also higher for PCE (odds ratio=2.3, p=0.014) and TCE (odds ratio=2.5, p= 0.003). However, the opposite finding was observed for trans-1,2-DCE with the likelihood of detection being lower on exterior walls (odds ratio=0.46 and two tailed p= 0.023)

As discussed in **Appendix E**, median sub-slab soil gas concentrations for PCE, and 1,1,1-TCA were significantly higher in sample zones with exterior walls. 1,1-DCE and 1,1-DCA were also more likely to be detected in sub-slab soil gas beneath sample zones with an exterior wall. When the indoor air data were normalized, there was not a consistent exterior wall effect on the normalized indoor air concentration. Thus, the physical reasons why a higher median indoor concentration or a higher likelihood of detection in indoor air for some compounds were observed are likely a complex combination of vadose zone and building envelope factors. Another possible confounding factor in this analysis is that interior wall sample zones would be expected to be more common in larger area buildings. However, a consistent relationship was not observed between building area and indoor concentration was not observed (**Appendix E**).

6.2.2.6 Soil Type Effects

As discussed in **Section 6.2.1**, soil type appears to have an effect on sub-slab soil gas concentrations and sub-slab soil gas concentrations in turn appear to affect indoor concentrations. Thus, by the transitive property of logic, soil type would be expected to affect indoor concentrations. The figures illustrating this effect are shown in **Appendix E**. Note however, that the effect of soil type appears to be less dramatic on indoor air concentration (3 to 5 times for PCE and TCE) than on sub-slab soil gas concentration (20 times for PCE and TCE). This phenomenon is expected, because fine soils directly beneath the building are expected to limit the transport of chlorinated solvents, but also the flow rate of soil gas into the structure.

6.2.2.7 Source Strength and Distance

Based on VI theory, indoor air concentrations attributable to VI are expected to be proportional to sub-slab soil gas concentrations. Sub-slab soil gas concentrations are, in turn, expected to be proportional to the strength of the source of the vapors and its horizontal and vertical distance from the sample zone. There are several fields in the database related to the distance between the sample zone and the source:

- Sample zone horizontal distance to primary vadose zone release point (note that this field was not populated in all records, because in some cases information on the primary release location is unknown)
- Sample zone depth to groundwater
- Measured maximum distance (the horizontal distance to the highest concentration well associated with the sample zone)

The strength of the groundwater source is represented primarily by the measured maximum groundwater (or groundwater vapor) concentration. The groundwater strength variable was explored in depth in **Section 6.2.1.1**.

Combinations between distance and concentration will be discussed in the section on multivariate analysis (**Section 6.3**).

Distance to Primary Release

The XY plots of distance to primary release included in **Appendix D** were generated prior to data screening. After data screening to remove indoor sources, a relationship is observable for both PCE (**Figures 6-37** and **6-38**) and TCE (**Figure 6-39**), although for TCE there is a higher degree of scatter. The relationship for PCE is especially clear with both the distance and PCE concentration log transformed[11] yielding an $r^2 = 0.33$ with a highly significant $p=0.0031$ ($N=24$) (**Figure 6-38**).

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[11] Note that in this analysis the zero distance to primary release becomes undefined and thus is omitted from the plot and calculation

Depth to Groundwater
A correlation between indoor air concentration and depth to groundwater alone, even in screened datasets was not observed (e.g., **Figures 6-40** and **6-41** for PCE and TCE, respectively). This is not surprising given the many factors affecting the transport processes between groundwater and indoor air.

As discussed in **Section 5.3.4**, a particular type of normalization can be done to calculate the AF_{soil}; normalizing the sub-slab soil gas concentration by dividing by the groundwater vapor concentration (recall that consistent with USEPA's database nomenclature the variable AF_{soil} is used for the ratio of the sub-slab concentration to the groundwater vapor concentration). This analysis would be expected to isolate the portion of the vapor intrusion pathway on which groundwater depth would be expected to have the most effect and assumes that the source is groundwater. This analysis is not expected to benefit substantially from either the preferential pathway or indoor source screens, so all data are included. No consistent relationship was observed with depth to groundwater with all available data plotted. Not all plots attempted were included in the report for brevity; however, some information about depth to groundwater is included in figures E5 to E8 of **Appendix E**.

Measured Maximum Distance
There did appear to be a relationship between normalized sub-slab soil gas concentration (AF_{soil}) and lateral distance to the maximum groundwater concentration (**Figures 6-42** and **6-43**). This relationship is also apparent in screened subsets of the indoor air concentration data for PCE and TCE (**Figures 6-44** and **6-45**). These graphs can be interpreted as suggesting that short distances to monitoring wells containing high concentrations of VOCs are associated with the potential for high indoor air concentrations (but not the certainty of high indoor air concentrations given the scatter in the data).

6.2.2.8 Sampling Date

Most vapor intrusion guidance documents recommend sampling in winter, reasoning that the stack effect is strongest in winter. A graphical analysis suggests that the highest concentrations in the dataset for PCE and TCE were measured between January and March (**Figures 6-46** and **6-47**). A quantitative exploration of this effect is presented in the multivariate analysis section.

6.3 Multivariate Analysis

The multivariate analysis methods were discussed in **Section 5.4.3**. The analyses were performed on the dataset after baseline, source strength, and strict preferential pathway screens. The analyses were performed separately for the following outcome variables:

- TCE and PCE in indoor air; explored both with and without a log transformation
- TCE attenuation factor
- TCE in sub-slab soil gas

The outcome variables studied were selected based on priority and data availability. Priority was given to the compounds that are most frequently the driver for mitigation action and had the largest available data sets; PCE and TCE. Additional multivariate analyses for other contaminants or factors could be considered in future analyses. The single strongest predictor variable in many of the multiple regressions performed was winter sampling, which was defined as a sample collected in the months from November through February. Examples of other predictor variables tested include building size, depth to groundwater and interpolated maximum groundwater concentration.

6.3.1 Indoor Air TCE as Outcome Variable

When TCE indoor concentration was analyzed as the outcome variable, 67 records (data points) were available with sufficient completeness of information on the predictor variables. With all 34 available predictor variables in the model (listed in **Appendix F**) and indoor concentration as the outcome variable, winter sampling was the only statistically significant predictor variable (winter p=0.040; coefficient 19.8, overall r^2= 0.59; adjusted r^2=0.14). All other terms in the model had similarly weak p values (>0.70). Winter was still the only significant variable (winter p=0.026, overall r^2=0.81 adjusted r^2=0.59) using log transformed indoor concentration as the outcome variable. The log transformed outcome variable gave a stronger fit, which is common with right-skewed outcome variables (Cornell, 2012). In this case, some non-significant terms were clearly better than others in an inspection of p values (for example many were in the range from 0.2 to 0.6) suggesting a path to a reduced model (multivariate analysis terms such as "reduced model" are explained in **Section 5.4.3**).

As discussed in S**ection 5.4.3** a manual stepwise multiple regression was performed. This stepwise procedure narrows in on the most important parameters (reduced model) based on a combination of reviewing p values, correlation analyses, and professional judgment. A reduced version of the log transformed concentration model with all data included reached an adjusted r^2=0.70 but still using the 17 term model. In this model, there were three individual terms with statistically significant p values (winter sampling 0.028, distance to primary release 0.036, presence of exterior wall 0.047). It is notable that distance to primary release and presence of exterior wall were variables that the single variable analyses presented above suggest are useful. An analysis of normalized indoor air TCE concentration (attenuation factor) as the outcome variable indicated winter was the only significant predictor variable, with a p=0.00057 and coefficient of 0.04. (The term coefficient here refers to a numerical quantity placed before and multiplying the variable in an algebraic expression; the larger the coefficient the stronger the influence of the predictor variable on the outcome variable.) The overall r^2, however, was only 0.14, so this analysis was not pursued further.

A reduced model, using log transformed indoor concentration as the outcome variable, in a subset of winter data (n=19), showed an adjusted r^2=0.86 using only four terms in the model. Each of the four terms had an individual term p<1.0E-06.
Log[TCE]= 3.6E-05*(sample zone area) – 1.2E-04*[sub-slab] + 5.8E-03[interpolated gw beneath zone] – 5.1E-03 *[max gw]/depth -1.01

The terms in this reduced model were reasonable based on the single variable analyses, in that the single variable analyses presented in **Section 6.2** also indicated that these predictor variables had an influence on the outcome variable of indoor air concentration. However, the model requires confirmation (which is desirable for any multiple regression model), as not enough data were available to have separate training and test datasets. Caution is urged in the application of this model, because the sign (+ or -) of these coefficients is not intuitively clear by inspection, for example indoor concentration is not expected to decrease with increasing sub-slab soil gas concentration, yet the coefficient in the model is negative. The finding of a coefficient sign, which is contrary to expectations, is a common occurrence in multiple regression analysis, and can have numerous meanings/causes including the following:

- It can indicate a meaningful relationship that is not apparent in the whole dataset, but is apparent when in the mathematics of the regression analysis another parameter is "held fixed."
- The variable with the contrary sign may be highly correlated to another confounding variable that was excluded from the analysis.
- Multicollinearity – a situation where two or more predictor variables are highly correlated to each other and there is high variance.
- Selection bias in the sample
- Outliers
- Problems in the definition of the predictor variables (Westfall, 2015; Kennedy, 2003)

Further work in a future project will be required to determine the meaning of the unexpected negative signs in this case.

The consistent finding that winter sampling is the single strongest predictor of high indoor air TCE concentrations in a population of nonresidential buildings drawn primarily from southern states is useful. Much vapor intrusion guidance assumes that winter will be the worst case due to the strength of the stack effect. However, some studies have cast doubt on that general assumption. For example Steck (2011) studied 80 houses in Minnesota and found that while individual houses had strong seasonal patterns, there was no consistent pattern across all the houses. Thus while 15% of the houses showed the highest concentrations in winter, 31% showed their highest concentration in spring and 17% in summer (Steck, 2011). A study in San Antonio, Texas, showed a statistically significant association of winter conditions with decreased indoor concentrations (Johnston and Gibson, 2013b). The findings of this study suggest that the current DoD guidance to sample at least once in winter is reasonable: "*If indoor air samples are taken it is generally recommended that they be taken on at least two separate occasions, typically during the summer and winter seasons. This will account for some of the seasonal variability that may affect vapor intrusion. There is no clear consensus on how to average the data collected over multiple seasons. A reasonable approach would be to evaluate the potential risk for each individual sample.*" (Tri-Service Environmental Risk Assessment Work Group, 2009).

6.3.2 PCE in Indoor Air as Outcome Variable

For PCE, 23 records were available with available information for all of the predictor variables. Starting from that dataset and an extensive list of predictor variables, a reduced model was selected with log indoor concentration as the outcome variable having five terms ($r^2=0.80$, adjusted $r^2=0.74$). All terms in the model were individually significant with $p<0.003$, except winter sampling for which $p=0.12$, with the following equation:
Log[PCE] =2.0 - 3.89E-05*(sample zone area)+ 0.38(winter) + 7.0E-03 [maxgw]/depth – 3.6E-03*[maxgw]/(depth$^{0.5}$) -1.7E-02*(distance to release)

As with the reduced models for TCE, the individual terms were those that were expected to be useful based on single-variable analyses presented in **Section 6.2**. Some of the terms had unexpected signs, such as the negative sign on the term [maxgw]/(depth$^{0.5}$). Both the reduced PCE and TCE models include terms for sample zone area and related to groundwater concentrations. An attempt was made to evaluate for PCE as the outcome the exact same set of terms as were used in the reduced model of TCE. However the results for r^2 and p were inferior to those discussed above for the PCE reduced model. By excluding some groundwater variables from the analysis, a somewhat larger dataset of 31 records was available. Analysis of this dataset proceeded to a 15-term model with r^2=0.62, adjusted r^2=0.073 in which winter sampling was the only individually significant variable (p=0.018) which suggests that it is the single most predictive variable analyzed.

In interpreting both the single variable and multivariable results, it is commonly expected that PCE and TCE would behave almost identically, given their analogous structures. However, some differences were observed in the single-variable analyses for groundwater/sub-slab soil gas correlation, sample zone area, exterior wall, as well as in the multivariate analyses. There is a growing body of research that suggests significant differences in behavior do occur between these two compounds:

- Seyedabbasi et al. (2012) modeled a PCE source and an entirely identical TCE source and found they behave very differently over the decades, because TCE has 5 times greater water solubility and thus is more rapidly depleted and has a much longer period in which its behavior is dominated by matrix diffusion as opposed to dense non-aqueous phase liquid (DNAPL) dissolution.

Newell et al. (2013) found evidence for this different behavior in field data (mass stored in thick clay layers that they read like tree rings as evidence of previous mobile phase concentrations) from two DoD sites.
A recent expert workshop summary report indicated that the role of TCE aerobic cometabolic biodegradation supported by natural organic matter may be underappreciated (Leeson et al., 2013).

Therefore, the fact that the PCE and TCE best fit multivariate models for this data set were somewhat different may be reflective of true differences in the environmental fate and transport of the two compounds. Similarly, the fact that in some of the single variable analyses PCE or TCE coefficients or significance differed, could be further evidence for a true difference in behavior between the two compounds.

6.3.3 TCE Sub-slab Soil Gas Concentration as Outcome Variable

The dataset with TCE sub-slab soil gas concentration as the outcome variable contained 151 records. A full model with 30 variables yielded a relatively good fit with the log transformed sub-slab soil gas concentration as the outcome variable (log model r^2=0.78, adjusted r^2=0.72; untransformed sub-slab soil gas concentration model r^2=0.28 adjusted r^2=0.10). In contrast to the indoor air analysis, winter sampling was not one of the most significant variables, suggesting that there is less seasonal variability with TCE sub-slab soil gas concentration as the outcome variable than for indoor air. While seasonal sub-slab concentration variations have been reported in other studies the direction of seasonal variability is not always consistent, even within one structure (Lutes 2013, Johnson, 2014). Within the full model, a total of eight terms had statistically significant individual p values:

- Building area p=8.8E-04
- Ceiling height min p=4.4E-03
- Building volume p=7.2E-04
- Depth to groundwater p=2.2E-02
- Engineered HVAC code p=2.3E-02
- Zone specific HVAC code p=4.7E-03
- Interpolated maximum groundwater concentration p=3.3E-03
- Distance to primary release p=1.2E-04

There were more strong predictors of sub-slab soil gas concentration than strong predictors of indoor concentration in the exploratory and single-variable analyses. The multivariable analysis of TCE also resulted in a greater number of highly significant variables based on sub-slab soil gas concentrations as compared to indoor concentrations. This could reflect the larger sub-slab soil gas dataset, and/or could be an indication that the sub-slab soil gas concentration is a function of less complex processes than indoor air concentration (where both vadose zone and building envelope factors would be expected to be important). It is also possible that the indoor concentrations display less predictable variability because, despite screening, some influences of indoor sources remain. The predictor variables were not expected to be predictive of indoor sources (with the exception of building use).

These eight statistically significant terms in the full model were then compared to the single variable analysis results. While the finding regarding ceiling height correlating with sub-slab soil gas concentration is unexpected, it agrees in sign with the single variable analysis for that variable (**Appendix E**). While the relationships with ceiling height, building volume, and HVAC parameters were not specifically hypothesized in the formulation of project objectives, they merit further investigation in the future because they could suggest that the building stack effects and air exchange rates influence contaminant migration into the sub-slab (and thus sub-slab soil gas concentration). Some single building studies (Lutes et al., 2013) and modeling exercises (USEPA, 2012b) have also hinted that stack effect strength and/or soil gas flows into the building affect sub-slab contaminant distributions. The relationship to building area and building volume could reflect capping effects as discussed earlier.

After multiple steps of model reduction, a reduced set of eight variables was arrived at in which every predictor variable was individually highly significant and that had an adjusted r^2 similar to the full model (r^2=0.72; adjusted r^2=0.70). The variables, their coefficients, and p-values are tabulated below.

Variable	**Coeff.**	**Std. err**	**p-value**
Intercept	1.1E+00	4.8E-01	2.2E-02
BUILDING_AREA	4.5E-05	7.6E-06	2.6E-08
CEILING_HEIGHT_MIN	9.4E-02	1.8E-02	3.6E-07
BUILDING_VOLUME_CALC	-1.8E-06	3.0E-07	1.6E-08
Industrial/Shop Building Use Classification (True = 1)	1.0E+00	2.4E-01	6.7E-05

Variable	Coeff.	Std. err	p-value
Engineered HVAC Code (True =1)	-8.5E-01	2.5E-01	9.2E-04
Vault Pit Code (True =1)	-2.3E+00	3.3E-01	1.7E-10
INTERPOLATED_MAX	7.7E-05	1.3E-05	1.5E-08
MEASURED_MAX	-3.9E-05	1.3E-05	2.0E-03
DISTANCE_TO_PRIMARY_RELEASE	-5.9E-03	8.0E-04	1.0E-11

A highly reduced model was able to retain an $r^2= 0.67$ and an adjusted $r^2=0.66$ while describing the log of sub-slab TCE with only six variables, each of which had an individual $p<0.000001$: Log [TCE SS] = 5.5E-05*(Building Area) +0.106*(ceiling height min)-2.3E-06(building volume) -1.39(VaultPitCode) + 8.83E-05[interpolated_maximum groundwater]-0.006*(distance to primary release)

In this model, the observed positive correlation between groundwater concentration and sub-slab soil gas concentration was expected based on basic vapor intrusion theory. The negative correlation between distance to primary release and sub-slab concentration was also as expected from the single variable analyses (presented in **section 6.2**) and theory. The coefficients of building area and ceiling height were also in agreement with single variable analyses, but a third related term, the building volume, at least partially cancels these area and height terms. It is notable that the presence of a vault or pit in the sample zone is associated with a more than an order-of-magnitude reduction in sub-slab soil gas concentration in this multiple regression. Although the vault variable was not prioritized for discussion in the single variable section, this effect was visible in a single variable box and whisker plot (**Appendix D**, **Figure 24**). A mechanistic explanation for this result would be that vaults or pits may provide efficient routes for ventilation of the shallow sub-slab soils and thus reduce sub-slab soil gas concentrations. The finding that sub-slab soil gas concentrations are strongly influenced by lateral distance to the primary release is in agreement with modeling studies recently published by Yao et al. (2013a), which find that sub-slab soil gas concentrations decrease exponentially as this lateral separation increases.

6.3.4 Comparison to Other Multivariate Vapor Intrusion Analyses

The multivariate findings in this analysis agree with those of the regression reanalysis of the USEPA residential database by Johnston and Gibson (2013a) in finding higher indoor air concentrations under winter conditions. The preceding multivariate results are not consistent with Johnston and Gibson (2013) findings of lower normalized indoor air concentrations (AFs) associated with fine-grained soils. As discussed previously, this most likely reflects that the USEPA residential database consists of buildings distant from the point of contaminant release while this NESDI database includes many buildings close to the point of contaminant release. As discussed previously, the multivariate analysis findings agree with the findings of Yao (2013a), who in reviewing the factors explaining variability in the USEPA database emphasized the role of source-building separation. Abreu and Johnson (2005) also emphasized the importance of source-building separation based on three-dimensional modeling studies, especially with shallow depths to groundwater (as are typical in the NESDI dataset). Johnston and Gibson (2013b) published a separate regression analysis of the factors influencing indoor air concentrations in a series of San Antonio residences. The multivariate analysis of

DoD buildings results of this study agree with the Johnston and Gibson (2013b) study in that a correlation between indoor air concentration and groundwater concentration was observed in both studies. The multivariate results for DoD buildings regarding winter sampling also agree with the time series analysis performed on the USEPA Indianapolis duplex dataset showing correlations between low and falling temperatures with higher indoor air concentrations (Lutes et al., 2013).

7.0 DECISION FRAMEWORK

The key outcome of this project is a VI decision framework, which is intended to allow the Navy to apply the results of the data analysis to management of VI sites at multiple stages in the project lifecycle. The concept of a decision framework was introduced in **Section 5.5**, which also describes the selected approach for presentation – a flow chart with an embedded scoring system. Readers desiring a "users manual" level presentation of the framework should refer to **Appendix H**. This section describes the development of the framework as it emerged from the data analysis in some detail.

This decision framework is conceptually related to the Navy VI Decision Process Tool (Caldwell, 2012) which is a computerized "expert system" that guides the user through the analysis of VI data and facilitates a weighted evaluation of multiple lines of evidence. A related approach to sitewide VI building prioritization was previously outlined by Lund et al. (2012) and Lund (2013). In that previous prioritization approach, quantitative scores were assigned for factors such as distance to VOC source, magnitude of concentration exceedance, occupancy, building area, and air exchange characteristics.

This quantitative decision framework is presented as a series of flowcharts (**Figures 7-1** to **7-2**) that ask basic screening questions to quickly identify atypical preferential pathway cases and very lowest risk cases and then lead to a scorecard (**Figure 7-3**) for the evaluation of the majority of the cases "in the grey area." The scorecard generates two scores:

- A total score indicative of the degree of overall predicted VI potential
- An uncertainty score that rates the relative amount of information available and thus reliability of the prediction (**Figure 7-3**)

The total VI potential score can then be applied:

- For prioritization decisions for initial investigation (**Figure 7-5**)
- Evaluations of whether indoor air results are reasonably consistent with other lines of evidence (**Figure 7-7**)
- Recommendations on the degree of vigilance needed in long-term stewardship (**Figure 7-7**)

Figure 7-4 shows graphically how **Figures 7-5** through **7-7** are applied throughout the project lifecycle to interpret the scorecard results. Just as the conceptual site model should be regularly revised, so to a particular building or sample zone should be rescored as the project progresses, and new information is developed.

Note that in **Figures 7-5** through **7-7** there is not a strict correspondence of a prioritization score to a recommendation. Rather, recommendations are shown for zones that shade into one another. This reflects the uncertainty of the understanding of vapor intrusion at this point in time and the need to apply professional judgment to site specific decision making.

It is important to note that this scoring system should not be used indiscriminately – buildings being evaluated for vapor intrusion should be within 100 feet of a subsurface concentration of

VOCs (consistent with regulatory and DoD recommendations [Tri-service Environmental Risk Assessment Workgroup, 2009]). Concentrations (sub-slab, indoor air and normalized indoor air) drop rapidly across the first 100 ft (as shown in **Figures 6-14** through **6-17** and **6-42** through **6-45**).

7.1 Linkage Between Data Analysis and Decision Framework

The factors highlighted in the quantitative decision framework are either those well accepted in the field or were derived from the data analysis efforts in this project.

7.1.1 Flowchart Basis

The following bullets provide the basis used in development of the flowcharts:

- A history of chlorinated solvent use is associated with a potential risk for vapor intrusion of those compounds or the role of certain building features is considered well accepted (ITRC, 2007).
- That atypical preferential pathways, for example dirt floor spaces and deep elevator shafts are potentially associated with increased risk of vapor intrusion is well accepted (ITRC, 2007). However, the use of these specific examples in the flowchart is not intended to limit the list of relevant unusual building characteristics. In other cases features such as hollow wall cavities and land drains have been shown to be important preferential pathways. In cases where preferential pathways are present, elevated indoor concentrations can be associated with moderate concentrations within the pathway (i.e., within a sewer pipe). The concentration within a preferential pathway (such as a sewer pipe) necessary to cause an exceedance of a screening level in indoor air has not been well defined in this or previous studies.
- The threshold used in the sub-slab soil gas flowchart (<33x indoor air screening level), to define a concentration below which a full scoring of the building is not merited, is based on a 50x safety factor from the threshold for expecting exceedances (1,000x) drawn from the graphical analysis of the screened PCE and TCE datasets in **Section 6.2.2.1**.
- The threshold used in the groundwater data flowchart (groundwater vapor concentration <1,000x indoor air screening level), to define a concentration below which a full scoring of the building is not merited, if there is no potential vadose zone source, is based on a 10x safety factor from the threshold for expecting exceedances. The threshold for expecting exceedances in the absence of the potential for a vadose zone source, is drawn from the graphical analysis of the screened PCE and TCE datasets in **Section 6.2.2.2**. This threshold is also supported by the USEPA (2012a) database analysis. Although this factor was derived from the analysis of PCE and TCE, it would be expected to apply to other contaminants with similar characteristics such as volatility and resistance to aerobic biodegradation.

7.1.2 Scoring System Basis

The parameters used in the scoring system were those judged most relevant after the quantitative data analysis. The relative weights assigned to the parameters reflect professional judgment, informed by the data analysis presented in **Section 6**, about the parameters' relative importance in influencing indoor air concentrations. The following bullets provide the basis used in development of the scoring system (VI scorecard):

- Basis for Average Sub-slab Concentration on Scorecard:
  - A sub-slab soil gas concentration >10,000x indoor air screening level is required in the scorecard for the site to receive a rating of increased VI potential. This concentration is derived from the graphical analysis of the screened PCE and TCE datasets in **Section 6.2.2.1**. A rough linear correlation was observed between soil gas concentration and indoor air concentration in the screened datasets. Therefore:
  - Ranges of concentration substantially lower (i.e., 300-2000x) were associated with negative point values indicating lower VI potential.
  - Ranges higher (i.e., 10,000-100,000x) were associated with positive point values indicating greater VI potential.
  - Sub-slab soil gas concentration was assigned a total weight range of 8 (possible score from -4 to +4) based on the associations with indoor air concentrations observed in the plots in **Section 6.2.2.1**. This assignment was also supported by a mechanistic association between sub-slab soil gas concentration and vapor intrusion potential.
- Basis for Average Groundwater Vapor Concentration on Scorecard:
  - A groundwater vapor concentration >10,000x indoor air screening level is required in the scorecard for the site to receive a rating of increased vulnerability to vapor intrusion. This was drawn from the graphical analysis of the screened PCE and TCE datasets in **Section 6.2.2.2**. Higher ranges (i.e., 10,000-100,000x) were assigned with positive point values, indicating greater vulnerability. The use of these ranges, which assume a relationship of increased indoor concentration with increased groundwater concentration can be justified both from the basic theory of VI, and the observations that:
  - Sub-slab soil gas concentrations of PCE and TCE increase with increasing groundwater vapor concentrations (**Section 6.2.1.1**)
  - Indoor concentrations of PCE and TCE increase with increasing sub-slab soil gas concentrations (**Section 6.2.2.1**)
  - Groundwater concentration was assigned a weight range of 4 (score from 0 to +4 was possible), based on the statistically significant correlations observed with indoor air concentrations of TCE (**Section 6.3.1**) and PCE (**Section 6.3.2**) in the multivariate analysis. This assignment is supported by a mechanistic association between groundwater concentration and VI potential.
- Basis for Sample Zone Area on Scorecard:
  - Sample zone area was used in the scoring system because after screening, a statistically significant relationship was observed between increasing sample zone area and decreasing normalized indoor air concentration (AF_{bldg}) for TCE and cis-1,2-DCE (**Section 6.2.2.3**). An effect of sample zone area was also found to be significantly correlated, in multivariate analysis, to indoor TCE concentration. The full range of

  observed sample zone area values was binned by order of magnitude because no clear inflection points were observed in the plots and the relationship was observed to be best fit by a linear plot on a log-log scale (**Section 6.2.2.3**).

  - A total weight range of 4 (2 to -2) was assigned to sample zone area because the relationship observed, while statistically significant, had a shallow slope and only explained a small portion of the total variability in indoor concentration. For example the Indoor Air Concentration vs Sample Zone Area figures (**6-30** through **6-32**) display considerably more scatter then is visible in the Indoor Air Concentration vs Sub-slab Soil Gas Concentration figures (**6-18** through **6-21**).

- Basis for Soil Type and Solvent Use/Disposal History on Scorecard:
  - For the purpose of preparation of the scorecard, the variables of soil type and solvent use in the building were associated. The reason for this association is that many of the mechanisms that explain the observed soil type effects (**Section 6.2.1.3**) would be expected to apply primarily near the point of release. Because the data were analyzed in an adjectival category (fine vs. coarse) only three scoring categories could be created.
  - A maximum weight range for these variables of 3 (2 to -1) was assigned to soil type, based on the strength of the effect observed in the single variable analysis (**Section 6.2.1.3** and **Appendix E**). The effect of soil type, while often significant, was only 3-5x in indoor air, while the effect of sub-slab soil concentration was considerably higher – multiple orders of magnitude. The weight assigned was tempered because the variable did not feature prominently in the outcomes of the multivariate analysis (**Section 6.3**).
- Basis for Sample Zone on Exterior Wall in Scorecard:
  - As discussed in **Section 6.2.2.5**, an association was shown for some compounds between higher indoor air concentrations and presence of the sample zone on the exterior wall of the building.
  - As discussed in **Appendix E, Section E.2.9** an association was also observed between presence of an exterior wall in a sample zone and higher sub-slab concentrations.
  - This factor was assigned a weight range of only 2 because the exterior wall effect was not observed to be statistically significant for all compounds, and the difference between medians with and without external walls is generally less than a factor of 10x. This factor was weighted cautiously because while some potential mechanistic explanations were described in this report for this effect, it is not widely discussed in the VI literature.
- Basis for Atypical Preferential Pathways on Scorecard:
  - Case studies suggest that the presence of atypical preferential pathways connecting an occupied space to a point of release or mass source are associated with many of the highest observed concentrations, that are linked to vapor intrusion (Johnson, et al., 2014; Riis et al., 2010). The analysis for this project shows this effect for TCE (**Appendix E**). Most of the quantitative analyses in this project were conducted with

datasets that were screened to remove samples with strictly defined (atypical) preferential pathways.

  - A maximum weight range for preferential pathway of three was assigned. There is a strong mechanistic and case study association of preferential pathways with increased indoor air concentrations. However, the effect of preferential pathways, and subsets of preferential pathways in producing high indoor air concentrations in the dataset was limited (**Appendix E**), perhaps because strictly defined preferential pathways were in many cases associated with low or ND sub-slab soil gas concentrations (**Appendix E**).

- Basis for Distance to Primary Release Point on Scorecard:
  - Short distances to primary release were given high scores because of the results of the single variable analysis (**Sections 6.2.1.4** and **6.2.2.6**). Narrow bins (i.e., 0-10 feet) were used for shorter distances and wider bins for greater distances from the point of release (i.e., 100-200 feet) because of the shape of the data graphs in **Sections 6.2.1.4** and **6.2.2.6**.
  - A total weight range of 8 was assigned to distance to primary release based on the strength of the observed relationships, the statistical significance of the observed relationships and the agreement of the observed relationships to mechanistic expectations.

7.2 Applications for Initial Building Prioritization and Data Evaluation

These flowcharts and embedded scoring system can be used at several different stages in site management:

- In initial site investigations, to prioritize the need for further evaluations, such as determining when indoor air samples are necessary. It is recommended that only buildings within 100 feet of a VOC plume or release point be evaluated using these tools, consistent with regulatory and DoD recommendations. The results presented in **Section 6** show that indoor air and sub-slab soil gas concentrations fall rapidly over the first 100 ft from a primary release point or measured maximum groundwater concentration.
- In site investigations that have progressed to include indoor air sampling, to evaluate if the observed indoor air concentrations are likely the result of vapor intrusion or if a more intensive search for indoor sources is merited.
- In planning for long-term stewardship of VI sites at buildings where mitigation was not necessary based on current exposure, but high sub-slab soil gas concentrations are expected to be present through the lifecycle of CERCLA remediation of subsurface sources.
- In planning for long-term stewardship of VI sites where future buildings may be constructed over VOC subsurface sources and rescoring of the VI potential as the CSM is refined through source remediation or building mitigation.

Single building flowcharts are provided for prioritization in two common cases:

- Groundwater VOC and building characteristics data only available (no sub-slab soil gas data) **(Figure 7-1)**

- Groundwater and sub-slab soil gas VOC data available, along with building characteristics **(Figure 7-2)**

To better describe how to use the flowcharts, the boxes on the flow charts are numbered on the figures:

- **Figure 7-1, Boxes 1 & 4 and Figure 7-2, Boxes 2 &5:** Information about how to identify the unusual building characteristics that could provide atypical preferential pathways later in this section and in **Section 5.2.4.2.** At the current time there is no consensus in the field on how to visually identify preferential pathways, so only lists of types of features that have been observed in specific cases to function as preferential pathways can be provided for guidance.
- **Figure 7-1, Box 2:** To address the question of whether chlorinated solvents are or were used or stored in the building for industrial applications, consider first the current building use. Hazardous materials inventories or interviews with building managers can provide information on current use of solvents. Historical information however then must also be considered. Historical evaluation of potential source areas may be contained in Preliminary Assessment/Site Inspection reports or Remedial Investigation reports at CERCLA regulated sites. At RCRA regulated sites this information may be in reports such as RCRA Facility Assessments or RCRA Facility Investigations. Often a clue can be provided by the historical name of a building or its known functions. Solvents are often associated with the following DoD activities and facilities: underground solvent storage tanks, landfills, disposal pits/dry wells, drum storage areas, fire/crash training areas, surface impoundments/lagoons, burn areas, waste lines, waste treatment plants, sewage treatment plants, oil/water separators, maintenance shops and yards, chemical disposal, plating shops, vapor degreasers and dip tanks (USEPA, 2004).
- **Figure 7-1, Box 3:** In order to estimate the groundwater concentration under the building only analytical data that represent concentrations at or near (10 feet below) the water table should be considered. The approximate groundwater concentration of the analyte under the Sample Zone can be determined by interpolation from isoconcentration maps that are frequently found in remedial investigation, RCRA facility investigation or groundwater monitoring reports. Interpolation of groundwater concentrations under the sample zone will almost always be based on monitoring wells located exterior to the building. Therefore, it would not generally take into account any potential increase of groundwater concentration beneath the building that may occur if there is a capping effect associated with the building (Schumacher et al., 2010) or if the source itself is beneath the building. Groundwater concentrations can then be converted into groundwater vapor concentrations using Henry's law. Henry's law calculators are available as stand-alone websites http://www.epa.gov/athens/learn2model/part-two/onsite/esthenry.html or as part of the widely used Johnson & Ettinger model.
- **Figure 7-1, Box 5:** In order to evaluate the potential for vadose zone sources many lines of evidence could be considered:
  - Soil gas sampling results (external to the building) are an excellent source of information. Comparison of soil gas results to the groundwater vapor concentration

  predicted from groundwater can often suggest whether vadose zone sources are significant.

  - When solvent disposal at the surface of the ground, discharge to sewers or solvent spills to the building floor are known to have occurred, the existence of a vadose zone source near or beneath the building should be presumed. If DNAPL concentrations are observed in groundwater, then the historical mechanism by which the solvents reached the water table should be considered. It is likely that free phase, adsorbed phase, vapor phase or soil moisture phase solvents will be present in the vadose zone unless the disposal was into a deep well (Environment Agency, 2003; Carr, 2011).
  - Results of bulk soil sampling for VOCs are considered a weak line of evidence in part because the subsample size analyzed is tiny compared to the total size of the vadose zone. According to EPA (2013) they "*can be used in a qualitative sense for this purpose. For example, high soil concentrations generally would indicate impacted soil. Unfortunately, the converse is not always true. Non- detect results for soil samples cannot be interpreted to indicate the absence of a subsurface vapor source, because of the large uncertainties associated with measuring concentrations of volatile contaminants introduced during soil sampling, preservation, and chemical analysis.*" Only a very small percentage of the soils in the vadose zone need to have stored VOC mass in order to sustain high soil gas VOC concentrations over a large volume of vadose zone soil.
  - Field screening with PID instruments of soil borings, data that is typically in the appendices of remedial investigation reports, can provide a useful semi-quantitative indicator of potential vadose zone mass storage. However this information must be used with caution because the instruments used are typically sensitive only to part per million concentrations in soil gas, and because the conditions under which the measurement are typically made do not allow these measurements to be related directly to a soil gas concentration.

- **<u>Figure 7-2, Boxes 1& 3:</u>** Sub-slab concentration information will generally only be available from sub-slab sampling in vapor intrusion oriented investigation reports. However if bulk soil sampling was performed beneath the building equilibrium soil gas concentrations could be calculated, subject to the cautions about bulk soil sampling discussed above.

In all cases, the framework assumes that some basic information will be available to the user:

- A scaled building floor plan, from which the approximate area of sample zones of interest can be calculated. Sample zones are rooms or spaces with limited air mixing with other areas within the building. A more extensive discussion of selecting and prioritizing sampling zones is provided at the end of this section.
- Results of a building walk-through or an interview with a person knowledgeable about the building, sufficient to determine if an atypical preferential pathway is present (elevator shaft, tunnel, open soil visible beneath pit, or wall, etc.). More information about preferential pathways is provided later in this section and in **Section 5.2.4.2**.
- History of building use, sufficient to determine whether chlorinated solvents were likely used in the building and/or released within or adjacent to the building, resulting in a potential vadose zone source.

- History of building use sufficient to estimate, if possible, the distance between the sample zone and the likely point of the primary release (where the chlorinated solvents likely entered the soil). Many sample zone primary releases will be the locations of surface disposal sites, leaking underground storage tanks, degreasers, solvent spills, disposal pits, and stormwater or sewer conveyance lines.

- Soil type information describing the predominant shallow soil type between the building slab and the water table. This can normally be determined from nearby site-specific boring logs for monitoring wells, boring logs for geotechnical design purposes, or from soil survey information (available nationally at http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). This information will be used to make a simple classification:
    - If silts or clays are indicated in boring logs or cross sections for the vadose (unsaturated) zone near or beneath the building, the User should consider "Fine" as the soil type. This includes strata containing coarser-grained components such as silty sand, gravelly clay, etc.
    - The "Coarse" soil type should be used for scoring in cases where no fines are indicated or only traces of fines are indicated in the boring logs or soil surveys.

In order to use this decision framework, sample zones within the building of interest need to be defined. The Sample Zone object represents an enclosed location within a building where at least one indoor air sample has or could be in the future be collected. The sample zone should include at least some regularly occupied spaces within the building. The conceptual idea that best represents Sample Zone is a box. A Sample Zone should have limited air mixing with other Sample Zones. Sample zones should be defined so that air is expected to be reasonably well and rapidly mixed throughout the zone. In order to better understand airflow through buildings, the information on HVAC systems and Airflow in the DoD Vapor Intrusion Handbook, Appendix H, pages 128 -129 should be reviewed (Tri-service Environmental Working Group, 2009). Additional useful information on this subject can be found in Shea (2010).

Some buildings may have an impractically large number of potential sample zones for an initial assessment. The following guidelines can be used in selecting priority sample zones for evaluation:

- At least one sample zone should be selected for each occupied section of the building that was separately constructed. Many DoD buildings have had multiple additions which may have independent foundation systems and are often separated by barriers to airflow. Additions can be identified through a review of building engineering drawing files. Alternately, additions are often apparent in the field based on the external appearance of the building, such as differing foundation styles, building cladding, rooflines etc. An additional aid in identifying additions to a building is a historical sequence of aerial photographs. Often such a sequence at roughly 5 to 10 year intervals has been assembled and reviewed as part of an initial site assessment.

- The selection of sample zones should include those proximate to expected atypical preferential pathways.

  Examples of Anthropogenic Preferential Pathways include:

  - Subsurface utility conduits (e.g., a sewer line intersecting contaminated groundwater or to which wastes may have been historically discharged)
  - Floor drains (e.g., around the gravel pack of the drain pipe where it enters the building or inside the pipe if contaminated groundwater has entered a sewer line and the trap is not maintained)
  - Building sumps or dry wells
  - Drainage pits
  - Large, unsealed penetrations through otherwise solid concrete floors
  - Unsealed saw-cut expansion joints in concrete floors, or floors where seals have desiccated or deteriorated over time
  - Utility conduits and surrounding granular fill, but only where there is a pressure gradient driving flow or the surrounding soil is too moist to allow appreciable vapor diffusion
  - Unlined crawlspaces, especially where the vadose zone is enough to make pumping important
  - Elevator pits and shafts
  - Open wall cavities connecting to the soil or crawlspace (Florida, 2007) or blocks that allow advective flow (see the discussion of block walls in USEPA 2008).

- Sample zones on the lowest occupied level should be prioritized. However in cases with a sparingly occupied or partial basement, sampling in both the basement and on the first floor is advisable.
- The selection of sample zones should include at least one representing each major type of heating and cooling system in use of the building. Ideally one sample zone should be assigned to each HVAC zone within the building and represent the areas likely to be negatively pressurized by the influence of exhaust fans or air returns (Tri-service Environmental Working Group, 2009; Shea, 2010).
- The selection of sample zones should include at least one occupied by each major type of employee who has the building as a routine duty station. For example buildings with both office workers and industrial workers routinely using solvents in their job duties should be divided into at least two sample zones.
- Sampling zones near the historic locations of contaminant release should be prioritized. This information may be inferred from previous site investigation reports, interviews with long term workers, or patterns in external soil gas or groundwater data sets.
- The results of this project suggest that small square footage occupied sample zones and those on exterior walls should be prioritized.

After describing the single building applications in more detail, **Section 7.2.4** will discuss generalizing this work to larger populations of buildings.

7.2.1 Single Building Prioritization – No Soil Gas or Indoor Air Data Available

The prioritization flowchart for use when only groundwater and building characteristic information is available is shown as **Figure 7-1**. The primary goal of the flowchart is to separate between:

- Cases where impacted groundwater is the only source of VOCs.
- Cases where impacted groundwater is present but a vadose zone source is also likely to be present due to a nearby release.

The flow chart also has a branch suggesting that buildings with no potential for vadose zone sources and low groundwater concentrations have very low VI potential, and do not require consideration of building or sample zone characteristics unless atypical preferential pathways are present. Buildings with atypical preferential pathways are recommended for a preferential pathway specific evaluation, with consideration for TCE rapid response if TCE is present.

However, in most cases, the flowchart leads to the need to complete the scorecard and evaluate the results using **Figure 7-5**, which provides recommendations for prioritization among buildings and sample zones. The scorecard also recommends calculating a simple index of the uncertainty of the determination, where each question in the scorecard that could not be definitively answered is assigned one point, and the total number of uncertainty points is interpreted according to **Figure 7-3**. Note that cases without sub-slab soil gas data will always score as at least moderate uncertainty, although a moderate level of uncertainty may well be acceptable if the prioritization score is low.

7.2.2 Single Building Prioritization – with Sub-slab Soil Gas Data Available

The prioritization flowchart for use when sub-slab soil gas, groundwater, and building characteristic information is available is shown as **Figure 7-2**. In this case, the sub-slab soil gas value and atypical preferential pathway information is used to conduct the initial screening. Buildings with sub-slab soil gas concentrations <33x the indoor screening level are considered to have low VI potential, and do not require consideration of building or sample zone characteristics. Buildings with atypical preferential pathways are recommended for rapid sampling consideration to manage potential acute or short-term exposure.

However, in most cases the flowchart leads to the need to complete the scorecard and evaluate the results using **Figure 7-5**, which provides recommendations for prioritization among buildings and sample zones. The scorecard also recommends calculating a simple index of the uncertainty of the determination, where each question in the scorecard that could not be definitively answered is assigned one point, and the total number of uncertainty points is interpreted according to **Figure 7-3**. Buildings with groundwater, sub-slab soil gas, and building characteristics information available receive a low uncertainty rating.

7.2.3 Single Building Evaluation with Indoor Air Data Available

When indoor air data have already been collected, there is little benefit to using the flowchart, but the scorecard can provide useful information. As the DoD VI handbook states:

> *Measured concentrations of VOCs in indoor air consist of three components:*
>
> *1. VOCs from subsurface VI*

> *2. VOCs from indoor air background sources*
>
> *3. VOCs from outdoor air background sources*
>
> *When determining whether VI is impacting the building at levels of concern, it is important to evaluate the contributions from each of these sources. Therefore, for all direct indoor air measurements, it is recommended that co-located and concurrent groundwater, near-slab or sub-slab soil gas, and outdoor air sampling be performed so that the potential confounding factors (e.g., background concentrations) can be evaluated….. [During sampling] (n)ormal activities may need to be curtailed to avoid adding volatiles to air. Stored chemicals and cleaning supplies may need to be removed from building.* (Tri-Service Environment Risk Assessment Workgroup, 2009)

In practice it is difficult to completely inventory all chemical uses in a large building and it may be impossible to curtail mission critical activities in the building during sampling. Thus, these multiple lines of evidence such as groundwater, sub-slab soil gas, and indoor air concentrations must be weighed together to evaluate the risk. Regulatory agencies frequently seek "concordance" among these lines of evidence but have provided little detail in how the inter-comparison of lines of evidence should be performed. The scoring system presented here can be helpful in evaluating whether observed indoor air concentrations are reasonably attributable to the observed sub-slab soil gas or groundwater concentration. The scoring system (interpreted according to **Figure 7-6**) provides a way to synthesize the experience of 49 other DoD buildings, to put observed indoor air concentrations in a context of what could reasonably be expected maximum concentrations in indoor air as a result of vapor intrusion at a DoD building.

In a case where the scoring system total is quite low but the indoor air concentration is high (represented by the orange box on **Figure 7-6**), it would be advisable to take additional steps to determine if an indoor source may be present. Those additional steps could include:

- Use of a compound specific, field portable, gas chromatography (GC) or gas chromatography/mass spectrometry (GC/MS) instrument to search the building for indoor sources and/or vapor entry points (Beckley et al., 2014);
- More exhaustive review and verification of chemical inventory information;
- Building pressurization/depressurization tests (McHugh et al., 2012);
- Analysis of the spatial pattern of compound ratios (i.e., PCE/TCE; PCE/TCA; etc.) in sub-slab soil gas and indoor air; and/or
- Use of tracers (i.e., radon) to determine a building-specific AF.

Background screening procedures are discussed in depth in NAVFAC (2011).

This comparison should not however be used in reverse direction. As illustrated by many of the figures in **Sections 6.2.2.1** and **6.2.2.2**, there is a wide range of indoor air concentrations experienced in indoor air associated with any given sub-slab soil gas or groundwater concentration. This is expected, because DoD buildings vary greatly in factors such as the quality/condition of the slab and amount of air exchange, parameters which were not quantified in this study. Therefore, it would be inappropriate to use a high prioritization score as a reason to discount a properly made observation of low indoor concentrations (blue box on **Figure 7-6**). However, such a dataset might suggest that substantial indoor or building envelope specific evidence may be required to allay concerns about VI. Such evidence might include multiple rounds of indoor air sampling, longer term indoor air sampling, building pressurization/depressurization tests or long term monitoring of sub-slab-indoor differential pressure.

The green box on **Figure 7-6** represents a situation where an indoor concentration above screening levels is found, and that is consistent with a high VI potential score. Under those circumstances, there are three options for next steps:

- Consider confirming exceedances and that they are due to VI (not background indoor sources);
- Decide whether to mitigate; or
- Consider conducting multiple sampling events if averaging over exposure time is allowed and conducting a building specific risk-assessment rather than making decisions based on screening levels.

In evaluating these options consideration can be made of the placement of the situation within the green box. For example, if a concentration in indoor air is observed many orders of magnitude above the screening level with only a moderately high VI potential score, which would suggest that additional effort should be placed on ruling out indoor air sources. Conversely, if an indoor concentration many orders of magnitude above screening levels is observed with a very high VI potential score, less exhaustive efforts to identify potential background sources may be undertaken. In such a situation, the mitigation option may be given higher emphasis.

Mitigation decision making should balance the degree of certainty that is available about the risks actually being present and their degree of hazard against the long-term costs, both economic and energy from mitigation system operation. While mitigation capital costs can be readily estimated, operating costs may be dependent on the degree of monitoring required by the regulatory agency or building owner. Monitoring requirements in turn currently vary dramatically across jurisdictions and with the degree of perceived risk posed by the site.

The purple box in **Figure 7-6** represents the case where low concentration indoor air results are in agreement with expectations from other lines of evidence, which are expressed by a low VI potential score. Situations close to the bottom left corner of the purple box are those with the strongest case for no further VI assessment.

7.2.4 Basewide or National Applications

The flowcharts and scoring systems are designed to be used on a single building level, because the data analysis for this project was conducted on the single building or sample zone level. However, these tools can easily be adapted to be used on a sitewide basis, by evaluating buildings individually against the scoring system and collating the results. Alternately, where multiple buildings of an essentially repetitive design and use are present, they can be evaluated as a group. Prioritizing buildings for investigation according to their risk for VI can be useful when it is desirable to evaluate the “worst case” buildings first, to determine whether risks are likely for the site as a whole (USEPA, 2009c). To date, most efforts to identify “worst case” buildings have been based only on plume maps, but this scoring system could allow such choices to take into account both environmental concentrations and building characteristics. The results of this tool can be used to integrate multiple lines of evidence when selecting sampling locations within or between buildings in accordance with USEPA (2012c, 2015).

Ultimately, it may be possible to interface this scoring system with NIRIS and with databases of Navy facilities to allow a more automated, nationwide prioritization effort to be pursued.

7.3 Applications for Long-Term Stewardship to Avoid Future Vapor Intrusion Risks

This tool can also potentially be useful for determining the type of activities that may be necessary in the future, at locations where multiple lines of evidence analysis indicate that current exposures attributable to VI are less than regulatory targets. Note that this report does not address long-term stewardship requirements for buildings with VI mitigation systems. The potential applications without mitigation are somewhat different for long-term stewardship of existing buildings and for future building construction and thus are described separately in this section although they are shown in one basic figure (**Figure 7-7**).

7.3.1 Long-term Stewardship of Existing Buildings

The USEPA (2009c) Region 3 guidance document states:

> *"In situations where the sub-slab source is significant but attenuates greatly so that the indoor air concentrations are low, and if this is confirmed through multiple sampling rounds, the project manager may elect not to take mitigative action at the building itself. However, as long as the significant source remains in the subsurface environment, follow-up monitoring of such a situation is recommended at a minimum…. Alternatively, the project manager may recommend that preventive mitigative action is the best approach."*

Such regulatory recommendations are often made because of concerns about the gradual deterioration of the building slab, the potential for building modifications, or contaminant migration.

It will be assumed here that the release to the environment in question occurred 15 or more years ago, that the plume has been stable or declining for at least 5 years, and, therefore, the soil gas concentrations can be assumed to be at quasi-equilibrium (Carr et al., 2011). A guide to the levels of long-term stewardship activity that may be appropriate with different VI prioritization scores is provided as **Figure 7-6**. Under these circumstances, the greater the VI potential and the closer to action levels indoor air concentrations are; the greater the frequency of ongoing monitoring that will likely be required. In situations with frequent monitoring requirements cost-benefit analysis can be applied to determine if mitigation for the purpose of reducing monitoring costs is merited. It is generally accepted that in mitigated structures differential pressure monitoring can substitute for some or all of the ongoing indoor air monitoring that may be required. All monitoring plans should include a provision for the eventual cessation of monitoring – for example a period of long term stewardship monitoring may provide sufficient evidence that aging of the building is not increasing the indoor air concentrations.

Similarly, the greater the VI potential the more extensive the institutional controls that will be required to prevent building modifications from introducing additional preferential flow pathways, increasing the driving forces from sub-slab to indoor air or reducing the air exchange rate.

7.3.2 Long-Term Stewardship of Future DoD Nonresidential Buildings

USEPA's Vapor Intrusion FAQs state that:

> *"Multiple lines of evidence generally should be used to assess the potential for VI in future buildings. Typically, a survey of site history and site conditions, including soil characteristics and subsurface geology, is conducted. Then, information to support a multiple lines of evidence analysis (groundwater data, soil gas data and soil concentrations) should be collected. Another line of evidence that can be used is the Johnson and Ettinger (J&E) model to estimate future conditions using typical building parameters. After appropriate lines of evidence have been obtained, the site manager should then evaluate whether ICs may be needed to complement other response actions (for example, engineered response action components) to limit the potential for VI in future buildings. For future development, the VI assessment may need to be re-evaluated because of changes in site conditions, such as land use, source remediation, or plume migration."* (USEPA, 2012c)

The scorecard developed here can be used for a multiple lines of evidence analysis for future DoD nonresidential construction. A guide to the levels of long-term stewardship activity that may be appropriate with different VI prioritization scores is provided as **Figure 7-6**. New construction provides a unique opportunity for cost effective mitigation. In certain cases of moderate VI potential building features intended for other purposes, such as moisture management, can provide adequate protection against VI (USEPA, 2008). The greater the VI potential, the more monitoring may be required after a new building is constructed. Also, the greater the VI potential, the more institutional controls may be required on future modifications of the new building that might affect its resistance to VI. This scoring system can also be used to help select sites for new construction when a choice of a location that meets other requirements exists.

8.0 COST ASSESSMENT

This project, will allow the Navy to implement more cost effective and scientifically defensible vapor intrusion evaluation strategies. Sampling approaches can be developed to optimize types and numbers of samples needed for maximum strength of the most critical lines of evidence enhancing our ability to evaluate vapor intrusion. These approaches will also ensure that the resources are directed toward obtaining only the essential data needed for VI investigations and mitigation measures. The decision framework will be a significant improvement over the current non-standard practice which is mostly based on assumptions not entirely valid for Navy industrial buildings.

A VI Assessment can run from $100K-$400K for a site with 2-10 buildings. The number of Navy VI sites is increasing and many of the sites in the database are rapidly approaching a stage where final decisions have to be made regarding VI investigations, mitigation, and monitoring. Overly conservative or unfocused VI investigations take time and cost money and can also potentially lead to implementation of costly mitigation measures not actually needed.

8.1 COST MODEL

The NESDI economic analysis tool was used to calculate Return on Investment (ROI) based on the following assumptions:

- The Navy will need to conduct 100 VI sampling events at Navy industrial buildings for VI screening
- VI sampling cost approximately $65K per sampling event
- Implementation of the VI decision framework prior to VI sampling for screening is expected to reduce the number of sampling events by 30% to 70 sampling events
- Implementation of the VI decision framework is expected to optimize the number of VI sampling locations thus reducing the cost of each sampling event by 40% to 50%.
  For ROI calculation, the sampling event cost is reduced to $35K per event for 70 sampling events.

The resulting ROI/Payback (yrs) was calculated at 0.86/1.17.

8.2 COST DRIVERS

The key outcome of this project is a VI decision framework, which is intended to be used for management of VI sites at multiple stages in the project lifecycle. The decision framework can be used to:

- Prioritize sites for initial investigation based on VI potential
- Design cost effective sampling approaches
- Evaluate whether indoor air results are reasonably consistent with other lines of evidence or whether they may be due to background sources
- Recommend the degree of vigilance needed in long-term stewardship or existing or future buildings.

Parameters affecting VI potential which must be collected to fully apply decision framework are:

- Average sub-slab concentration
- Average Groundwater Vapor Concentration
- Sample zone area
- Soil Type
- Solvent Use history
- Location of sample zone relative to exterior wall
- Existence of Atypical Preferential Pathways
- Distance to primary release

The decision framework can be applied without all of the above to various degrees of effectiveness, depending on values of parameters collected.

Cost to use the decision framework to determine VI potential at a site will depend on:

- Number and size of buildings at a site
- Availability of data needed to use framework (i.e. is data easily obtained from RI/FS report, INFADs or other sources)
- Familiarity of individual applying framework with site

8.3 COST ANALYSIS AND COMPARISON

This section presents estimated cost for applying the decision framework at a Navy industrial site where a VOC plume is present and multiple buildings are potentially impacted by VI. Assumptions for the basis of the cost analysis are:

- Five buildings at the site in question consisting of 1 large (>100,000 ft^2), 2 medium (<100,000 ft^2) and 2 small (<10,000 ft^2) buildings
- RI/FS completed or in-progress with groundwater data available and well defined plume
- Framework will be applied by contractor or RPM who is very familiar with the site and buildings at the site
- Building floorplans are readily available
- Building surveys have been conducted to identify atypical preferential pathways, background sources, sample zones and other building characteristics. (Since this type of survey is necessary for any VI investigation, with or without the decision framework application, the cost for this survey is not included in the cost analysis for framework application.)

Cost to apply framework:

1. Collection of site specific information from RI/FS, specific for decision framework application:

    - 2-8 hours (@110/hour) depending on building size = $220-$880
    - Total Cost of 1 large, 2 medium and 2 small buildings = $1980

2. Cost to run information through framework and develop recommendations based on above scenario:

    - 2 hours/building x 5 buildings = 10 hours (@110/hour) = $1,100

Total cost to apply framework based on typical site above:

$1980+$1100=$3080

9.0 CONCLUSIONS, RECOMMENDATIONS, AND IMPLEMENTATION ISSUES

9.1 Conclusions Drawn from this Study

The key conclusions of this work are drawn from an analysis of DoD commercial/industrial buildings after screening to remove the effect of indoor sources and atypical "strict" preferential pathways:

- PCE and TCE show a correlation between sub-slab soil gas and indoor air concentrations as expected; however, only very high sub-slab soil gas concentrations (relative to USEPA [2014] defaults, which are based primarily on residential buildings) result in indoor air concentrations in excess of conservative indoor air screening levels. For example, PCE concentrations in sub-slab soil gas in excess of 100,000 µg/m^3 were necessary before concentrations in indoor air exceeded the USEPA (2014) indoor air screening level of 47 µg/m^3. TCE concentrations in excess of 2,000 µg/m^3 were required in sub-slab soil gas before indoor concentrations exceeded 3.0 µg/m^3. This observed degree of concentration reduction (i.e., attenuation) across the industrial/commercial building envelopes is far greater than assumed in current screening approaches based on residential datasets. If expressed as AFs, the PCE and TCE plots suggest that use of an AF of 0.001 for military nonresidential buildings is appropriate in the absence of atypical preferential pathways. That value would be 100x less conservative than the value of 0.1 currently in use in the USEPA (2014) VISL calculator for both the residential and commercial scenarios. The cis-1,2-DCE dataset indicated that there were relatively minimal impacts on indoor air concentrations regardless of the sub-slab soil gas concentrations.

- The correlation between groundwater vapor concentration and sub-slab soil gas concentration for PCE appears approximately linear on a log-log plot, suggesting a power law relationship between the two variables. A similar but weaker relationship was observed for TCE. Analysis of the relationship between groundwater vapor concentration (calculated through Henry's Law) and indoor air suggests that exceedances of indoor air screening levels should only be expected when the groundwater vapor concentration exceeds 10,000x the indoor air screening level in DoD buildings.

- The EDA **(Appendix D)** suggested that subsurface sources of vinyl chloride do not generally result in significant VI impacts, which may be related to its aerobic biodegradation potential. 1,1,1-TCA concentrations, while somewhat more frequently detected, were well below risk-based screening levels, so discriminating VI from background sources may not be needed. All indoor air results for 1,1-DCE in the database were well below risk based screening levels and none of the samples for 1,1-DCA exceeded the industrial indoor risk based screening level **(Appendix D).** However, it was determined that the available dataset was not sufficiently large to fully explore these topics.

- Increasing sample zone area was significantly associated with decreasing indoor concentration on a log-log plot. This fits a mechanistic hypothesis that the indoor concentration should be highly diluted in large, well-mixed sample zones if the source is:
  - Due to a discrete activity

  - A preferential pathway, or
  - If vapors are intruding through only a portion of the floor in a large space.

- Higher sub-slab soil gas concentrations were associated with fine (i.e., silt or clay) soil types for PCE; TCE; trans-1,2-DCE; cis-1,2-DCE; 1,1,1-TCA; and 1,1-DCE. The median concentration in fine soils exceeded the median concentration in coarse soils by 20 times for PCE and TCE. Higher normalized sub-slab soil gas concentrations were also associated with fine soils for PCE and TCE. These results suggesting a higher soil gas concentration in fine soils was unexpected, but may have a physical explanation. Fine soils can result in a more even soil moisture distribution from the water table to the surface, which some modeling studies suggest would result in significantly higher sub-slab soil gas concentrations with fine soils. Although fine soils are generally expected in the vapor intrusion literature to be protective by reducing the rate of contaminant migration through advection and diffusion from groundwater, there are indications in the literature that an opposite effect may in fact occur. In the modeling study, Shen et al. (2013) predicted that in clay soil types that moist soils are present much closer to the foundation than would be true for a sand soil. Thus, they predict that at equilibrium, the VOC concentrations from a groundwater source will be closer to the building with fine soils. The NESDI study, unlike previous VI studies, included a significant number of buildings in which the primary release of contaminants occurred. In buildings where the release occurred, the association of fine soils with higher sub-slab concentrations with fine soils is expected since fine soils reduce mass transport through volatilization and leaching.
- A statistically significant higher median indoor air concentration of TCE was observed in sample zones with exterior walls. The odds of detection in indoor air were higher in sample zones with exterior walls for 1,1-DCA; PCE; and TCE. Median sub-slab soil gas concentrations for PCE and 1,1,1-TCA were significantly higher in sample zones with exterior walls. 1,1-DCE and 1,1-DCA were also significantly more likely to be detected in sub-slab soil gas beneath sample zones with an exterior wall. When the indoor air data were normalized, there was not a consistent exterior wall effect on the normalized indoor air concentration. Thus, the physical reasons for this observation of a higher median indoor concentration or a higher likelihood of detection in indoor air (for some compounds) are likely a complex combination of vadose zone and building envelope factors. This is a novel finding that requires replication in future studies.
- The single strongest predictor variable for high indoor concentrations, in many of the multiple regressions performed was winter sampling. "Winter" was defined in this study as a sample collected in the months from November through February.
- Multivariate analyses of indoor air data were able to explain the majority of the variance in indoor air concentration using a small number of variables that were generally also individually significant (such as sample zone area, sub-slab soil gas concentration, groundwater concentration, and depth to groundwater). For example, using the logarithm of TCE indoor air concentrations and a data subset of winter data (n=19) a model with only four terms showed an adjusted R-square value of 0.86, each of which had an individual p-term less than 0.000001. The model requires confirmation; however, not enough data were available in the database to have separate training and test datasets. Caution is urged in the

application of this model because the sign of the coefficients is not always intuitively obvious.

- In the multivariate analysis of PCE, a reduced model was selected with log indoor concentration as the outcome variable having five terms (r^2=0.80, adjusted r^2=0.74). The terms were similar to those in the TCE analysis (sample zone area, groundwater concentration, depth to groundwater, and distance to point of release). All terms in the model were individually significant with $p<0.003$, except winter sampling for which $p=0.12$. Again, caution is needed because some of the terms have unexpected signs and there were not enough available data to validate the model on an independent dataset.
- In a multivariate analysis of sub-slab soil gas concentration as the outcome, more predictor variables were individually significant than for indoor air. The sub-slab soil gas analysis showed significant correlations for some unexpected variables, which suggests hypothesis for follow-up studies. Significant correlations were also observed to sub-slab soil gas concentrations with variables that fit theoretical expectations such as groundwater concentration, distance to primary release, and building area.
- The results of this study have been used to develop a quantitative decision framework presented in **Section 7**. The decision framework takes the form of a flowchart and scoring system. Applications of the scoring system to building prioritization, interpretation of indoor air data in the context of other lines of evidence, and long-term stewardship (both current and future buildings) are included in **Section 7**.

9.2 Recommendations for Future Data Collection and Analysis

This section discusses how the results of this project can be built upon to meet the specific needs of DoD, to improve the overall understanding of vapor intrusion potential into commercial/industrial buildings, and potentially facilitate incorporating the findings into VI guidance documents on the national and state levels. The database developed in this project is designed to be expandable to serve as a routine tool for the management and analysis of VI risks at DoD sites. For example, as new toxicological information is developed, regulatory screening levels are expected to frequently change; this database could be used to understand the implications of such changes for Navy VI sites.

Ideally this database should interconnect with both environmental databases and building properties databases such as NIRIS and INFADS, which are Navy-specific. NIRIS provides analytical data from environmental measurements. Within INFADS, buildings are part of “Class 2 property” a grouping that also includes utilities located within 5 feet of the exterior wall (NAVFAC, 2008). Numerous types of information useful in VI studies are included in INFADS, such as heating systems, elevator shafts, pits and special foundations, facility area, basements, construction type, year built, and year improved.

9.2.1 Routine Data Collection at Navy Buildings Being Investigated for Vapor Intrusion

Navy CLEAN program contractors and others managing VI issues at Navy sites need to continue collecting the information needed for better understanding VI at the building level, site /operable unit level, Base level and national level. This could be accomplished through a standardized Vapor Intrusion Navy Electronic Data Deliverable (VI NEDD). The VI NEDD could be modular, with basic and advanced sections. Details of the proposed VI NEDD are presented in **Appendix G**. The basic information would be required for all building-specific studies, while the advanced section would document more extensive building science measurements such as those described in "Appendix H: Evaluating the Building Envelope in Vapor Intrusion Investigations" of the DoD VI Handbook (Tri-Service Environment Risk Assessment Workgroup, 2009). An additional benefit from this effort, is that the database and the VI NEDD developed from this project will enable Navy RPMs and contractors to update the VI database, share lessons learned from VI investigations, and thus enhance the VI-related decision-making process. The VI NEDD should be completed to include the characteristics of any zone within a building in which either a sub-slab soil gas or indoor air sample or both are collected for purposes of evaluating vapor intrusion.

When preferential pathways are identified in the field as a key element controlling internal concentrations, measurements of the concentration within the pathway and the flow rate through the pathway would be valuable. For example when a drain or sewer is determined to be the key factor, the concentration within the pipe and flow from it should both be measured at multiple time periods so contaminant flux can be calculated.

9.2.2 Follow-on Research Recommendations to NESDI and/or ESTCP

- This database and survey research project would benefit by site-specific observational studies and controlled experimental studies to further test the findings/hypothesis. Potential future activities include: **Conduct Further Study of Temporal Variability in Indoor Air** - Since the amount of temporal variability information in this database is small (as discussed in **Section 6.2.2**), the highest priority recommendation is that the Navy characterize temporal variability in several DoD industrial/commercial buildings. It is expected that such a study would likely reveal that the temporal variability characteristics of DoD buildings differs from that of residential structures.
- **Refine Methods of Distinguishing Indoor Sources from Sub-Slab Sources -**The process of screening undertaken in this study has made clear that a substantial percentage of the detections of PCE, TCE, 1,2-DCA and 1,1,1-TCA in DoD nonresidential buildings are likely attributable to indoor sources (**Table 6-1**). Therefore our second priority recommendation is that the Navy continue to refine methods for discriminating between indoor and sub-slab sources, such as pressure cycling (McHugh et al., 2012).
- **Enlarge the Number of Records in the Database -**Since the population of buildings and sample zones studied was fairly small, adding additional sites, buildings, and sampling rounds as they become available would improve the statistical power of the study, which is especially important to the multivariate analysis.
- **Improve the Information Content of the Database** - There were practical limitations to the types of information that could be entered in this project's database. The project relied on information that had already been collected and reported by other DoD projects. In most of those other projects, extensive characterization of important building science parameters had not been performed.
- **Testing of Specific Hypothesis -** This report focuses on some specific predictor variables that appeared to be promising after the EDA. Although conclusions were drawn about these variables, additional confirmatory studies would be valuable. These include: the role of

building and sample zone area/volume in controlling indoor air concentration through dilution; the role of soil type in facilitating or controlling vapor intrusion; the role of exterior walls in vapor intrusion; the role of preferential pathways in affecting sub-slab soil gas concentrations; associations between specific classes of building/sample zone uses and specific contaminants; the relationship of PCE/TCE indoor air concentrations with flooring type; the relationship between HVAC operation and sub-slab soil gas concentration.

Additional details of these recommendations are included in the subsections below.

9.2.2.1 Conduct Further Study of Temporal Variability in Indoor Air

VI remains a concern at Navy Environmental Restoration Program sites. A critical problem with VI assessments is that the current regulatory approaches assume that temporal variability in indoor air concentrations of VOCs at industrial buildings is significant and difficult to predict with current investigation methods. These approaches draw on research findings from studies in single-family residences, but have been applied uniformly to all types of buildings. The current regulatory approaches result in prolonged, extensive and costly VI investigations, and implementation of vapor mitigation measures that may not actually be needed. A demonstration that indoor air temporal variability is less significant in industrial buildings affected by VI could substantially decrease investigation costs, reduce the need to install and operate vapor intrusion mitigation systems in some cases, and lessen stakeholder and regulatory agency uncertainties in VI decision-making.

Recently-presented research findings (Johnson, 2014) from the residence in Layton, Utah, suggest that the current VI indoor air sampling strategies, using 8- or 24-hour duration sampling using Summa canisters, is ineffective in characterizing VI. It has been suggested that intensive sampling using long-term sampling (approximately two-weeks in duration) may be more effective. While the Layton, Utah, findings are constrained by being conducted in only a single residential structure, the concept of sequential long-term sampling throughout the year may have significant value in better understanding and predicting VOC temporal variability (Lutes, 2012, 2014), particularly at industrial buildings. A more detailed assessment of temporal variability in this manner could support reduced sampling, coupled with statistical data analysis methods, to better characterize indoor air variability at lower investigation costs. Previous investigations conducted at VI-affected industrial buildings at Naval Air Station (NAS) Jacksonville, Florida, involved concurrent collection of grab (e.g., 5 min), 24-hour, and two-week samples.

9.2.2.2 Refine Methods of Distinguishing Indoor Sources from Sub-Slab Sources

It would be valuable to demonstrate that near-worst case VI conditions can be induced by controlled building pressure in industrial/commercial buildings or zones within buildings. Controlled building depressurization methods, with the ability to overcome indoor air temporal variability, may provide a method for characterizing worst case VI, or VI potential, in certain buildings, with relatively few sampling events. Additional studies which build on the existing ESTCP work can refine the protocol of controlled building depressurization in industrial/commercial buildings as a VI investigation technique. Prior research funded by ESTCP (McHugh et al., 2012) has concluded that relatively small pressure gradients are sufficient to control the flow of soil gas through the building foundation, such that building pressure controls can be used to alternately pressurize and depressurize a building and either "turn off" or "turn on" soil vapor flow into that building. VOC concentrations from indoor air samples collected under these two conditions can be used to identify sources for VOC entry into a building.

DoD industrial/commercial buildings are often large, multipurpose buildings with multi-HVAC zones. VI in large industrial/commercial buildings must often be evaluated by specific zones depending on air exchange and air flow. A proposed project would apply the controlled building pressure method to individual zones in up to seven buildings, alternately depressurizing, attempting to achieve -2.5, -5 and -10 Pascals (Pa) and pressurizing attempting to achieve to +5 Pa relative to outdoors using a blower door method. Indoor air concentrations at each pressure level would be measured in real time using an Inficon HAPSITE® gas chromatograph/mass spectrometer (GC/MS). Concentrations in indoor air that are higher under depressurized conditions may be an indication that VI is occurring in a building/zone. Multiple samples per zone would be collected to develop ranges of concentrations and other descriptive statistics under pressurized and depressurized conditions. Indoor air concentrations from multiple levels of depressurization would be examined to determine if higher indoor air concentrations result from greater depressurization. Ideally this research would be coupled with a one-year temporal variability study. Building depressurization data would be collected over several two week periods during the year, to assess the effect of seasonal variability on building depressurization. Two-week and 24-hour indoor air sampling would be collected during the depressurization events, to determine if there is an effect in longer-term indoor air concentrations from induced depressurization.

9.2.2.3 Enlarging the Number of Records in the Database to Support Further Analysis

Numerous VI projects are ongoing at DoD sites which include:

- Additional monitoring rounds at sample zones contained in the database that would provide information about temporal variability, including the role of season which proved important in the multi-variate analysis.
- Additional building investigations at the same facilities contained in the database, which would improve the ability of the analysis to discriminate between geological factors and those particular to a single building (including building envelope and release history).
- Investigations of VI at facilities not included in this database, which would expand the range of geological and meteorological factors available for analysis. As discussed in **Section 5**, most of the facilities in the database currently are coastal and characterized by relatively shallow groundwater. The Northern states of the U.S. are underrepresented. Addition of Army, Air Force, or other government agency sites would be expected to make the database more nationally representative.
- The need for the database to be nationally representative is dependent on the intended purpose of the analyses performed on it. If the purpose of an analysis would be to guide the management of other Navy sites, then analyzing a database that is predominantly coastal would be acceptable. However, if conclusions are desired about how VI risks should be managed DoD-wide, or in commercial/industrial buildings nationwide, then national

geographic representation is more important. Regulatory policy and guidance are likely to be established for management of commercial/industrial/institutional buildings as a group, rather than specific to DoD buildings.

9.2.2.4 Improving the Information Content of the Database

The information included in the database could be improved by conducing more extensive characterization of important building science parameters. For example, HVAC systems were only coded in broad categories of "engineered," "zone specific," and "none." This categorization does not provide all of the information needed to evaluate HVAC systems' effect on VI:

- Whether the HVAC system provides cooling, heating, exhaust ventilation, or some combination of those (important for understanding the stack effect and building depressurization).
- Whether the HVAC system is operated continuously, only when the building is occupied, or only when cooling or heating is required.
- Whether the HVAC system is operated in a 100% recirculation, with a fixed percentage of outside air added to the recirculation air, or with a variable percentage of outside air added to the recirculation air.

Coding suggestions for a standardized data collection approach for HVAC systems are provided in **Section 9.2.1**.

The database also did not contain extensive information about floor systems. Although most of the buildings were slab-on-grade, information was not generally available in the underlying reports about:

- Slab thickness
- Condition of slab (degree of cracking)
- Presence, depth, and location of thickened features that may control sub-slab soil gas migration such as load beams, footings, foundation walls, piers, etc.
- Presence and type of expansion or control joints in the slab
- Presence of membranes or moisture barriers beneath the slab that may have been installed for purposes of moisture or soil gas control
- Presence of sub-slab gravel or aggregate layers
- Presence of sub-slab drain tiles or pipes

Much of this information could be gathered from review of historic drawings at DoD facilities, although the process would be laborious.

The database did not attempt to segment the building according to formal HVAC zones and did not include measurements of air exchange rate. HVAC zones are generally defined as portions of the building in which air circulation is controlled by a given thermostat to maintain thermal comfort. HVAC zones can be readily identified from mechanical diagrams of the building and sometimes field observations. Minimum mechanical air exchange rates in modern buildings will have been defined during the design process. The database did not contain information about the above-grade building envelope that would contribute to air exchange, such as the degree of weatherization, or the presence of roof vents. The database did not contain information about the number and type of doors and their usual operation, which may to be important to evaluating VI in facilities such as hangars and warehouses where large doors are commonly kept open during many of the operating hours.

Since many of the facilities studied were located in mild climates, were constructed many years ago, and were not fully served with engineered HVAC systems it is likely that open windows may have also contributed to air exchange rates in some buildings. Information on window type, number, and operation was not included in the database.

Because VI is believed to be temporally variable, it would also be beneficial to include basic meteorological information for the sampling period, such as mean external temperature, mean internal temperature, precipitation over a proceeding time period, wind speed, and direction. With the exception of interior temperature, most of this information is publically available, but would require a significant effort to extract by matching sampling date/time information with public records for the nearest weather station. It would also be beneficial to include climatological information for the facilities, which could be easily assigned based just on their known locations, according to the Koppen classification for example.

In addition to the building science parameters, some additional information about the subsurface conditions would be a valuable addition to the database:

- Information about the presence or absence of light non-aqueous phase liquids (LNAPL) or DNAPL in proximity to the building. Although this project did not seek to study petroleum hydrocarbon compounds, information about the presence or absence of these common co-contaminants would have enabled additional mechanistic analysis of the behavior of biodegradable chlorinated aliphatic hydrocarbons, for which co-metabolic processes under either aerobic or anaerobic conditions can be important. Some information on the dissolved phase and sub-slab concentrations of hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX) is available in the underlying database but was not analyzed for that purpose. Some additional data, such as total petroleum hydrocarbon (TPH) concentrations in groundwater can be found in NIRIS.
- Data on soil moisture content, which is generally believed to be a critical control on VOC transport in the vadose zone. Such information may have been collected at many sites in order to report concentrations of soil analytes on a dry solids basis; but was not included in this database.
- Indications of the degree of annual variation in the water table depth. This has also been considered a key controlling factor for mass transport between the saturated and vadose zones.
- Soil gas concentrations, at locations other than sub-slab. This would be especially valuable if they were available at multiple depths.
- Information about mass storage or source architecture. For example, some workers characterize storage as being predominantly from free-phase DNAPL vs. adsorbed mass vs. matrix diffusion. This in turn effects the amount of flux of contaminant the source can

deliver. Leading references for these concepts include Environment Agency (2003) and Brusseau (2013).

9.2.2.5 Testing of Specific Hypothesis

Statements have been made in the peer-reviewed literature that question whether the fundamental understanding of the VI conceptual model currently in the field is accurate. For example:

> *"This shows that there must exist processes, which keep the measured indoor air concentration from changing linearly with calculated ground- water source vapor or measured sub-slab soil vapor concentration…. In the United States Environmental Protection Agency's vapor intrusion (VI) database, there appears to be a trend showing an inverse relationship between the indoor air concentration attenuation factor and the subsurface source vapor concentration. This is inconsistent with the physical understanding in current vapor intrusion models."* (Yao, 2013b)
>
> Others have questioned whether the "classic" model of VI, i.e., that VI predominantly arises from transport from groundwater which off-gasses, leading to diffusion through deep soil gas, then advection from shallow soil gas to indoor air, is really the dominant mechanism.
>
> Some have suggested that vadose zone transport, vadose zone mass storage, or preferential flow paths are actually predominant. Therefore, although it was not the original goal of this project, there is a potential for this database (or an expanded version of it) to be used to analyze the agreement of large building data with the various steps of the model.

This report focuses on some specific predictor variables that appeared to be promising after the EDA. Although conclusions were drawn about these variables, additional confirmatory studies would be valuable, for example:

- The role of building and sample zone area/volume in controlling indoor air concentration through dilution could be more definitively explored by an intensive study of specific sites where a large group of collocated buildings are dominated by a single groundwater source. The selected site should have a well-defined groundwater or deep soil gas concentration spatial pattern. The buildings selected for such a study could be those in which a primary release is not expected. Near simultaneous measurements could be made in several buildings during several seasonal sampling rounds. Tracer gasses could be used to estimate soil gas entry rates and air exchange rates for the studied sample zones. Such a study would also allow alternative/ novel hypotheses suggested in **Appendix E** to be explored, such as that VI may increase with increasing building height due to the stack effect.
- The role of soil type in facilitating or controlling vapor intrusion could best be explored through multiple studies of individual buildings and their immediate surroundings. Separate buildings could be selected for such a study that were known to be controlled by groundwater transport, and known to be controlled by primary releases at the building. Measurements of groundwater concentration in well-defined narrow-screened intervals in the upper most zone of the shallow aquifer could be coupled with simultaneous multi-depth soil gas concentration measurements and indoor air concentration measurements. Differential pressure measurements could also be continuously acquired to document driving forces. Tracer gasses could be used to measure the volumetric flow rate of soil gas

into the building. Water table variations would be observed and sets of observations gathered at various water table stages.

- A mechanistic understanding of the role of exterior walls in VI suggested by this study could be improved through intensive single-building studies. Buildings would be selected for study with well-documented foundation systems, including typical features believed to be important such as floating slabs and continuous footings/load beams. Sub-slab soil gas concentration would be collected systematically across the building in intersecting transects or a grid pattern. The segmentation of the sub-slab zone would be defined through either vacuum influence testing or tracer testing. The overlying segmentation of the indoor spaces into HVAC zones could also be mapped. Simultaneous indoor and sub-slab soil gas samples could be taken, along with differential pressure measurements. Field instruments could be used to document specific soil gas entry points.

Appendix E of this report also suggests some hypotheses about VI that the dataset was not sufficient to verify:

- Data analysis suggested that the presence of preferential pathways or specific subgrade structures such as pits or vaults may actually reduce soil gas concentrations, presumably by having facilitated gradual venting over time. This could be best investigated by intensive single-building studies that use tracers to relate soil gas flow rates from the sub-slab into the structure, sub-slab soil gas exchange rates with outside air to mass flux leaving the sub-slab layer. However, it is also important to understand where those vapors are migrating.
- A larger dataset would allow potential associations between specific classes of building/sample zone uses and specific contaminants/indoor sources to be better explored. For example, relatively high concentrations of PCE were observed in offices. This may be due either to the current use of PCE as a dry cleaning agent, the colocation of office functions in buildings with industrial uses of PCE are ongoing, or to historical releases of PCE to the environment.
- The data analysis suggested an association between PCE and TCE indoor concentrations with bare concrete or vinyl sheet flooring (Appendix E.1.13). The dataset was not large enough to determine whether this could be causative (for example, sorption by the carpet, carpet backing, or wood) or whether this is a confounded observation. Confounding could occur because it is expected that bare concrete and vinyl tile are flooring types associated with more industrial and utilitarian spaces, which are more likely to have indoor sources, or be proximate to the point of release. A larger dataset with reliable information on primary release point, HVAC zones, floor coatings, and building uses would be needed to unravel this relationship. Alternately, field studies could be conducted at locations with known vapor intrusion at levels that did not require mitigation but where floor coverings were scheduled for replacement.
- For several contaminants, the concentrations in sub-slab soil gas beneath zones with engineered HVAC systems (as compared to zones with no HVAC system or only zone-specific HVAC) were notably higher. A possible mechanistic explanation for these observations is that positively pressurized indoor environments minimize the natural attenuation of VOC concentrations in the sub-slab via volatilization. However, the statistical power of this observation is limited, because the engineered HVAC systems are by far the

most frequent case in the dataset. This is another example where a larger dataset might allow causative and confounding factors to be better distinguished. Alternately, intensive single-building studies could potentially observe the mass transfer rates out of the sub-slab zone with the HVAC system turned on and off.

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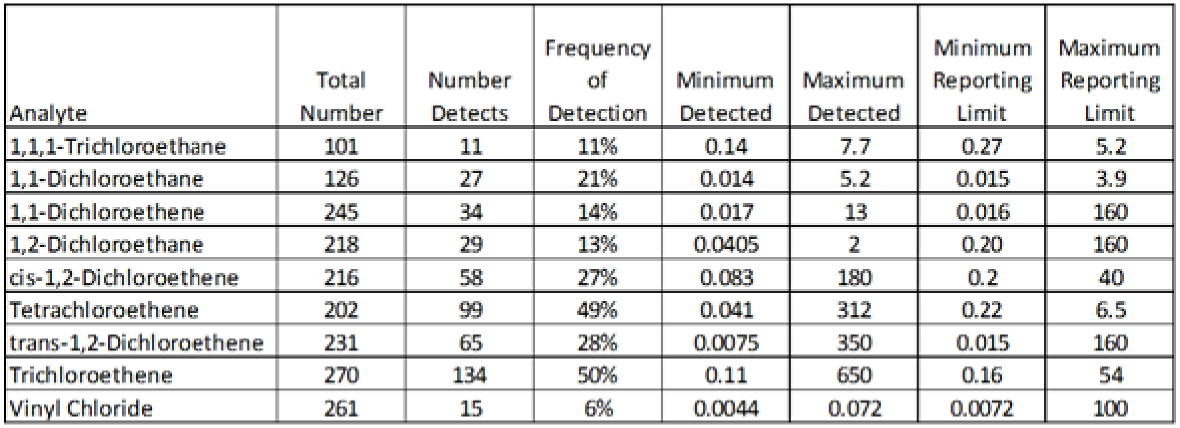
Tables

Table 4-1. Building Use and Number of Buildings in Project Database

NESDI Project #476

Building Use	Number of Buildings	Percent
Garage/boathouse	2	4%
Industrial or Shop	23	47%
Mixed use	8	16%
Office	11	22%
Residential (Barracks)	2	4%
Retail	1	2%
Warehouse	2	4%
Total	**49**	

Table 5-1. Frequency of Detection of VOCs in Indoor Air Samples



Analyte	Total Number	Number Detects	Frequency of Detection	Minimum Detected	Maximum Detected	Minimum Reporting Limit	Maximum Reporting Limit
1,1,1-Trichloroethane	101	11	11%	0.14	7.7	0.27	5.2
1,1-Dichloroethane	126	27	21%	0.014	5.2	0.015	3.9
1,1-Dichloroethene	245	34	14%	0.017	13	0.016	160
1,2-Dichloroethane	218	29	13%	0.0405	2	0.20	160
cis-1,2-Dichloroethene	216	58	27%	0.083	180	0.2	40
Tetrachloroethene	202	99	49%	0.041	312	0.22	6.5
trans-1,2-Dichloroethene	231	65	28%	0.0075	350	0.015	160
Trichloroethene	270	134	50%	0.11	650	0.16	54
Vinyl Chloride	261	15	6%	0.0044	0.072	0.0072	100

Table 5-2. Frequency of Detection of VOCs in Sub-slab Soil Vapor Samples

Analyte	Total Number	Number Detects	Frequency of Detection	Minimum Detected	Maximum Detected	Minimum Reporting Limit	Maximum Reporting Limit
1,1,1-Trichloroethane	150	96	64%	0.2728	530,000	1.1	60,021
1,1-Dichloroethane	142	59	42%	0.6	96,000	0.81	44,522
1,1-Dichloroethene	263	46	17%	0.74	114,980	0.19	280,000
1,2-Dichloroethane	269	6	2%	0.4047	2.1	0.18	280,000
cis-1,2-Dichloroethene	213	95	45%	0.13	475,779	0.19	280,000
Tetrachloroethene	219	202	92%	0.5494	16,956,033	1.15	10,852
trans-1,2-Dichloroethene	244	87	36%	0.1	110,000	0.18	280,000
Trichloroethene	260	222	85%	0.095	7,000,000	0.18	1,666
Vinyl Chloride	272	7	3%	0.088	40,000	0.18	180,000

Table 5-3. Literature Indoor Air Background Concentration Information Used in This Study

: Analyte	90th percentile of the BASE study indoor air distribution (NYSDOH, 2006 Appendix C-2)	Median of 90th Percentile Concentration from multiple studies as used in USEPA, 2012a	95th Percentile Rago, 2014, Commercial Buildings	Selected background value for the purpose of this study and for indoor air screening	Source Strength Screening Level for Sub-slab = 50X selected value	Source Strength Screening Level for Groundwater Vapor = 1000x selected value
	100 public and commercial office buildings, Sampled 1994-1996, Three samples per building	Fifteen studies of residences sampled 1990-2005, total 2898 samples	10 Offices and 10 schools, sampled 2013 in Mass; some multiple floors, total 37 samples			
1,1,1-Trichloroethane	20.6	3.1	0.3	20.6	1030	20600
1,1-Dichloroethane	<0.7	<RL		<RL	<RL	<RL
cis-1,2-Dichloroethene	<1.9	<RL		<RL	<RL	<RL
Tetrachloroethene	15.9	3.8	8.2	15.9	795	15900
Trichloroethene	4.2	0.5	24.6	4.2	210	4200
Vinyl Chloride	<1.9	0.01		0.01	0.5	10
1,1-dichloroethane	<0.7	<RL		<RL	<RL	<RL
1,1- Dichloroethene	<1.4	0.8		0.8	40	800
1,2- Dichloroethane	<0.9	0.1		0.1	5	100

Table 6-1. Number of Detected Concentrations in Indoor Air after Each Screening Step

Detected Indoor Air	TCE	PCE	cis-1,2-DCE	trans-1,2-DCE	1,2-DCA	1,1-DCA	1,1,1-TCA	VC
No screen	134	99	58	65	29	27	11	15
Baseline screen	133	99	58	65	29	27	11	15
Baseline screen + Source strength screen	98	64	58	65	8	27	9	9
Baseline screen + Background screen	48	8	58	65	22	27	0	10
No screen + Preferential pathway=false	107	78	37	56	28	11	11	8
Baseline screen + Source strength screen + Preferential pathway=false	78	43	37	56	7	11	9	2
Baseline screen + Background screen + Preferential pathway=false	39	7	37	56	22	11	0	6

Table 6-2. Descriptive Statistics of Detection Limits for Nondetectable Samples in Indoor Air and Soil Gas

	Indoor Air	**Nondetects Distributions of Detection Limits**							
Percentile	**Trichloroethene**	**1,1-Dichloroethene**	**1,2-Dichloroethane**	**Vinyl Chloride**	**1,1,1-Trichloroethane**	**1,1-Dichloroethane**	**cis-1,2-Dichloroethene**	**Tetrachloroethene**	**trans-1,2-Dichloroethene**
5th	0.21	0.25	0.25	0.01	0.41	0.29	0.32	0.23	0.02
25th	0.23	0.39	0.40	0.21	0.50	0.41	0.38	0.31	0.32
50th	0.50	0.57	0.65	0.51	0.59	0.54	0.75	0.45	0.75
75th	1.07	10.00	10.00	5.11	0.89	0.79	10.00	0.57	10.00
90th	13.00	10.00	10.00	6.00	1.36	1.01	10.00	1.07	10.00
95th	13.00	10.00	10.00	6.00	2.01	1.42	10.00	2.03	10.00

	Sub-Slab Soil Gas	**Nondetects Distributions of Detection Limits**							
Percentile	**Trichloroethene**	**1,1-Dichloroethene**	**1,2-Dichloroethane**	**Vinyl Chloride**	**1,1,1-Trichloroethane**	**1,1-Dichloroethane**	**cis-1,2-Dichloroethene**	**Tetrachloroethene**	**trans-1,2-Dichloroethene**
5th	0.19	0.23	0.22	0.20	1.27	1.01	0.22	1.21	0.21
25th	0.46	0.59	0.73	0.48	4.33	1.30	0.44	13.56	0.52
50th	2.23	1.20	1.30	1.20	27.41	8.09	1.10	17.00	1.98
75th	61.75	18.00	40.47	29.00	210.00	54.83	156.61	80.00	95.00
90th	1074.76	200.00	226.66	214.00	1129.48	752.82	987.24	424.00	467.85
95th	1144.62	1014.10	955.20	935.58	4918.98	1206.14	6530.00	2754.37	1229.10

Table 6-3. Distributions of Detection Limit Values for Non-detectable Samples in Indoor Air and Sub-slab Data Sets

	Indoor Air	Nondetects Distributions of Detection Limits (µg/m^3)							
Percentile	Trichloroethene	1,1-Dichloroethene	1,2-Dichloroethane	Vinyl Chloride	1,1,1-Trichloroethane	1,1-Dichloroethane	cis-1,2-Dichloroethene	Tetrachloroethene	trans-1,2-Dichloroethene
5th	0.21	0.25	0.25	0.01	0.41	0.29	0.32	0.23	0.02
25th	0.23	0.39	0.40	0.21	0.50	0.41	0.38	0.31	0.32
50th	0.50	0.57	0.65	0.51	0.59	0.54	0.75	0.45	0.75
75th	1.07	10.00	10.00	5.11	0.89	0.79	10.00	0.57	10.00
90th	13.00	10.00	10.00	6.00	1.36	1.01	10.00	1.07	10.00
95th	13.00	10.00	10.00	6.00	2.01	1.42	10.00	2.03	10.00

	Sub-Slab Soil Gas	Nondetects Distributions of Detection Limits (µg/m^3)							
Percentile	Trichloroethene	1,1-Dichloroethene	1,2-Dichloroethane	Vinyl Chloride	1,1,1-Trichloroethane	1,1-Dichloroethane	cis-1,2-Dichloroethene	Tetrachloroethene	trans-1,2-Dichloroethene
5th	0.19	0.23	0.22	0.20	1.27	1.01	0.22	1.21	0.21
25th	0.46	0.59	0.73	0.48	4.33	1.30	0.44	13.56	0.52
50th	2.23	1.20	1.30	1.20	27.41	8.09	1.10	17.00	1.98
75th	61.75	18.00	40.47	29.00	210.00	54.83	156.61	80.00	95.00
90th	1074.76	200.00	226.66	214.00	1129.48	752.82	987.24	424.00	467.85
95th	1144.62	1014.10	955.20	935.58	4918.98	1206.14	6530.00	2754.37	1229.10

Table 6-4. Sample Zones with More than 3x observed PCE Sub-slab Variability

Sample Zone Number	Sample Zone Area	Building Area	Max Building Height	Analyte	Number of Pairs	Number of IA Samples	Average IA	Max IA	Min IA	(max)/ (min)	Number of SG Samples	Average SG	Max SG	Min SG	(max)/ (min)
1606-1	47000	64,800	18	PCE	8	2	3.15	5.97	0.34	18	3	6844	20347	2	10,000.1
37-1	200	10,068	18	PCE	10	3	2.03	4.54	0.20	22	2	37341	74607	75	1,000.0
3703-1	0	78,500	36	PCE	52	4	3.10	4.34	1.70	3	26	149651	1424307	2577	552.6
902-2	700	64,800	18	PCE	4	1	12.21	12.21	12.21	1	2	2012	4002	23	173.5
1606-2	23000	64,800	18	PCE	8	2	3.39	6.51	0.27	24	3	742	2103	21	100.0
137-5	65900	620,400	25	PCE	8	1	0.51	0.51	0.51	1	2	19	36	2	17.1
101N-2	6200	7,440	22	PCE	3	1	0.56	0.56	0.56	1	3	30	68	7	9.3
HP57-1	1200	15,000	30	PCE	7	3	2.26	3.19	0.88	4	5	5	14	2	8.0
137-2	5300	620,400	25	PCE	0	1	0.51	0.51	0.51	1	2	412	730	94	7.8
133-1	130000	279,700	42	PCE	24	1	0.49	0.49	0.49	1	9	93	190	26	7.3
10	1200	7,680	13	PCE	16	2	5.77	11.00	0.54	20	2	3	5	1	6.5
133-3	32000	279,700	42	PCE	16	2	0.45	0.50	0.40	1	3	740	1300	230	5.7
103-1	4050	64,130	20	PCE	2	1	0.43	0.43	0.43	1	2	23600	40000	7200	5.6
902-1	13400	64,800	18	PCE	0	1	0.07	0.07	0.07	1	2	6443	10852	2035	5.3
1284-A	1800	12,000	10	PCE	0	6	0.36	0.45	0.25	2	6	35	55	11	5.1
1601-1	2916	66,165	23	PCE	32	4	0.31	0.47	0.14	4	5	297	509	102	5.0
101S-1	600	79,152	58	PCE	1	1	2.90	2.90	2.90	1	3	91	160	33	4.8
3B-1	545	1,600	15	PCE	8	3	112.36	311.99	8.82	35	2	10444916	16956033	3933800	4.3
103-3	1200	64,130	20	PCE	2	1	3.40	3.40	3.40	1	2	74000	120000	28000	4.3
1601-2	57165	66,165	23	PCE	8	2	0.51	0.81	0.20	4	3	554	1017	258	3.9
HP57-2	400	15,000	30	PCE	4	2	1.56	2.10	1.02	2	3	9	14	4	3.4
1253-B	15975	18,000	40	PCE	12	4	0.31	0.35	0.26	1	4	30	47	15	3.1

Table 6-5. Sample Zones with More Than 3x Observed TCE Sub-slab Variability

Sample Zone	Sample Zone Number	Sample Zone Area	Building Area	Max Building Height	Analyte	Number of Pairs	Number of IA Samples	Average IA	Max IA	Min IA	(max)/(min)	Number of SG Samples	Average SG	Max SG	Min SG	(max)/(min)
Medical Training Simulation	902-1	13,400	64,800	18	TCE	4	1	13.43	13.43	13.43	1	2	994160	1988315	6	336364.0
Warehouse open area	Shed 3-2	45,906	13,125	26	TCE	40	10	84.20	170.00	35.00	5	8	1610319	7000000	450	15555.6
Front Warehouse	133-1	130,000	279,700	42	TCE	24	1	0.49	0.49	0.49	1	10	7987	31000	2	14761.9
Lounge	HP57-2	400	15,000	30	TCE	4	2	2.28	4.35	0.22	20	3	1795	5374	0	11112.1
Open shop areas	Shed 6-1	43,438	50,723	22	TCE	50	17	48.94	130.00	3.00	43	10	195769	1500000	290	5172.4
Company Office	HP57-1	1,200	15,000	30	TCE	4	3	0.29	0.54	0.12	5	4	381	1505	1	1473.7
Test Bay	3703-1	0	78,500	36	TCE	52	4	0.27	0.28	0.27	1	26	2656	15047	22	682.9
101C:AI01/GS04/GS05	101C-1	2,100	35,000	36	TCE	2	1	1.20	1.20	1.20	1	2	710	1400	20	70.0
101C:AI02/GS01/GS03	101C-2	6,985	35,000	36	TCE	2	1	0.50	0.50	0.50	1	2	343	670	15	44.7
Retail Area	1606-1	47,000	64,800	18	TCE	8	2	2.55	4.73	0.38	13	3	7	18	0	42.5
103:AI06/GS02/GS10/GS09	103-1	4,050	64,130	20	TCE	2	1	0.46	0.46	0.46	1	2	3705	7200	210	34.3
Office Space	1601-1	2,916	66,165	23	TCE	32	4	0.81	0.97	0.70	1	6	12996	32780	1129	29.0
Womens Restroom	37-1	200	10,068	18	TCE	4	3	0.82	1.07	0.64	2	2	33	64	2	26.7
105:AI02/GS04	105-2	1,200	54,978	27	TCE	2	1	0.48	0.48	0.48	1	2	21	41	2	25.6
101N:AI02/GS02/GS03/GS04/GS10	101N-2	6,200	7,440	22	TCE	3	1	0.44	0.44	0.44	1	3	599	1400	87	16.1
795:AI02/GS03/GS04	795-2	16,800	58,240	34	TCE	2	1	4.50	4.50	4.50	1	2	14	25	3	9.6
Supply Area	1606-2	23,000	64,800	18	TCE	4	2	2.71	5.16	0.27	19	3	3	6	1	9.2
Back Right warehouse	133-3	32,000	279,700	42	TCE	16	2	2.15	3.10	1.20	3	3	62000	100000	14000	7.1
U10 - 9004 - 9028 U10 - 9003 - 902	1253-B	15,975	18,000	40	TCE	8	4	0.23	0.31	0.18	2	4	1	2	0	6.3
103:AI03/GS01/GS12	103-3	1,200	64,130	20	TCE	2	1	1.20	1.20	1.20	1	2	19750	34000	5500	6.2
Office 1	1556-1	64	90,984	47	TCE	4	6	7.32	17.00	0.11	155	2	11	18	3	5.8
PMO Storage	3B-1	545	1,600	15	TCE	8	2	1.75	3.22	0.27	12	2	21227	36005	6449	5.6
Room 113	6	360	91,000	12	TCE	4	1	0.21	0.21	0.21	1	2	19	31	6	5.1
101S:AI01/GS01/GS02/GS03	101S-1	600	79,152	58	TCE	0	1	2.30	2.30	2.30	1	3	73	130	26	5.0
Test Room	3402-2	3,540	3,940	15	TCE	8	1	0.47	0.47	0.47	1	2	15	24	6	3.9
U10 - 9011 - 9033 U10 - 9010 - 90	1284-A	1,800	12,000	10	TCE	0	6	0.21	0.23	0.19	1	6	0	1	0	3.8
Drum Storage	137-3	4,300	620,400	25	TCE	4	1	1.90	1.90	1.90	1	2	2030	3100	960	3.2
General Warehouse	1601-2	57,165	66,165	23	TCE	8	2	0.73	0.75	0.70	1	3	29914	53738	16659	3.2
Conference/Office	10	1,200	7,680	13	TCE	16	2	0.33	0.45	0.21	2	2	0	0	0	3.1
Room 125	1	360	91,000	12	TCE	8	2	0.21	0.21	0.21	1	4	148	240	81	3.0

Figures

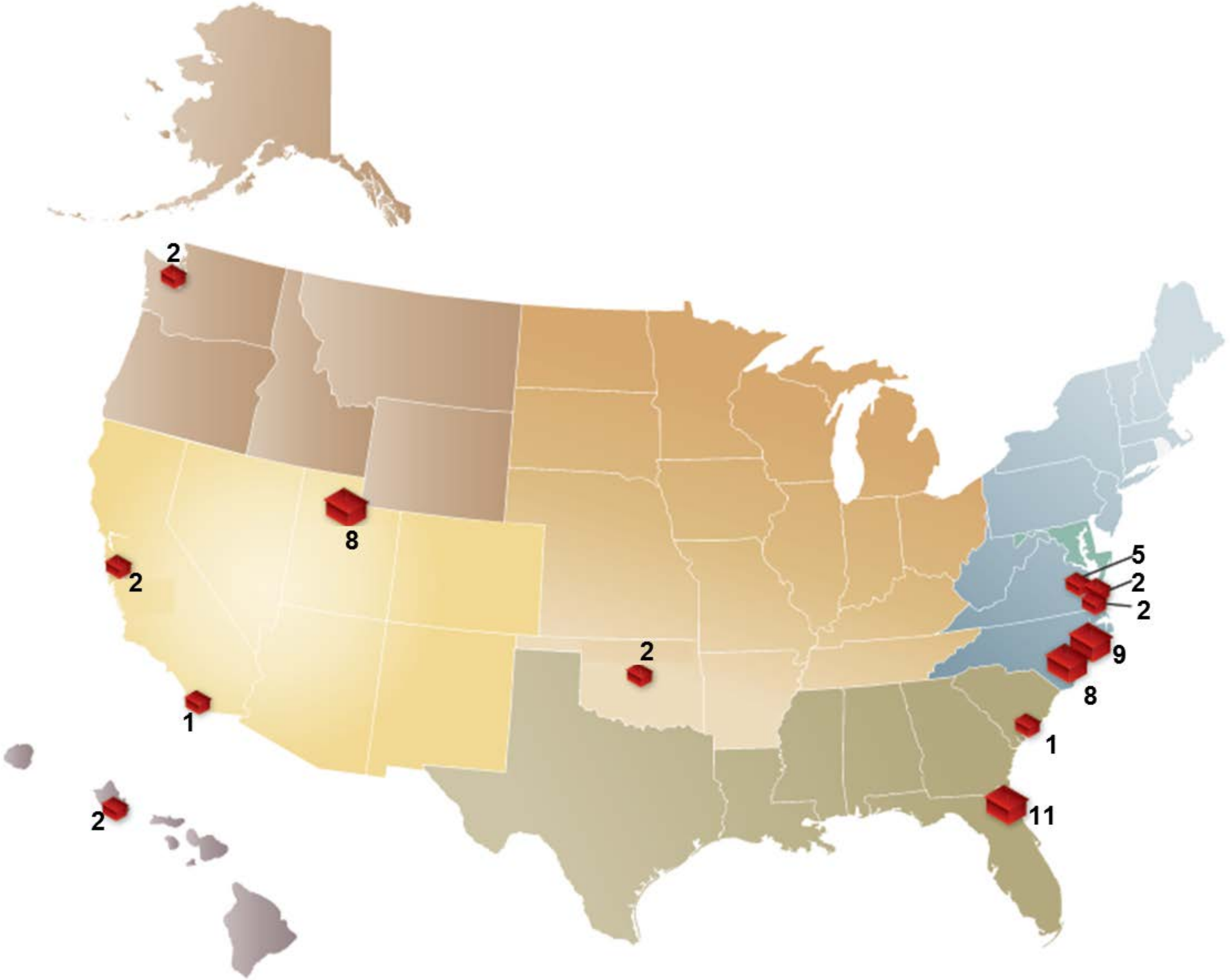
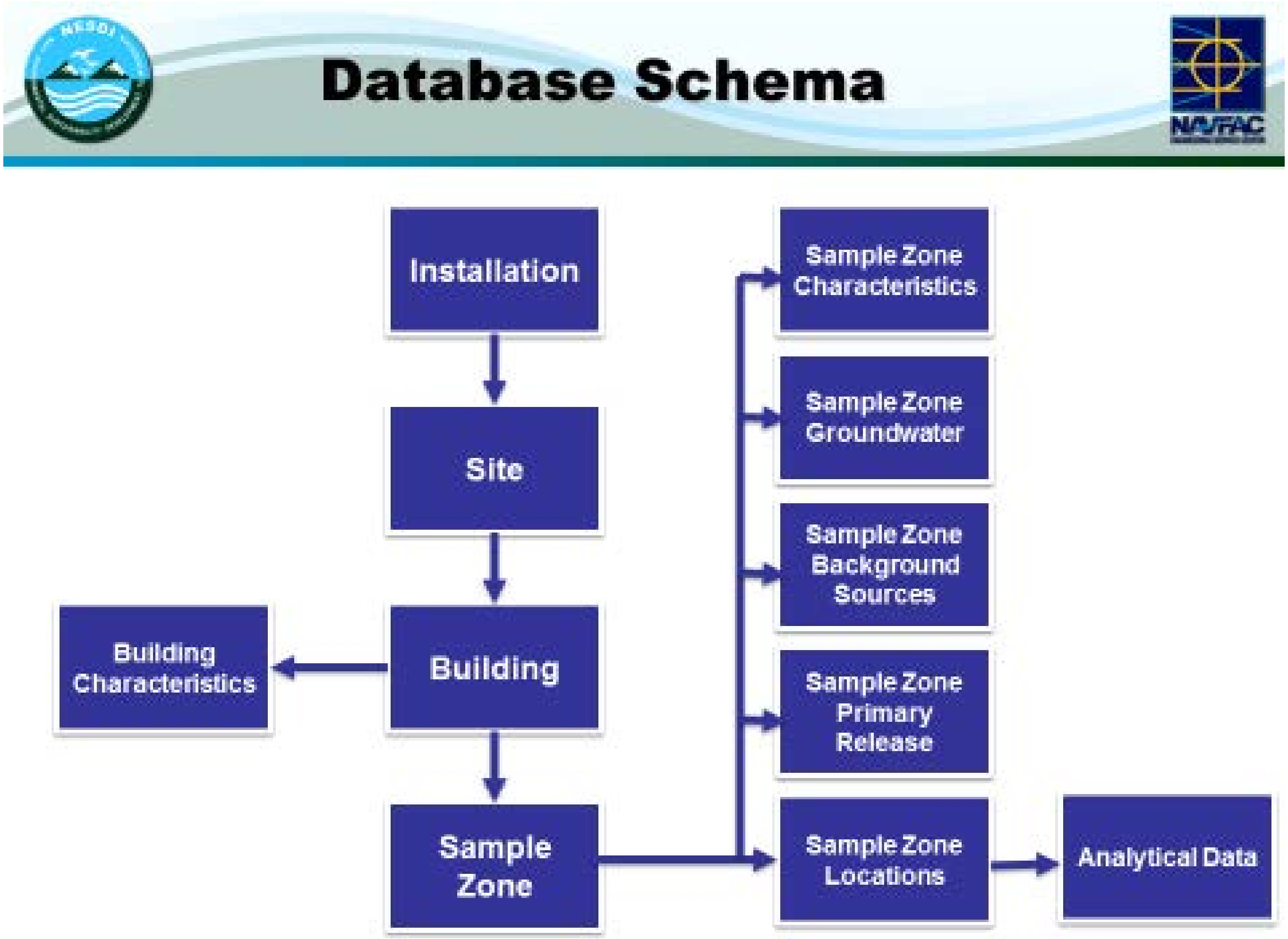


Figure 4-1. Facilities in Database



Database Schema

Installation

Site

Building

Building Characteristics

Sample Zone

Sample Zone Characteristics

Sample Zone Groundwater

Sample Zone Background Sources

Sample Zone Primary Release

Sample Zone Locations

Analytical Data

Figure 5-1. Database Schema
NESDI Project #476

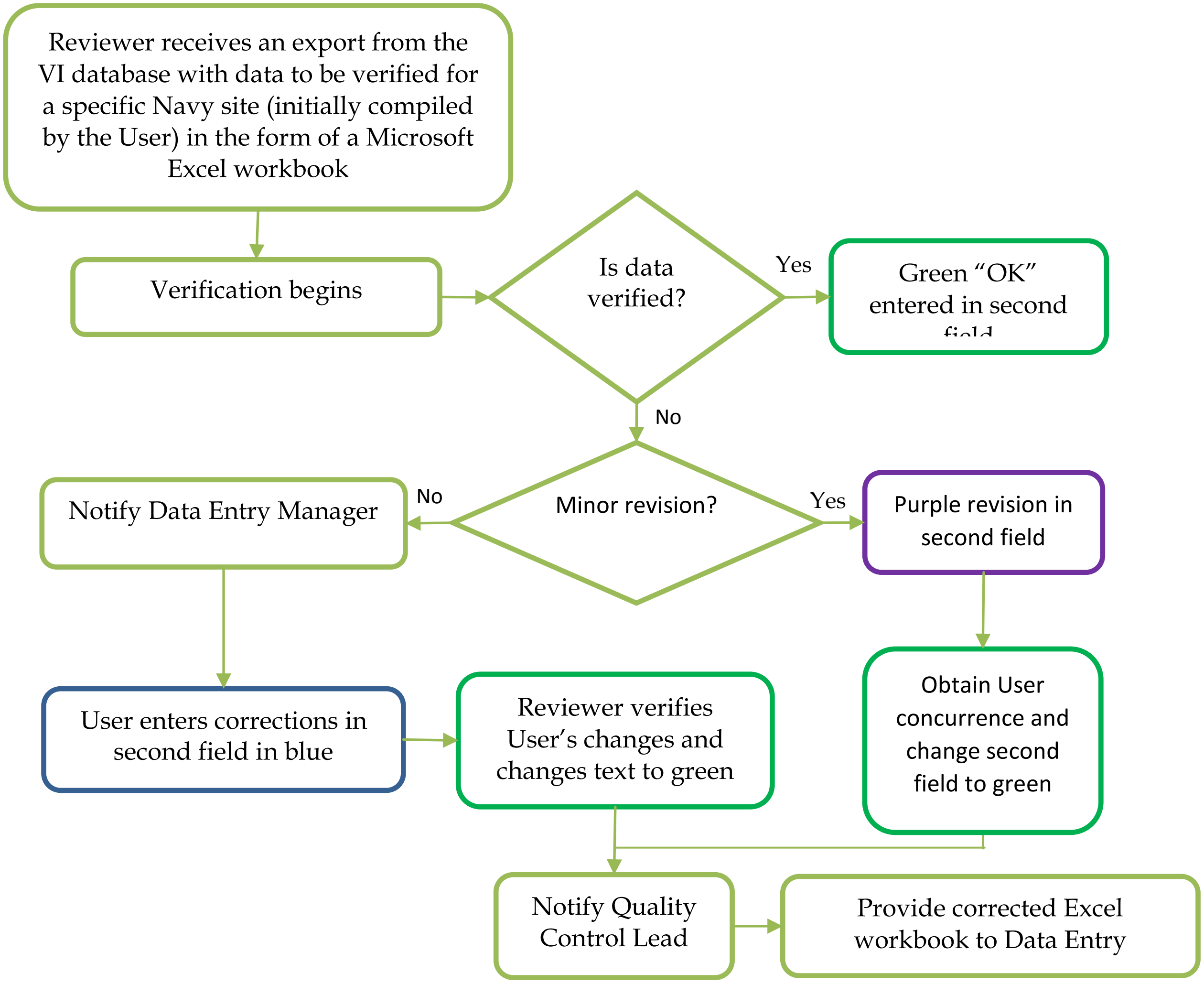
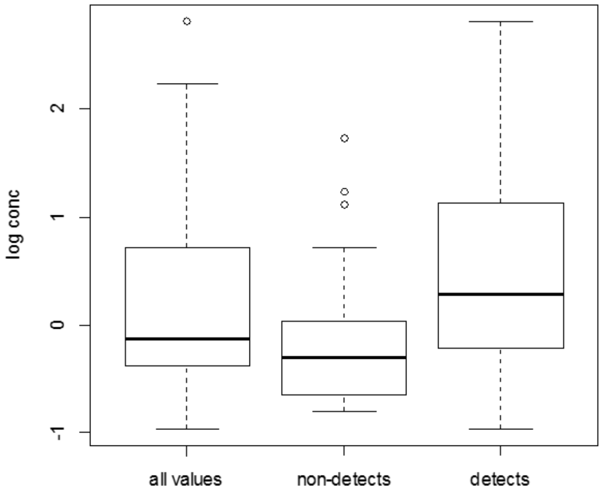
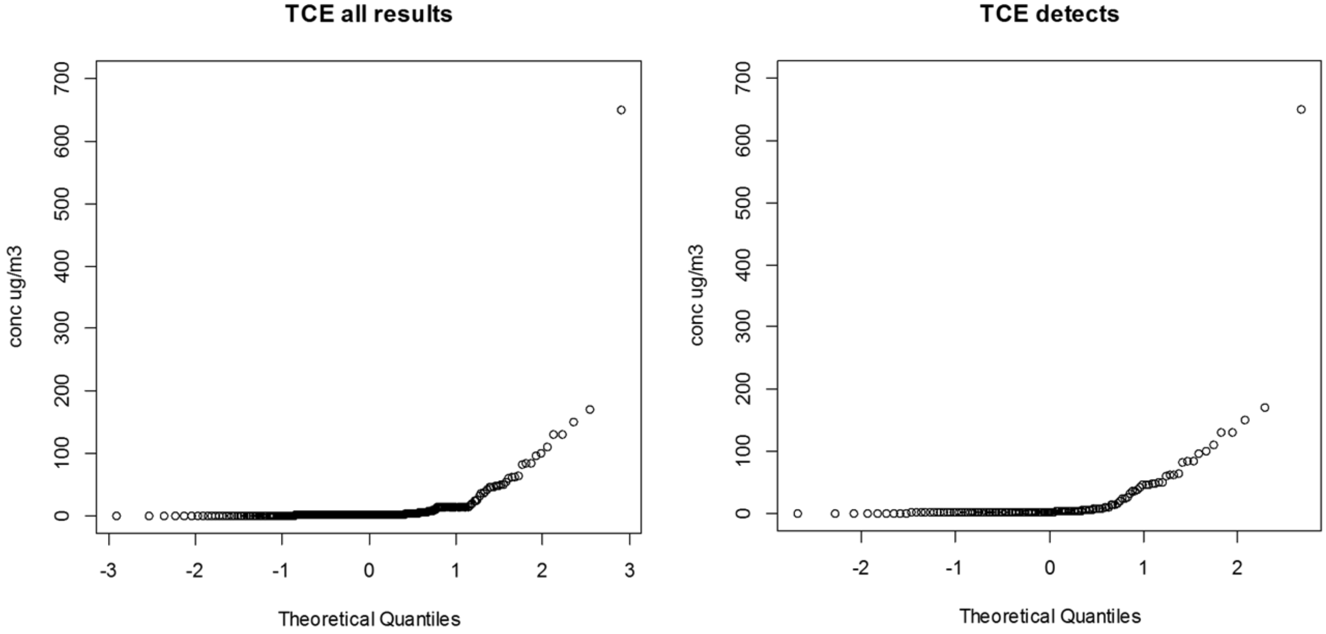


Figure 5-2. Flowchart of Quality Control/Quality Assurance Process
NESDI Project #476



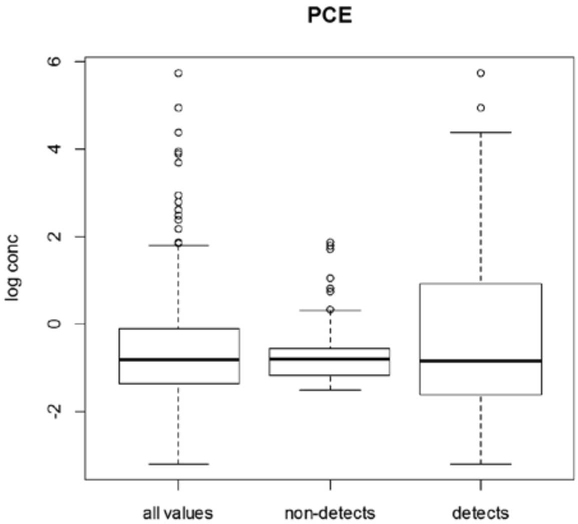
TCE

	KM	All Results	Detects
25th	0.13	0.42	0.62
50th	0.42	0.75	1.9
75th	2.6	5	13
90th	31	31	61
95th	62	61	97


TCE all results

TCE detects

Figure 5-3. Graphical Analysis and Order Statistics of TCE Indoor Air Data
NESDI Project #476



PCE

	KM	All Results	Detects
25th	0.13	0.26	0.2
50th	0.20	0.44	0.43
75th	0.47	0.9	3
90th	3.2	4	11
95th	11	11	41

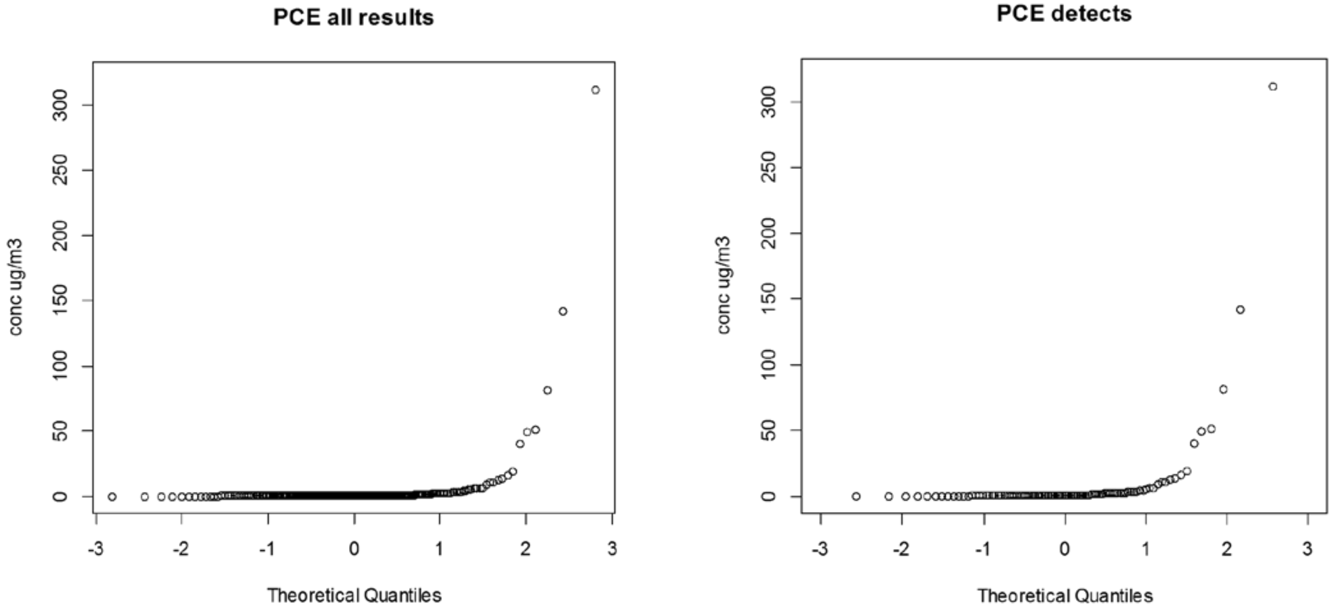
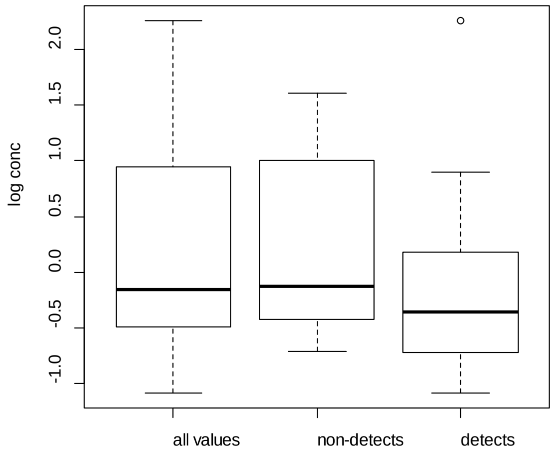
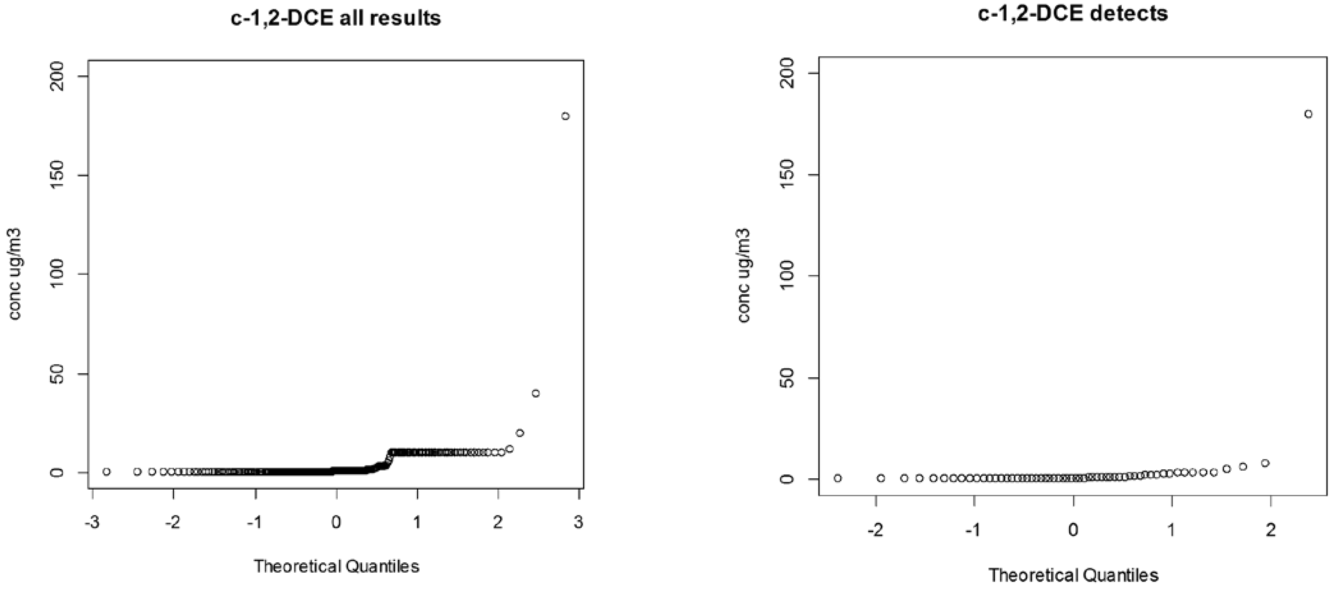


Figure 5-4. Graphical Analysis and Order Statistics of PCE Indoor Air Data
NESDI Project #476



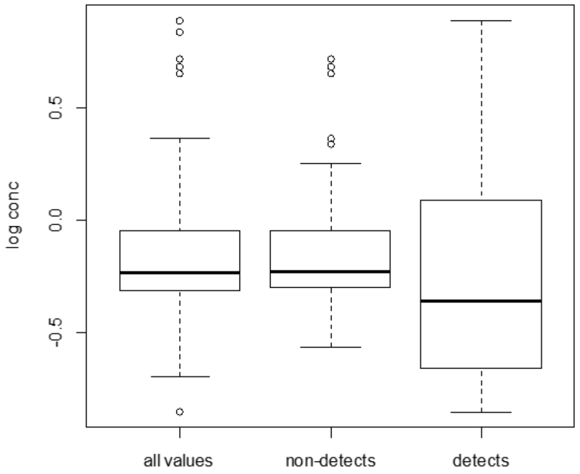
C-12-DCE

	KM	All Results	Detects
25th	0.11	0.32	0.19
50th	0.20	0.70	0.44
75th	0.26	8.4	1.5
90th	1.4	10	3
95th	3	10	5


c-1,2-DCE all results

c-1,2-DCE detects

Figure 5-5. Graphical Analysis and Order Statistics of cis-1,2-DCE Indoor Air Data
NESDI Project #476



1,1,1-TCA			
	KM	All Results	Detects
25th	0.20	0.48	0.22
50th	0.22	0.58	0.44
75th	0.23	0.90	1.34
90th	0.44	1.36	6.9
95th	0.51	2.3	7.3

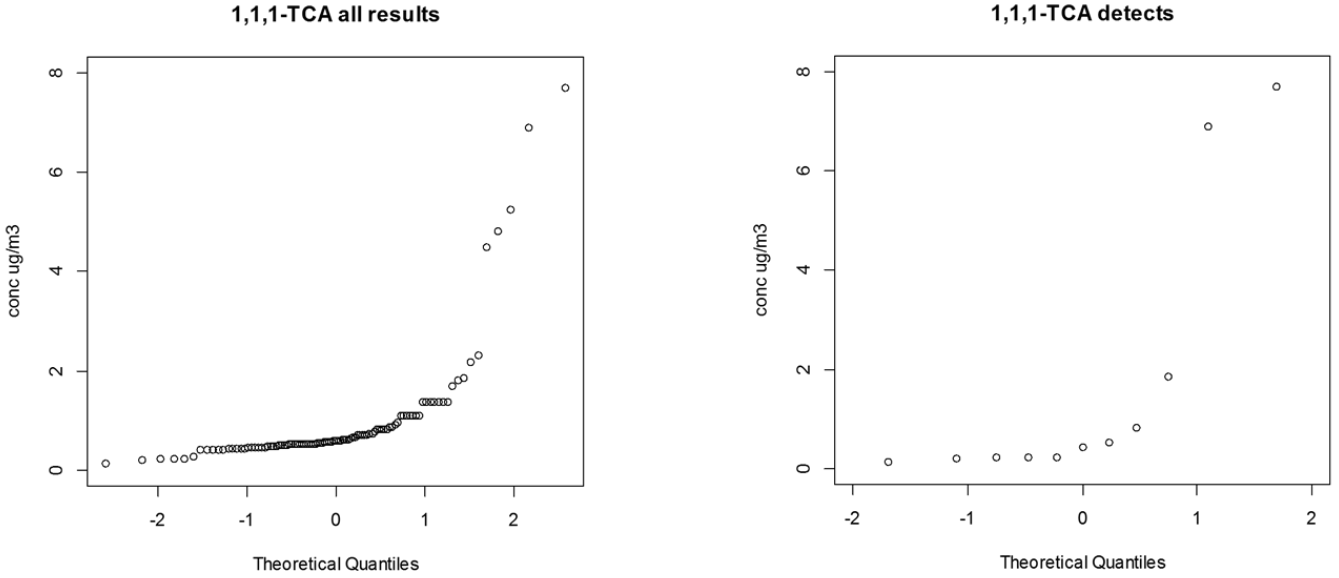


Figure 5-6. Graphical Analysis and Order Statistics of 1,1,1-TCA Indoor Air Data
NESDI Project #476

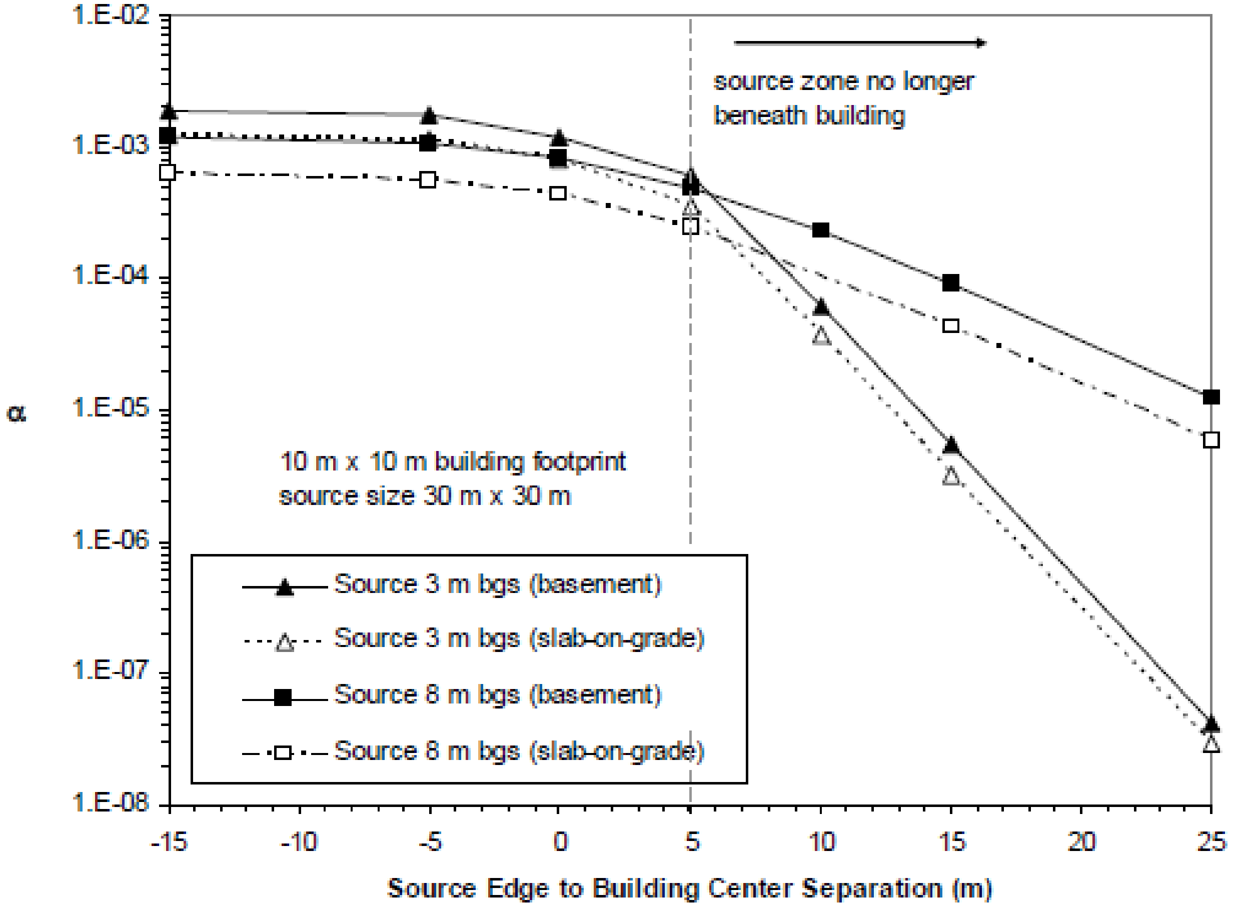


Figure 11. Relationship between source-building lateral separation distance and normalized indoor air concentration (α).

The separation is measured from the edge of the source zone to the center of the building; negative values and values <5 m indicate that the source is to some extent beneath the building.

Basement and slab-on-grade scenarios. Source located at groundwater table at depths 3 m and 8 m bgs.

(Abreu and Johnson, 2006)

Figure 5-7. Abreu and Johnson (2006) Relationship Between Source-Building Lateral Separation Distance and Normalized Indoor Air Concentration

NESDI Project #476

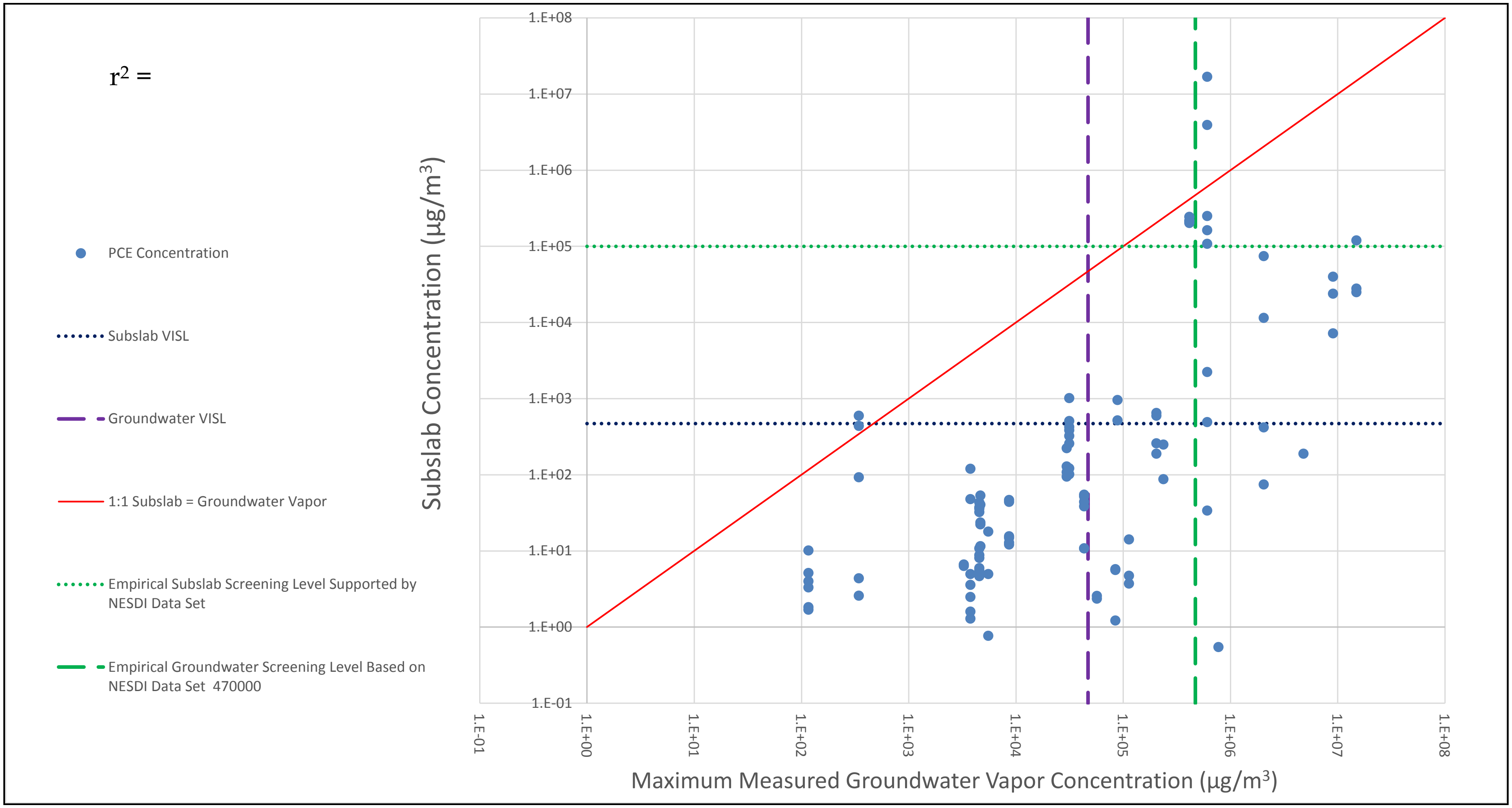


Figure 6-1. PCE Sub-slab Soil Gas Concentration vs. Measured Maximum Groundwater Concentration; All Detectable Data
NESDI Project #476

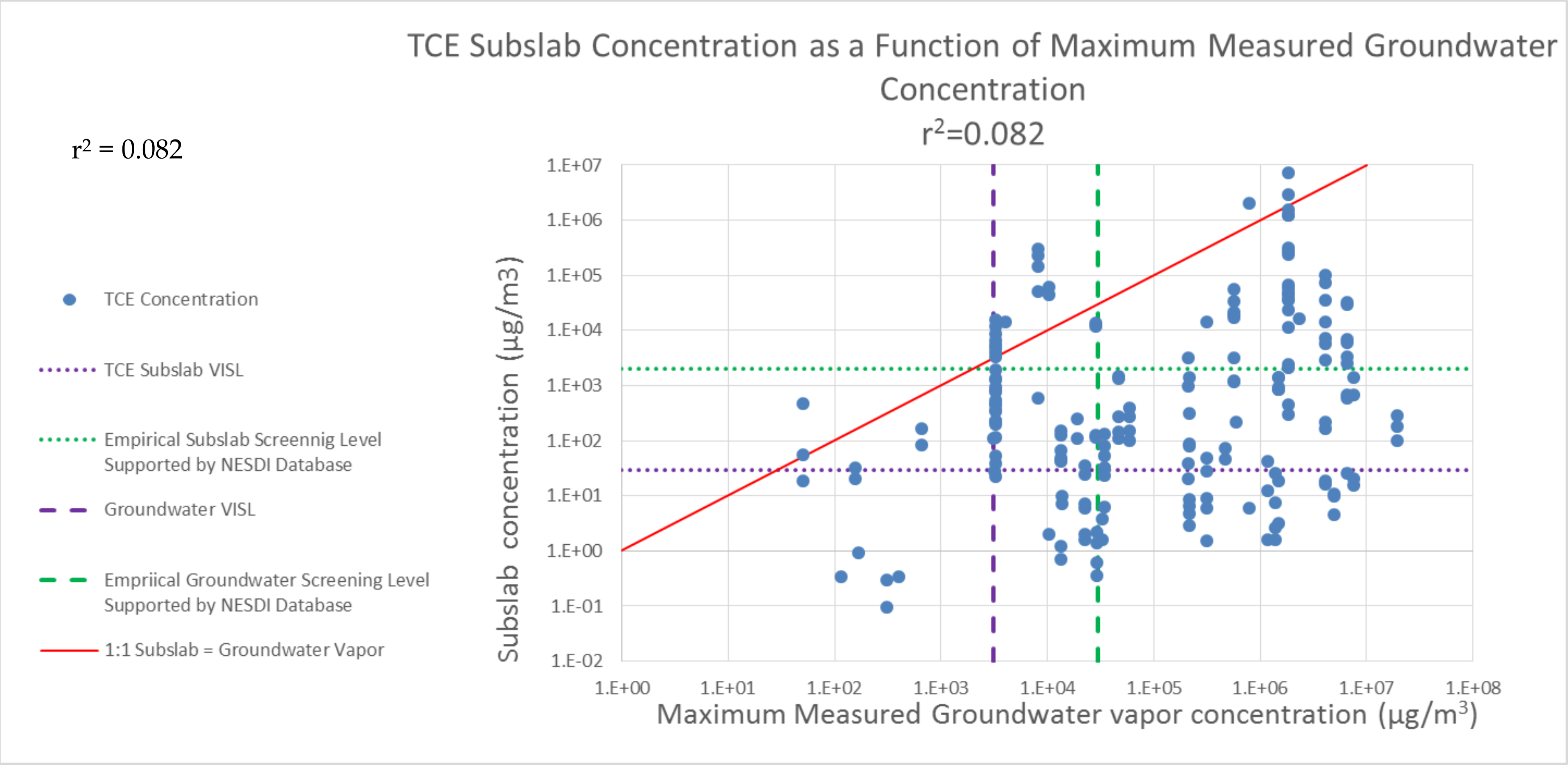
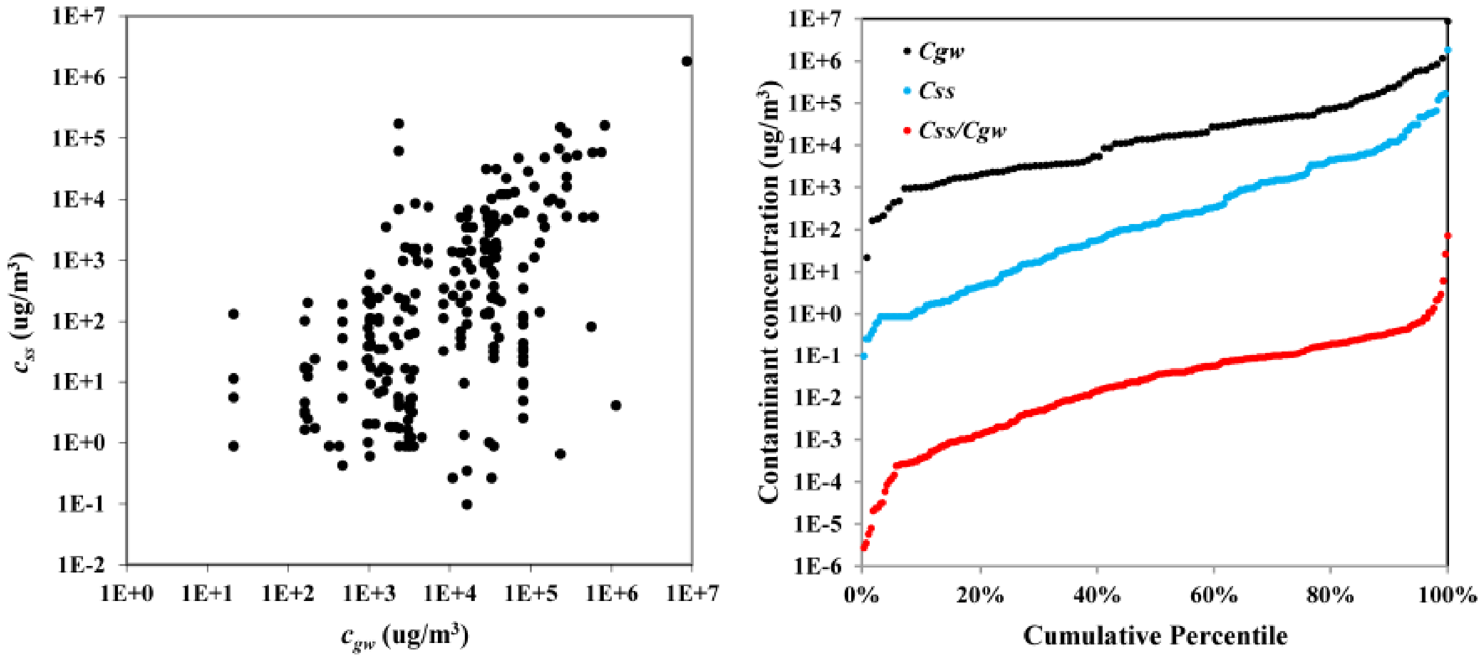


Figure 6-2. TCE Sub-slab Soil Gas Concentration vs. Measured Maximum Groundwater Concentration; All Detectable Data
NESDI Project #476



(a) (b)

Figure 3. Groundwater and subslab PCE and TCE vapor concentration data from the U.S. EPA's VI database (duplicates of c_{gw} were removed in (b)).[1]

Figure 6-3. Yao (2013) Plots of PCE and TCE Groundwater Vapor Concentration and Sub-slab Soil Gas Concentration
NESDI Project #476

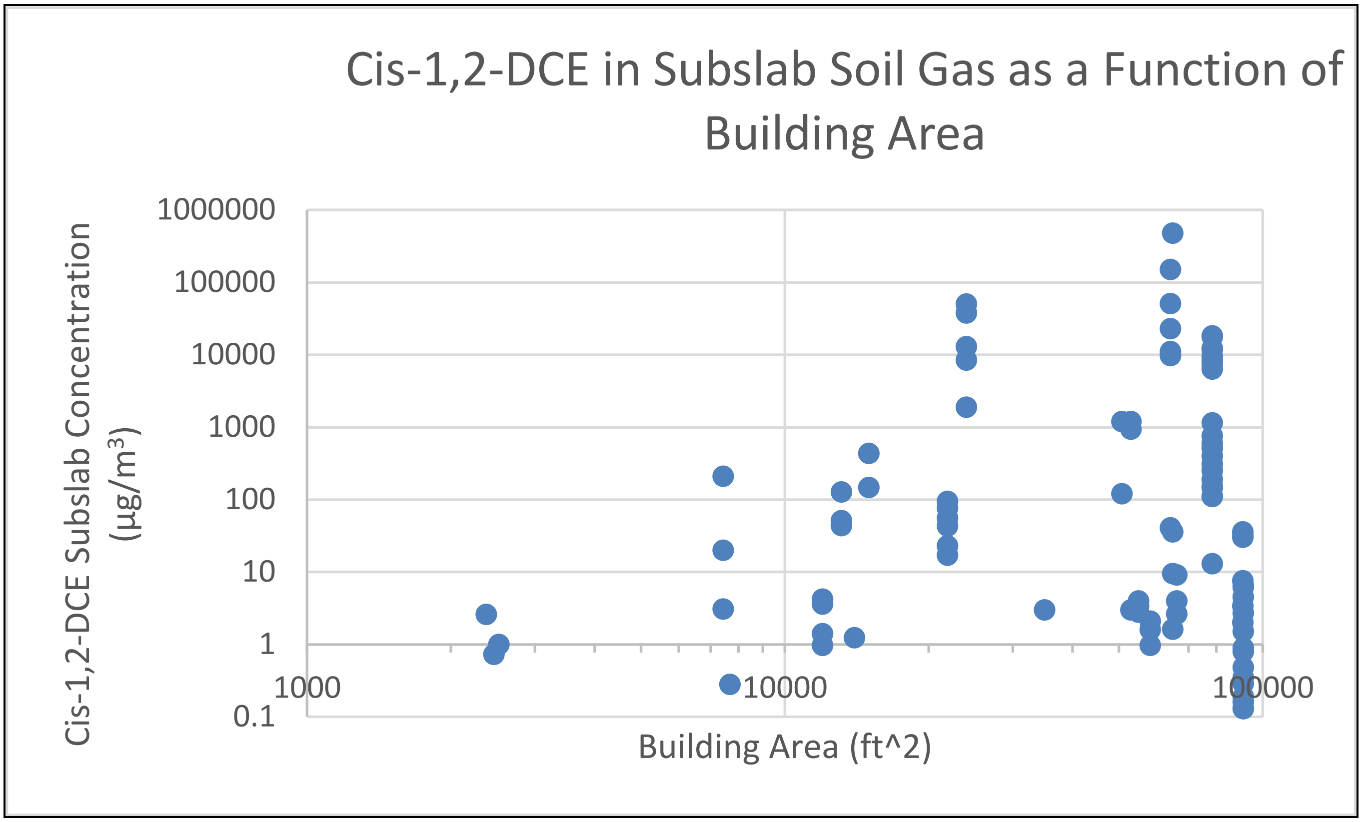


Figure 6-4. Cis-1,2-DCE in Sub-slab Soil Gas vs. Building Area; Detected Results Only
NESDI Project #476

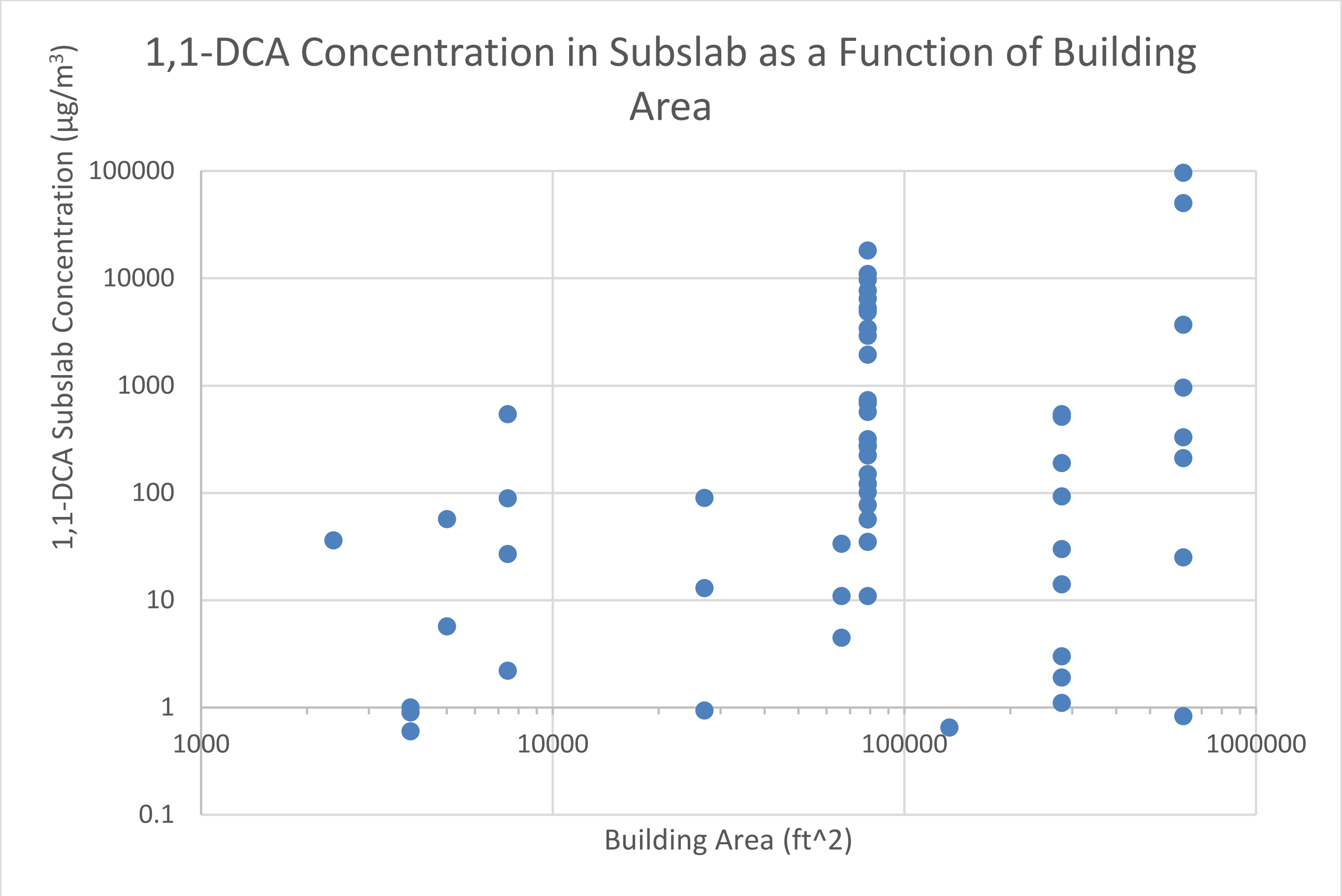
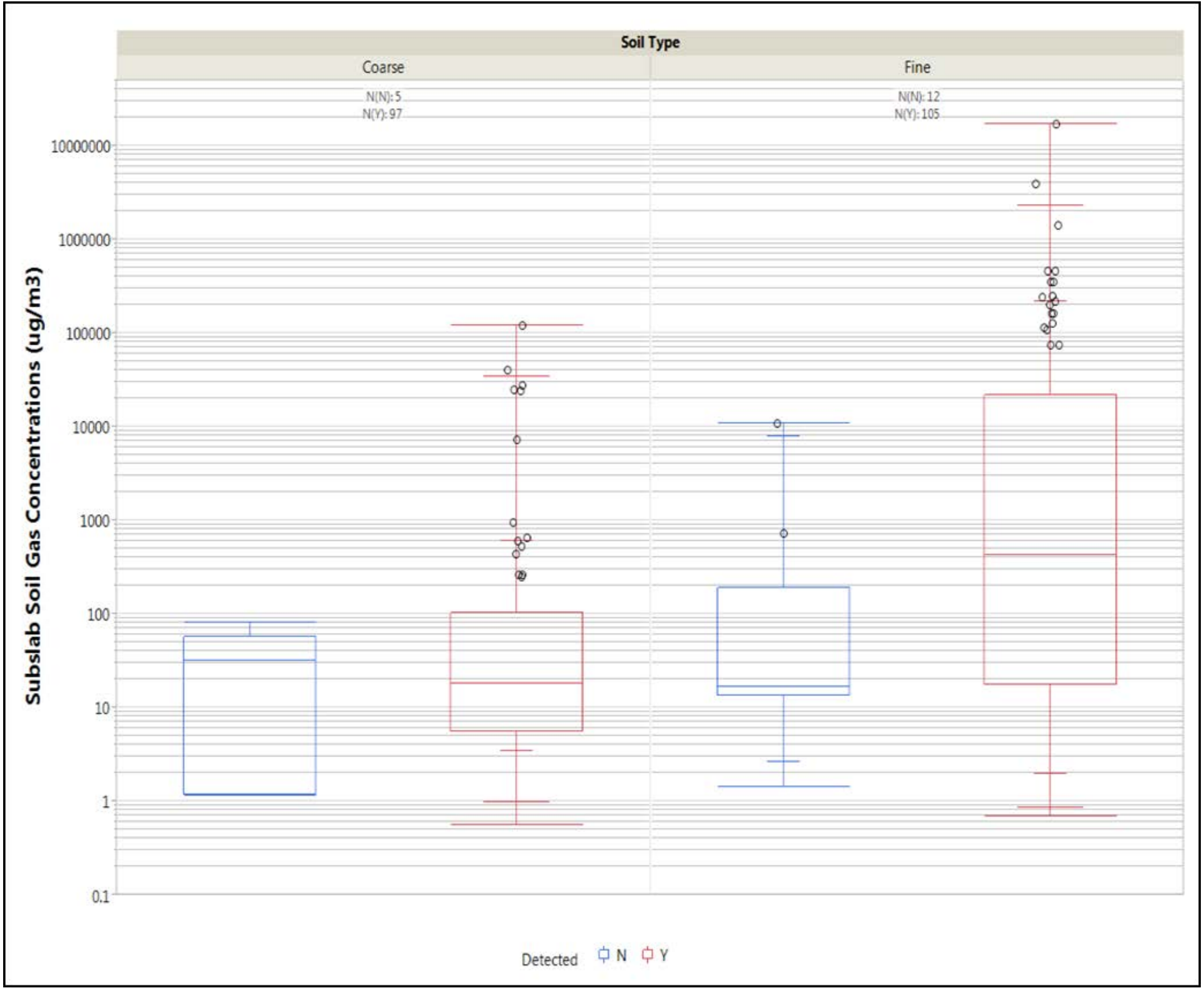
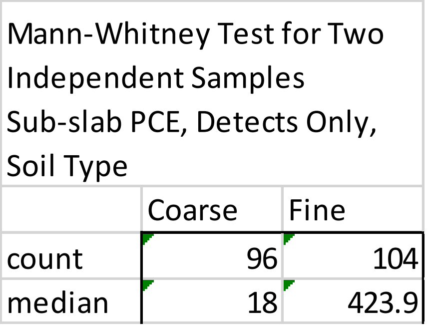


Figure 6-5. 1,1-DCA in Sub-slab Soil Gas vs. Building Area; Detected Values Only
NESDI Project #476

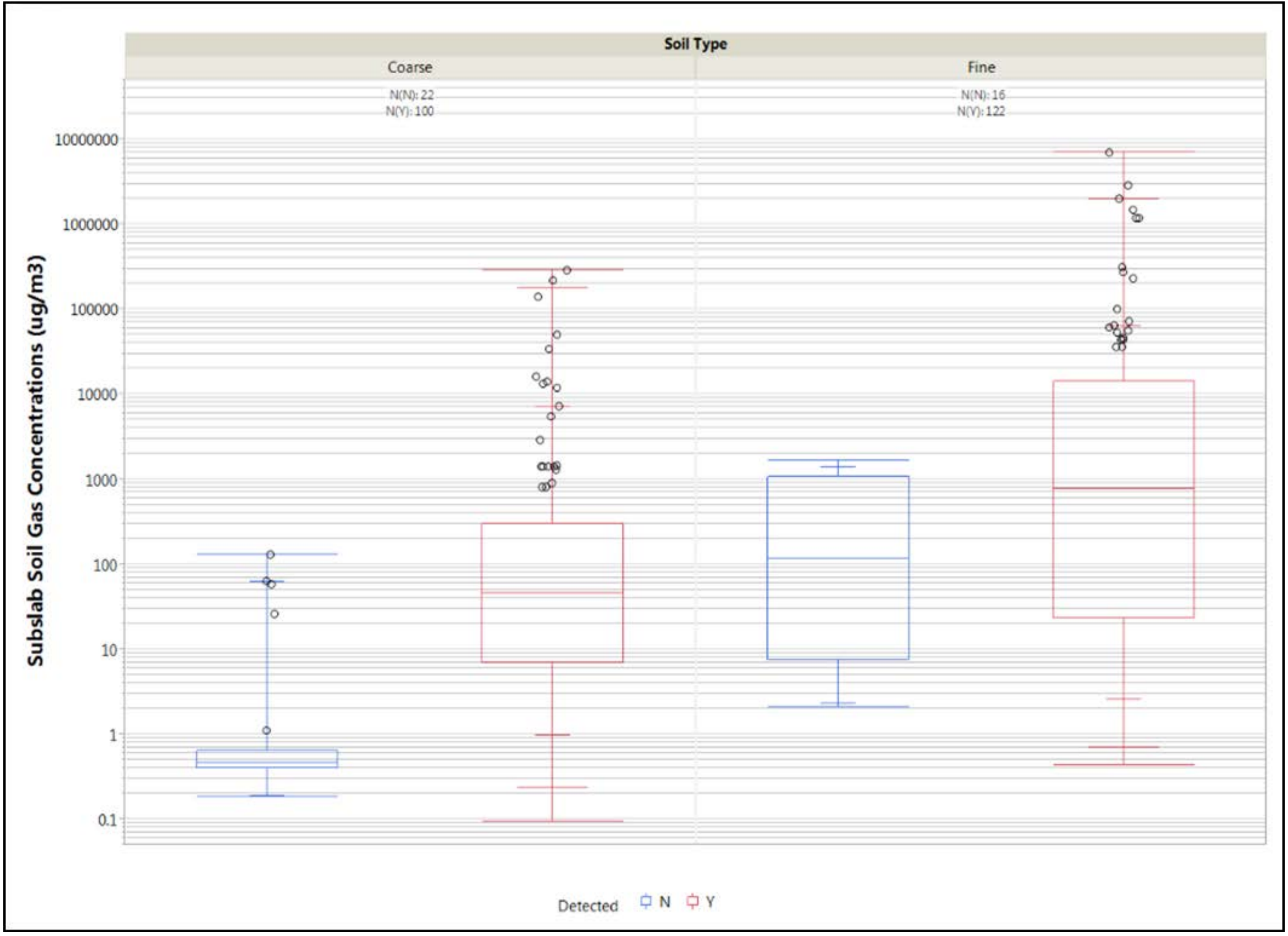




Mann-Whitney Test for Two Independent Samples Sub-slab PCE, Detects Only, Soil Type		
	Coarse	Fine
count	96	104
median	18	423.9

Significant, p value, 2 tailed = 8E-6

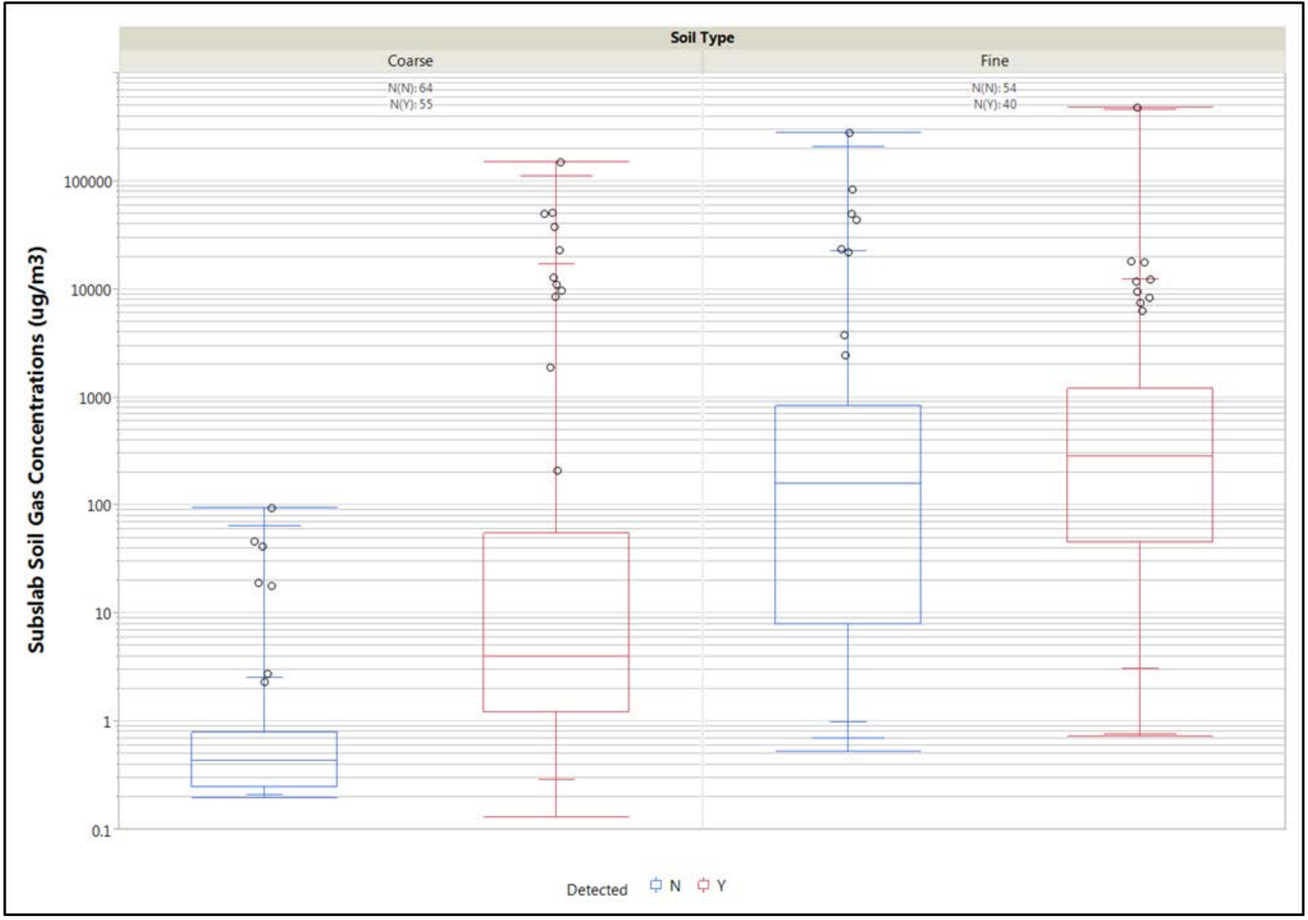
Figure 6-6. PCE Sub-slab Soil Gas Concentration vs. Soil Type
NESDI Project #476



Mann-Whitney Test for Two Independent Samples Subslab TCE Soil Type		
	Coarse	Fine
count	99	121
median	46.8	806.1

Significant, p value, 2 tailed = 2E-6

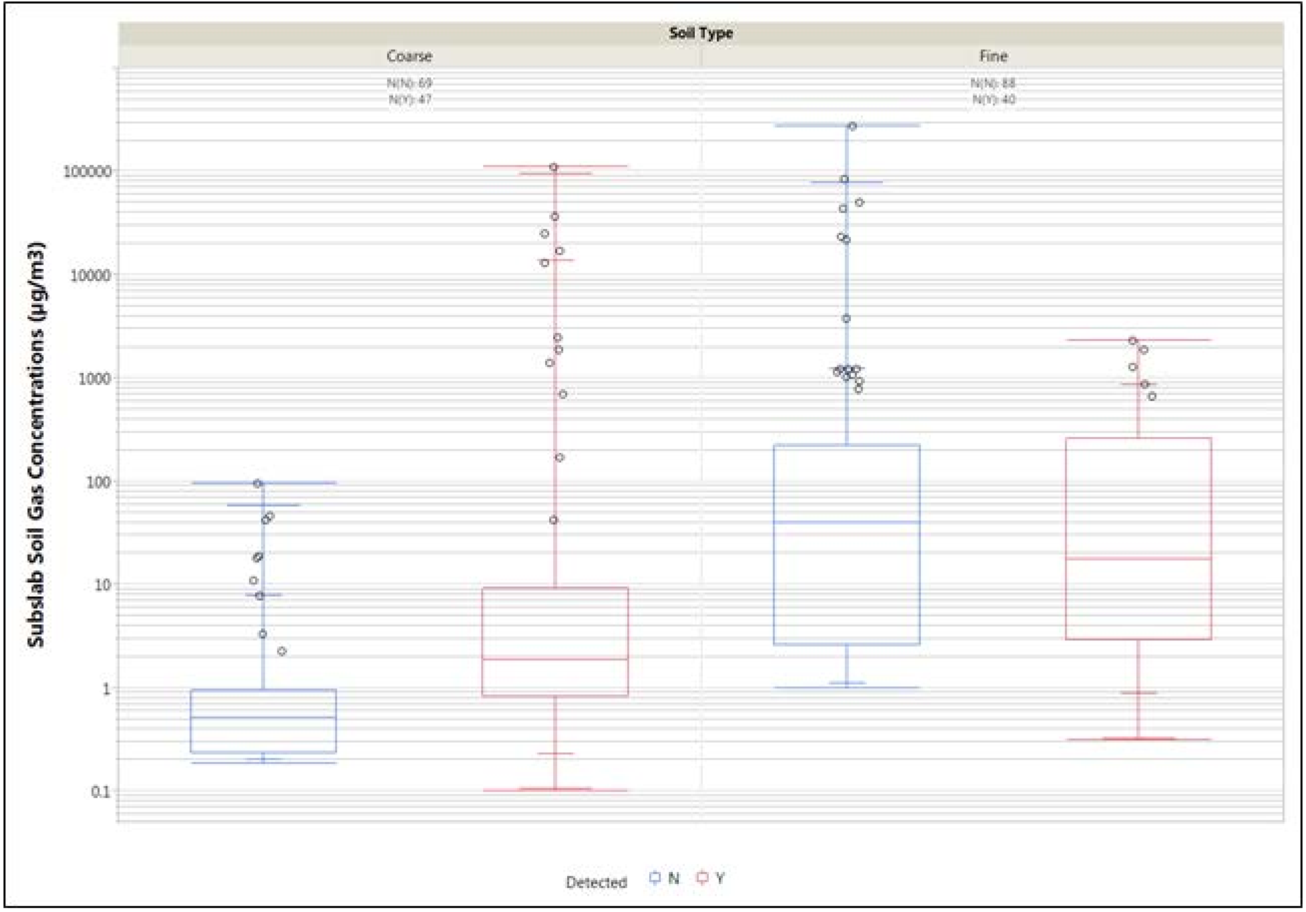
Figure 6-7. TCE Sub-slab Soil Gas Concentration vs. Soil Type
NESDI Project #476

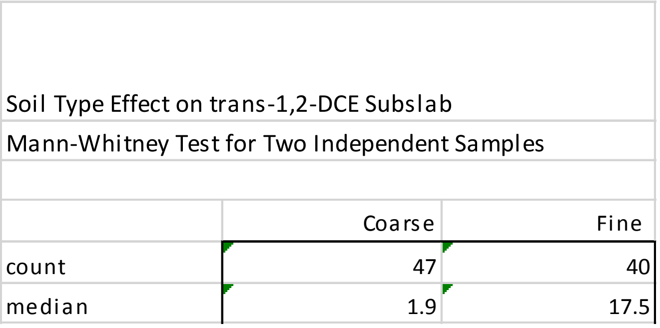


Soil Type Effect on Subslab cis-1,2-DCE		
Mann-Whitney Test for Two Independent Samples		
	Coarse	Fine
count	55	40
median	4.0	281.5

Significant, two tailed p<0.001

Figure 6-8. Cis-1,2-DCE Sub-slab Soil Gas Concentration vs. Soil Type
NESDI Project #476

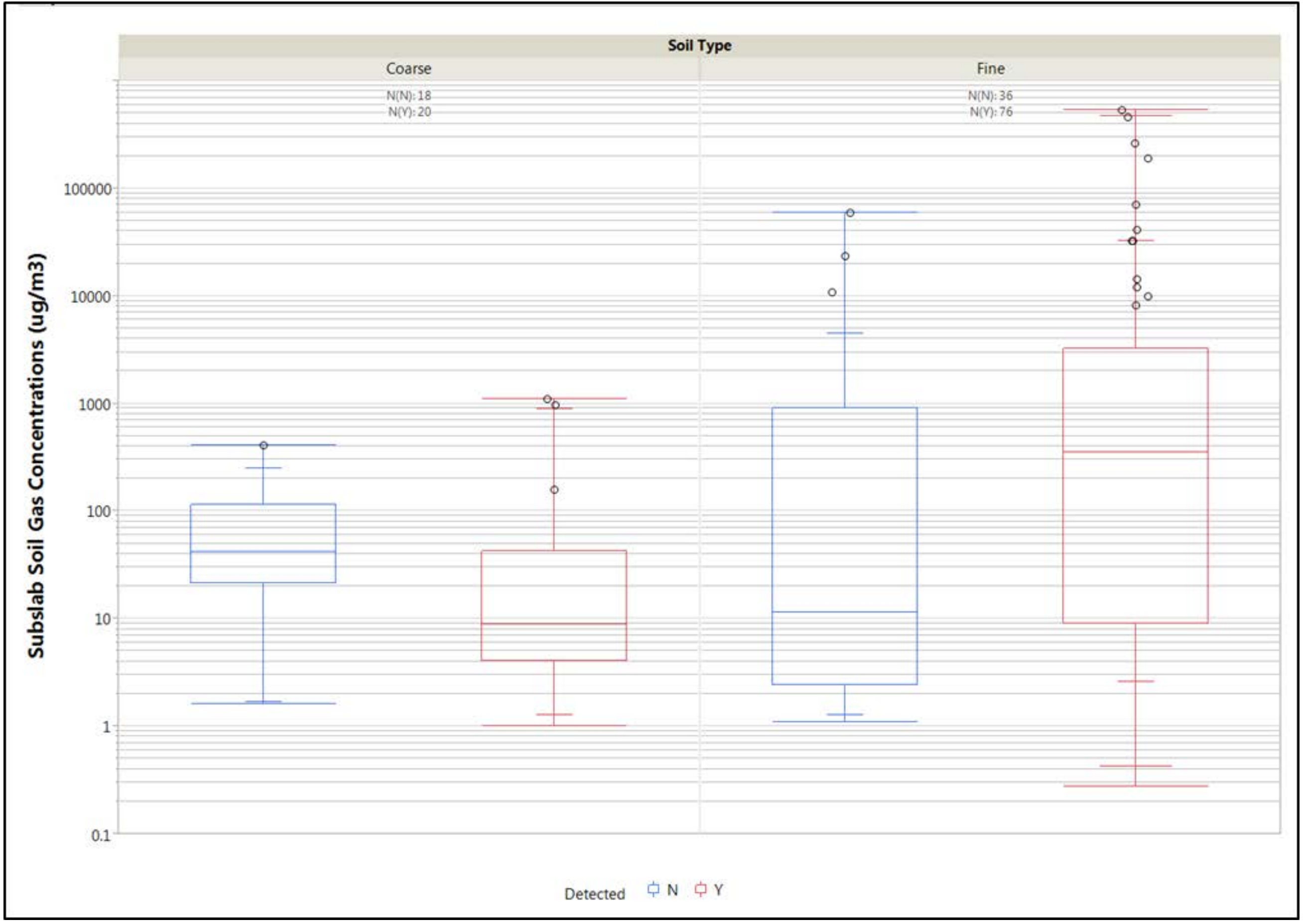




Soil Type Effect on trans-1,2-DCE Subslab		
Mann-Whitney Test for Two Independent Samples		
	Coarse	Fine
count	47	40
median	1.9	17.5

Significant two tailed p =.008

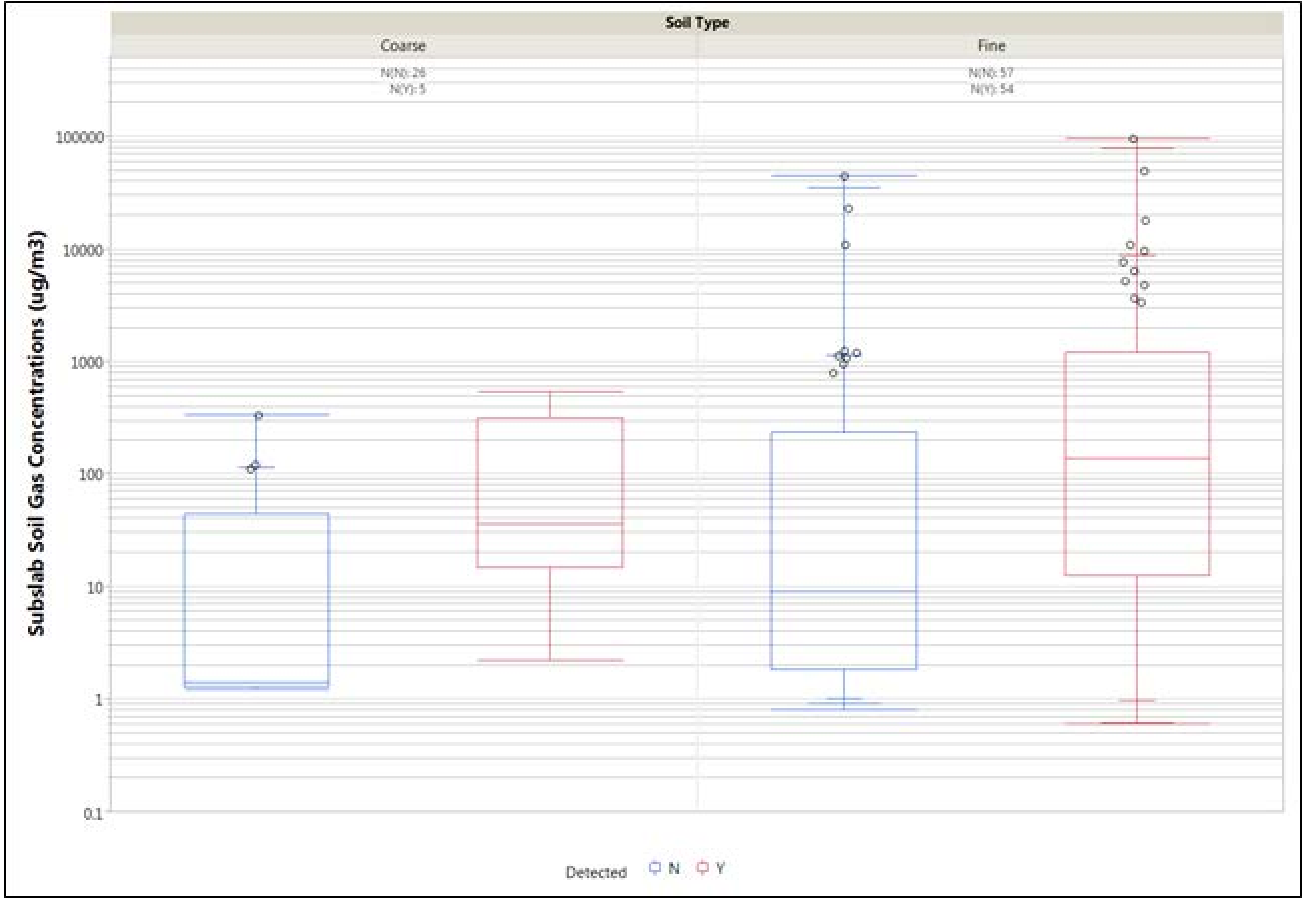
Figure 6-9. Trans-1,2-DCE Sub-slab Soil Gas Concentrations vs. Soil Type
NESDI Project #476



Soil Type Effect on Subslab 1,1,1,-TCA		
Mann-Whitney Test for Two Independent Samples		
	Coarse	Fine
count	20	76
median	8.9	349.1

Significant, two tailed p=0.001

Figure 6-10. 1,1,1-TCA Sub-slab Soil Gas Concentrations vs. Soil Type
NESDI Project #476

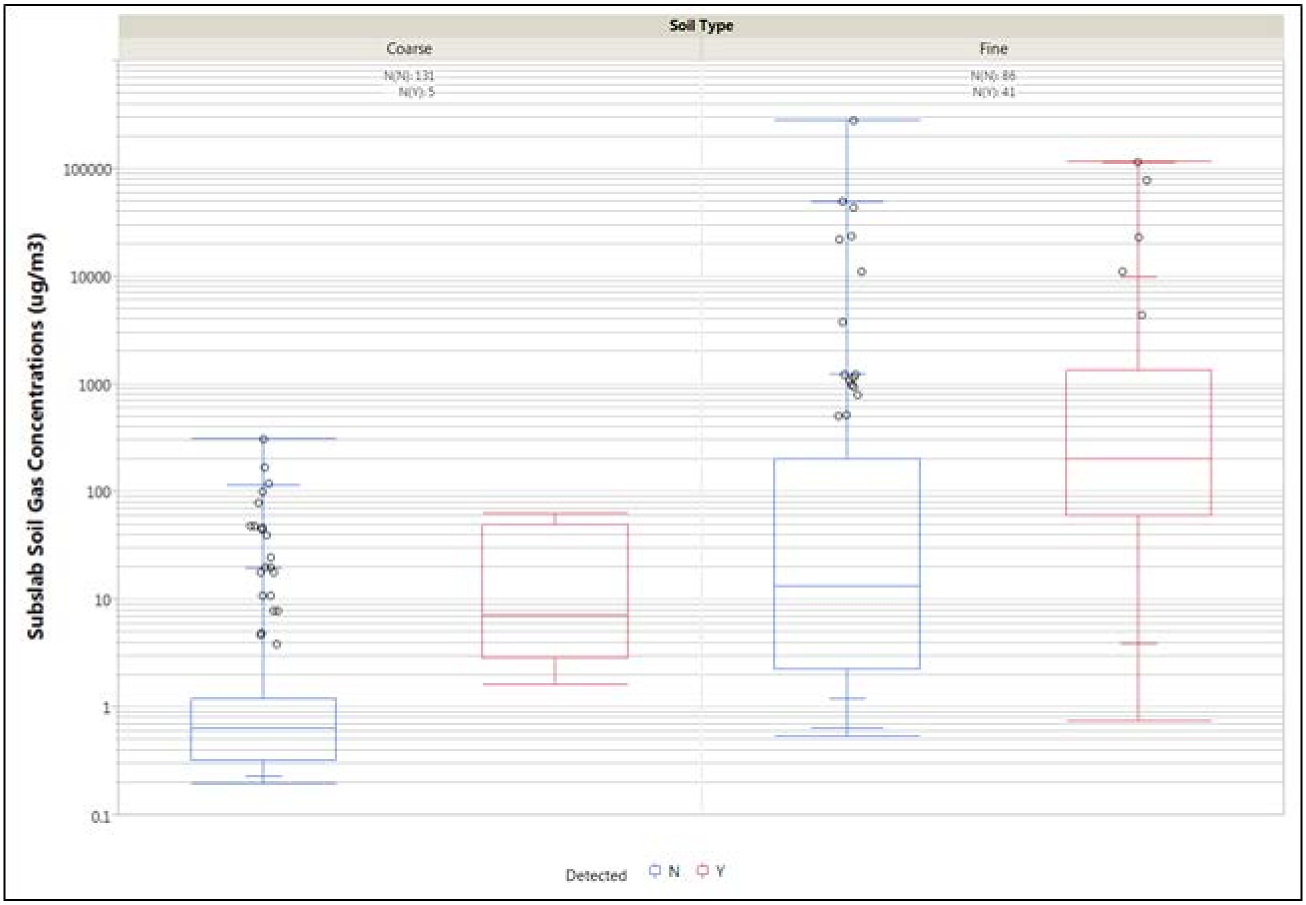


Soil Type Effect on Subslab 1,1-DCA		
Mann-Whitney Test for Two Independent Samples		
	Coarse	Fine
count	5	54
median	36	136

NOT A SIGNIFICANT DIFFERENCE BY Mann Whitney Test of detected samples

But significantly increased odds of detection two tailed p=0.001; Odds ratio 4.92

Figure 6-11. 1,1,-DCA Sub-slab Soil Gas Concentrations vs. Soil Type
NESDI Project #476



Soil Type Effect on Subslab 1,1-DCE

Mann-Whitney Test for Two Independent Samples

	Coarse	Fine
count	5	41
median	7.1	200

Significant, two tailed p=0.011 in Mann-Whitney also

Significantly more likely detection in fine soil two sided p<0.001 odds ratio 12.5

Figure 6-12. 1,1-DCE Sub-slab Soil Gas Concentrations vs Soil Type
NESDI Project #476

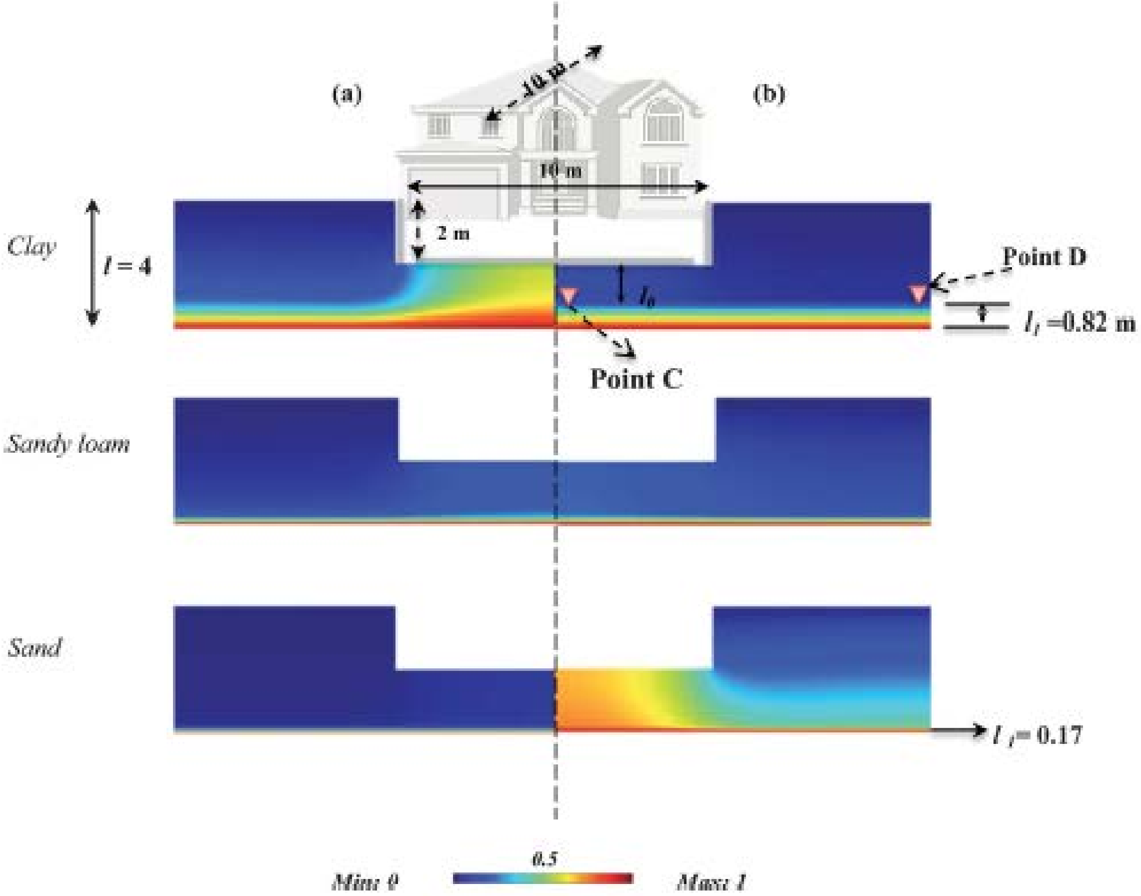


Fig.6 3D modeling results: cross-section plots of vapor concentration. (a) The true soil moisture profile was calculated using van Genuchten relations; (b) soil moisture content is adapted from the U.S. EPA version of the Johnson and Ettinger model, and described by two distinct soil layers.

Figure 6-13. Shen (2013) Moisture Retention Modeling
NESDI Project #476

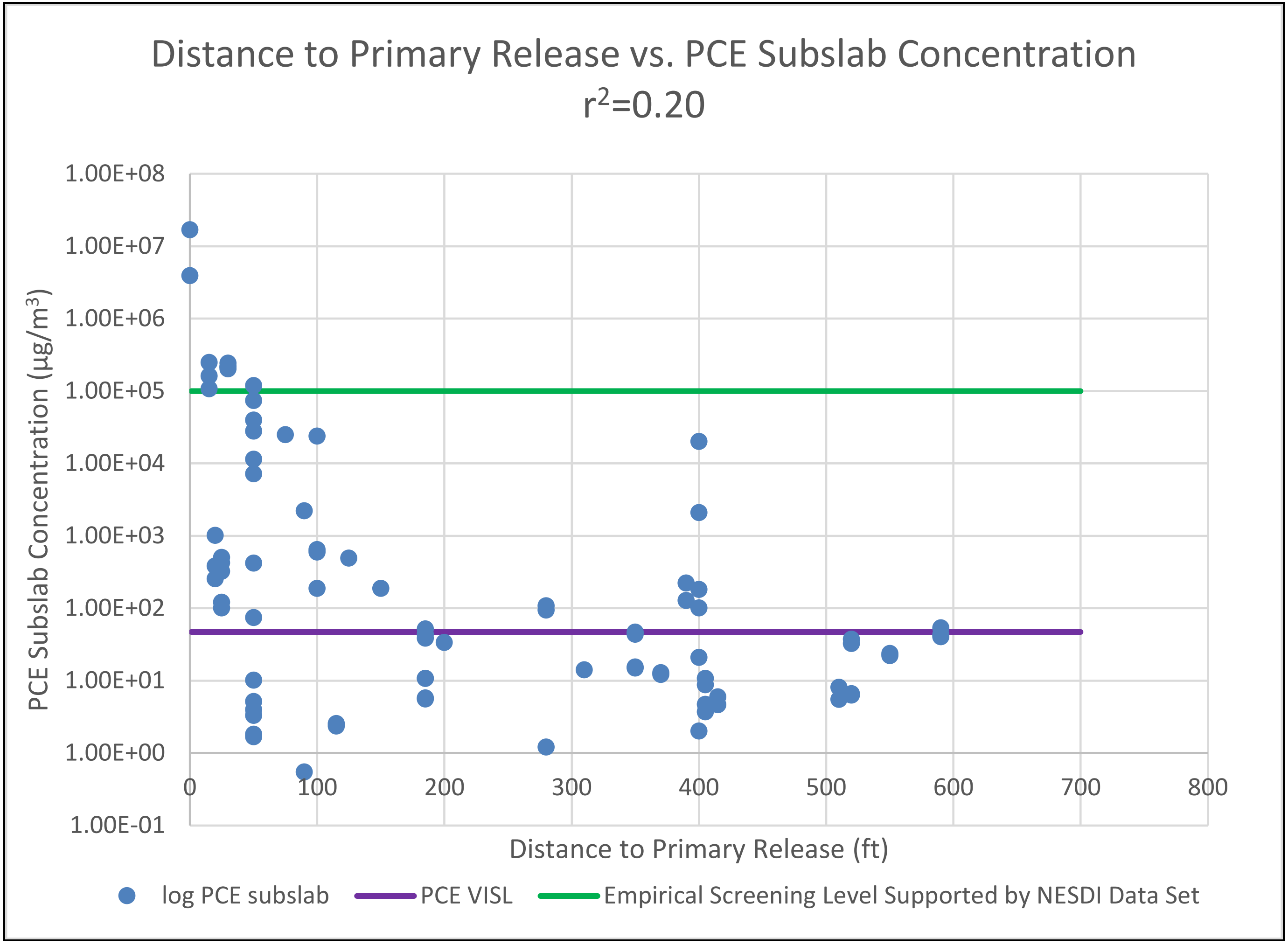


Figure 6-14. PCE Sub-slab Soil Gas Concentration vs. Distance to Primary Release; Statistically Significant Log of Concentration vs. Distance to Primary Release, r^2 = 0.20, p<0.001
NESDI Project #476

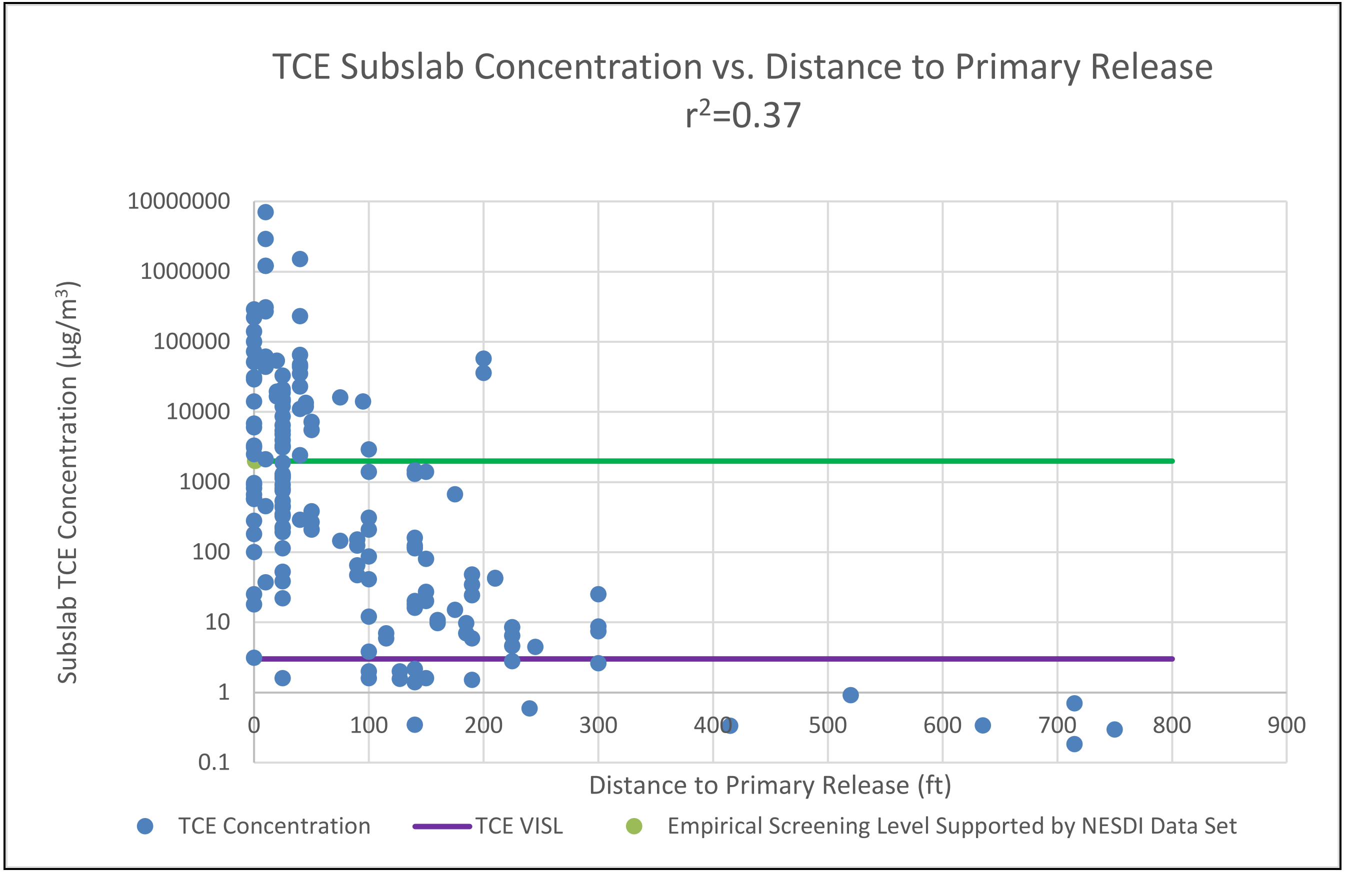


Figure 6-15. TCE Sub-slab Soil Gas Concentration vs. Distance to Primary Release
NESDI Project #476

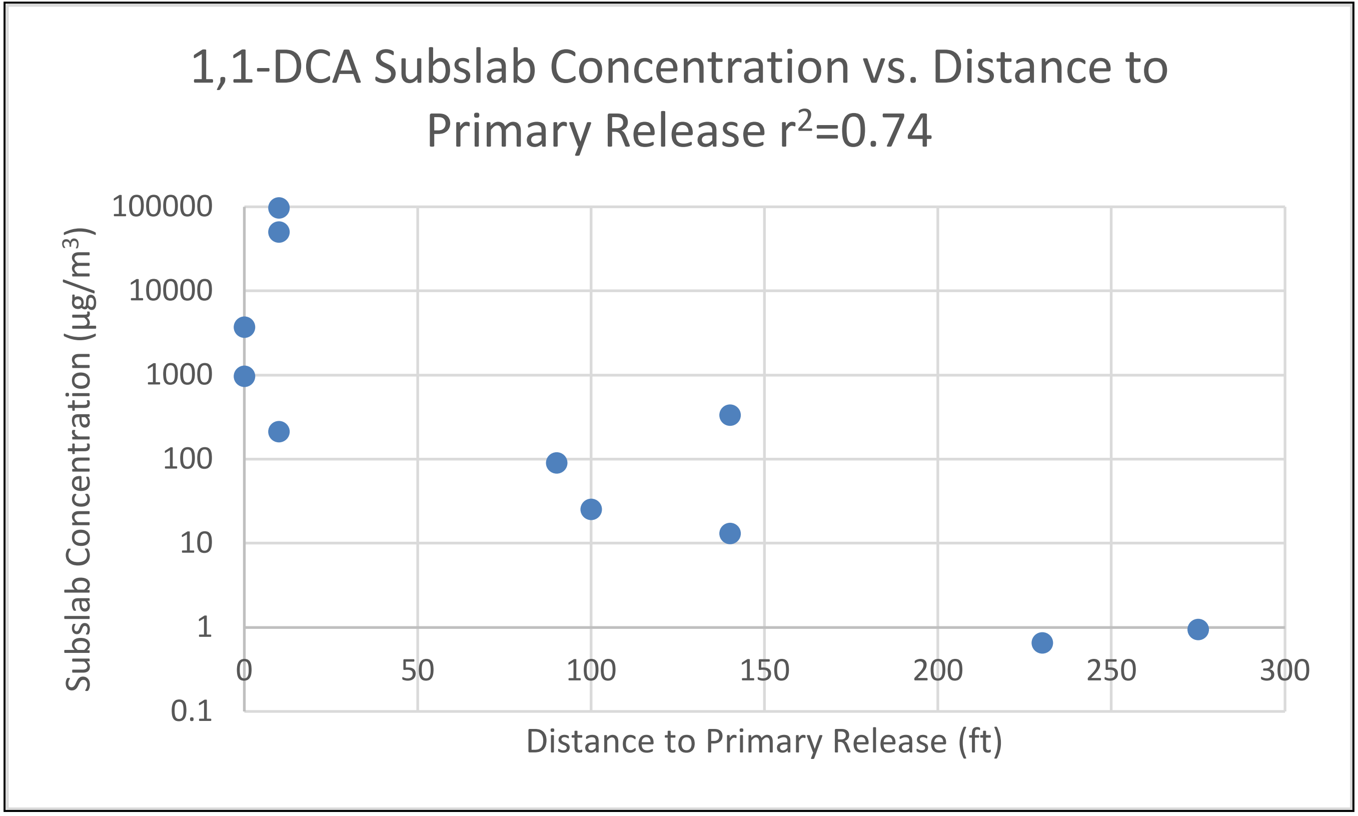


Figure 6-16. 1,1-DCA Sub-slab Soil Gas Concentration vs. Distance to Primary Release
NESDI Project #476

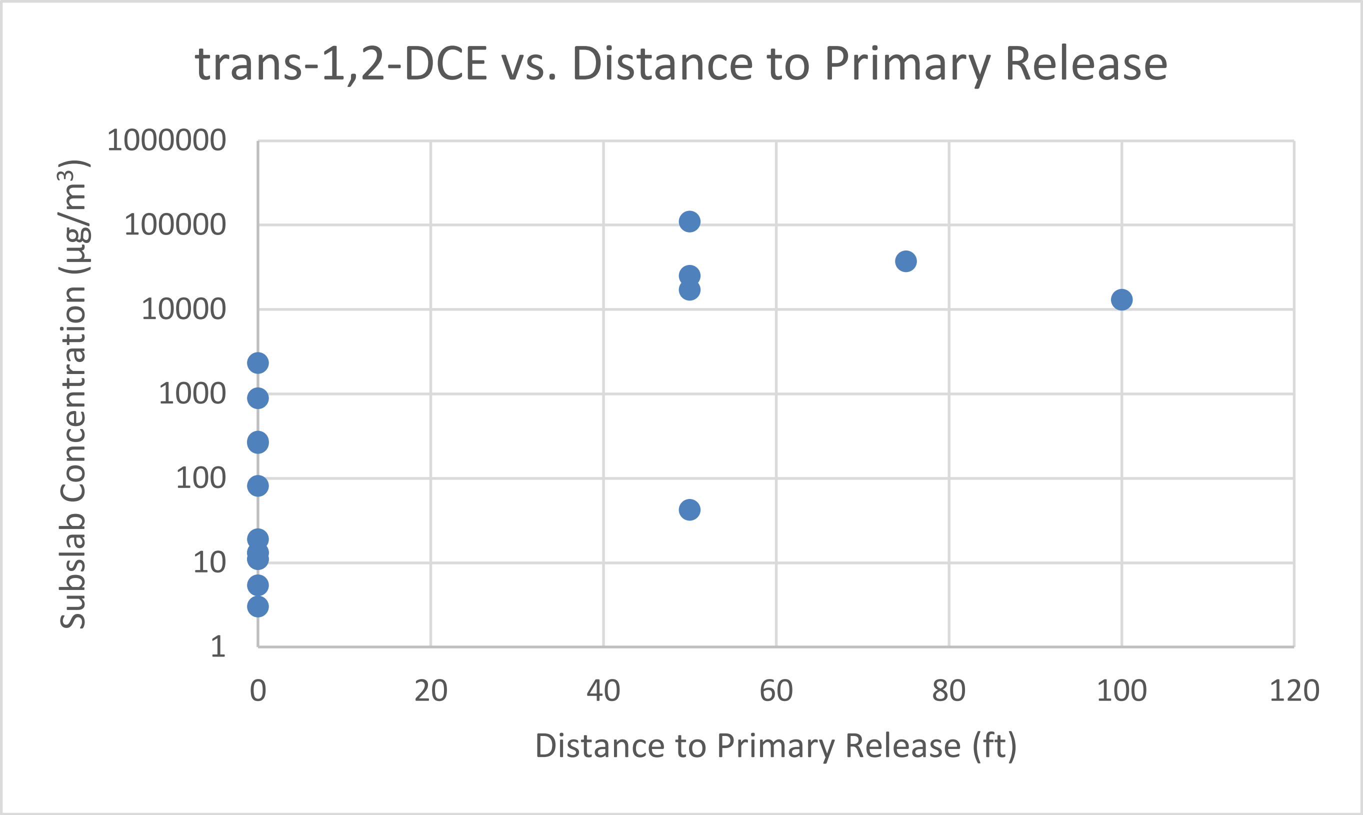
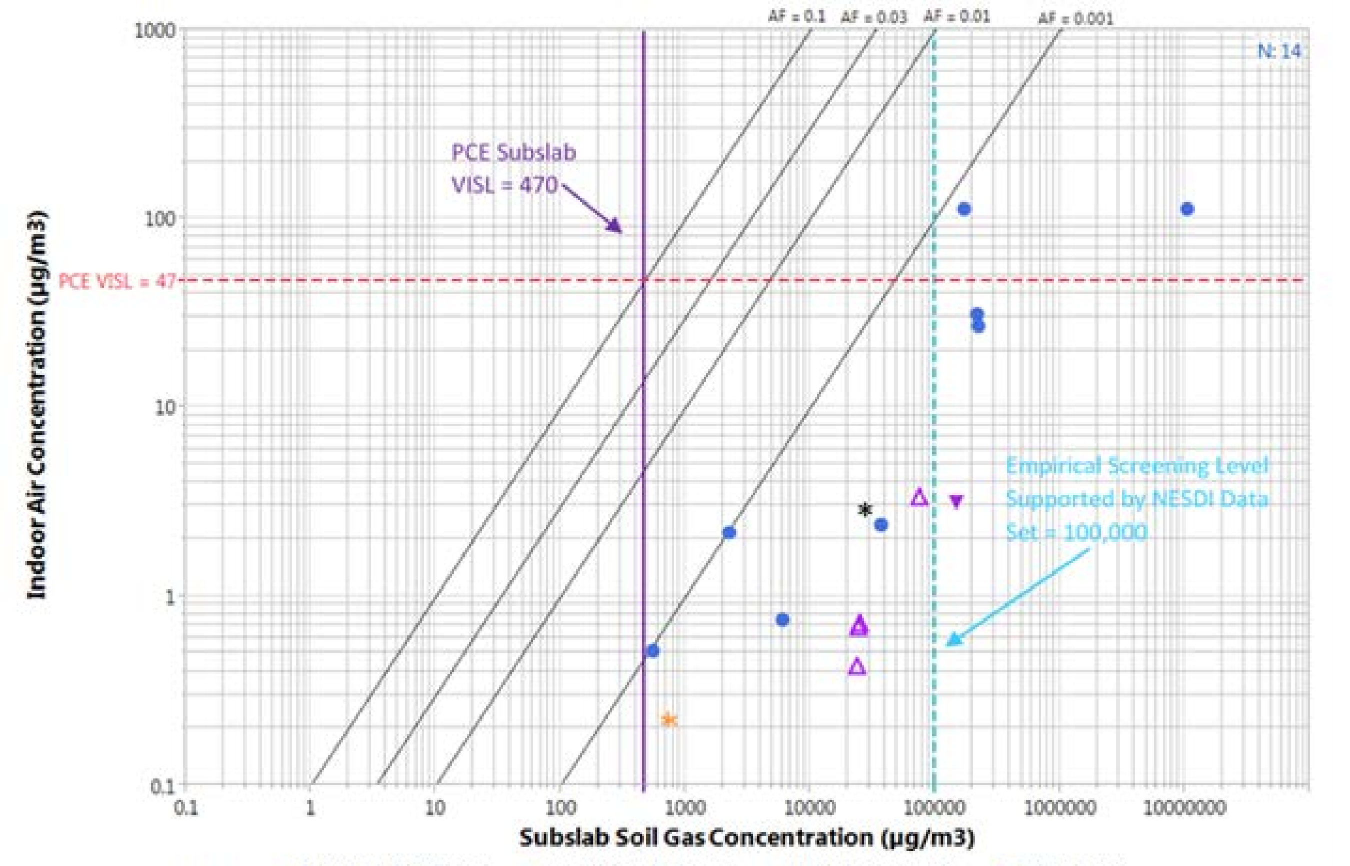
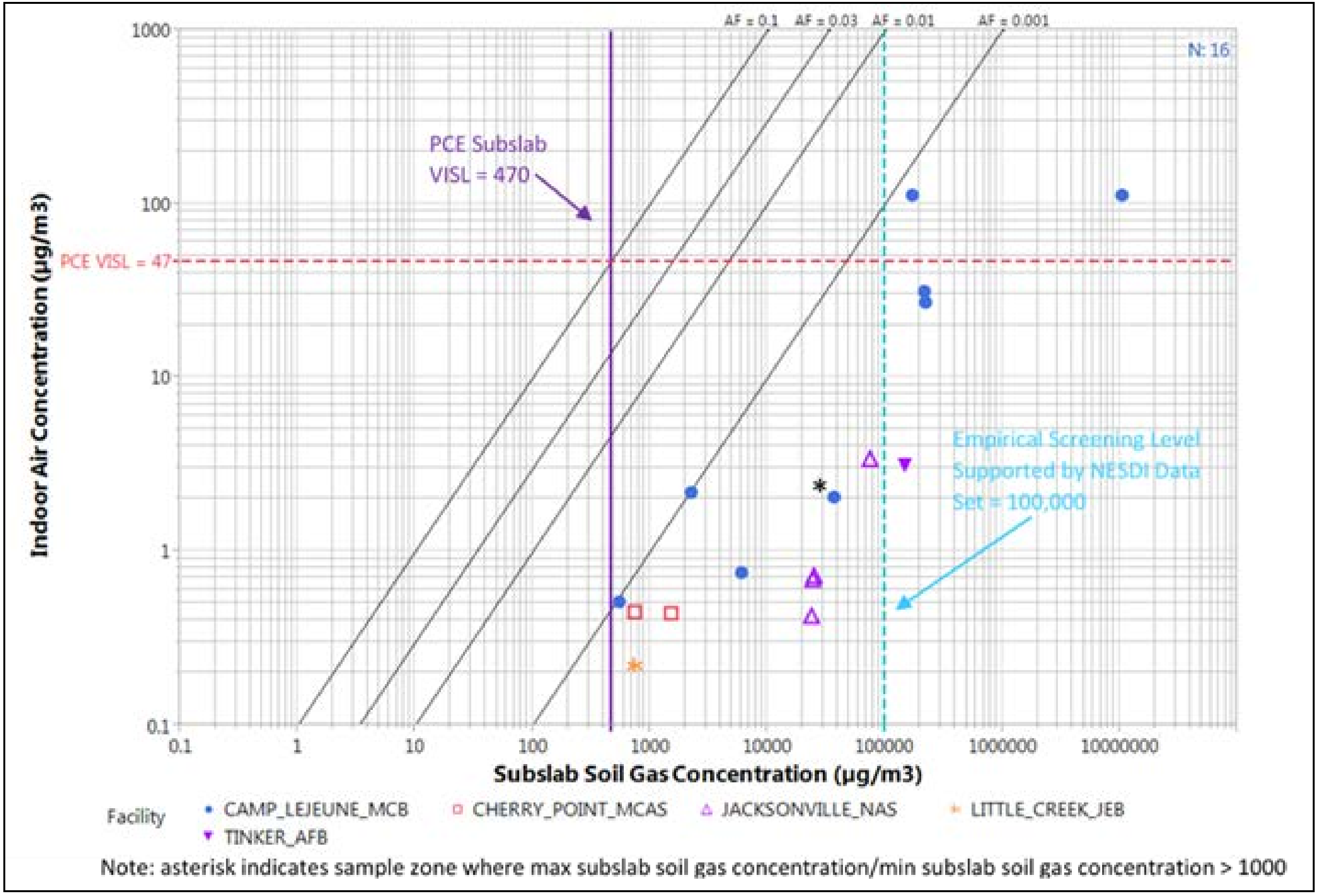


Figure 6-17. Trans-1,2-DCE Sub-slab Soil Gas vs. Distance to Primary Release
NESDI Project #476



Note: asterisk indicates sample zone where max subslab soil gas concentration/min subslab soil gas concentration > 1000

Figure 6-18. PCE Concentration in Sub-slab Soil Gas vs. Indoor Air
Sample Zone Averages; Detectable Data Only Included
Baseline screen + Source strength screen + Preferential pathway=false
NESDI Project #476



Note: asterisk indicates sample zone where max subslab soil gas concentration/min subslab soil gas concentration > 1000

Figure 6-19. PCE Concentration in Sub-slab Soil Gas vs. Indoor Air
Sample Zone Averages with Nondetects Considered at Detection Limit
Baseline screen + Source strength screen + Preferential pathway=false
NESDI Project #476

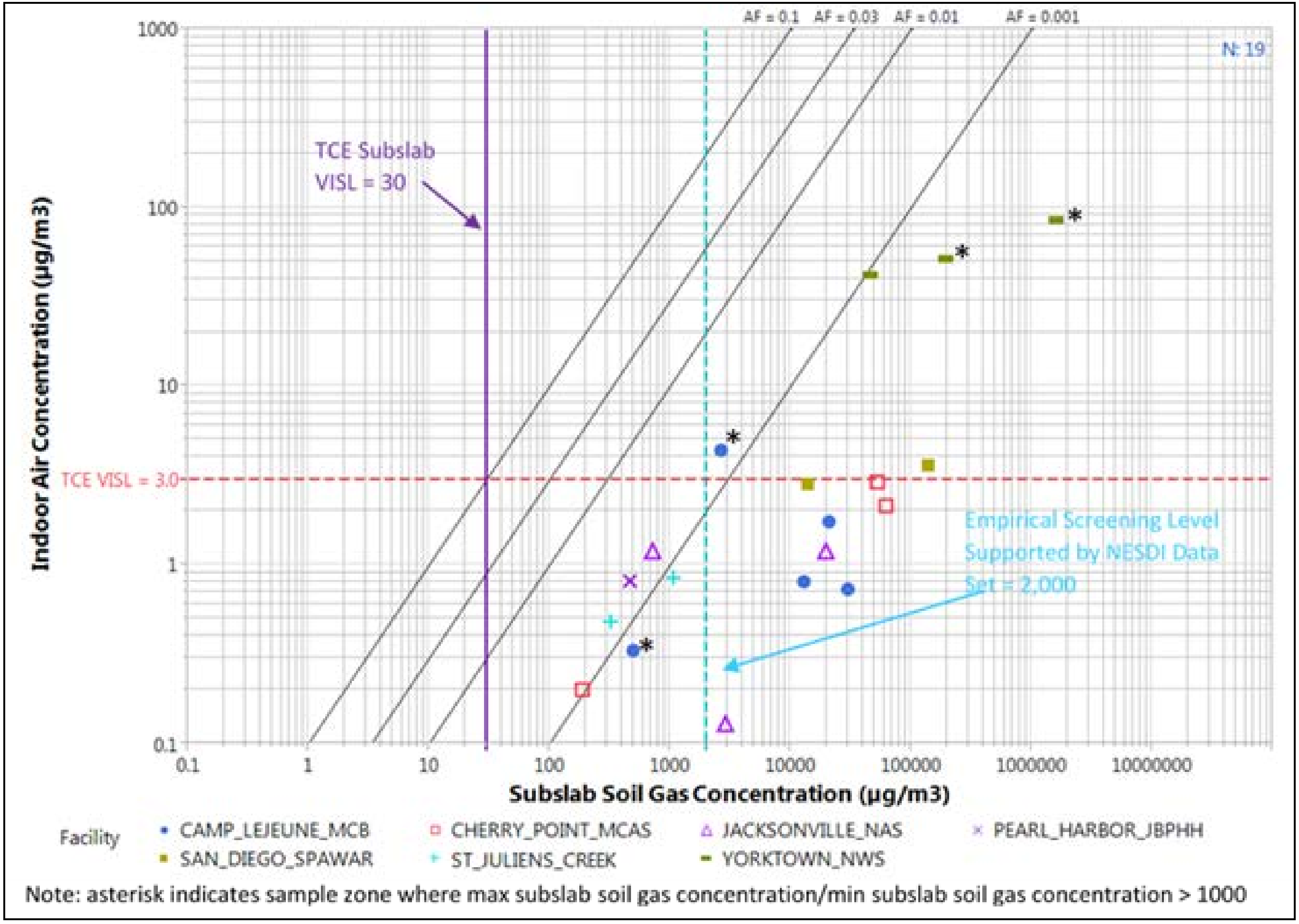


Figure 6-20. TCE Concentration in Sub-slab Soil Gas vs. Indoor Air
Sample Zone Averages; Detectable Data Only Included
Baseline screen + Source strength screen + Preferential pathway=false
NESDI Project #476

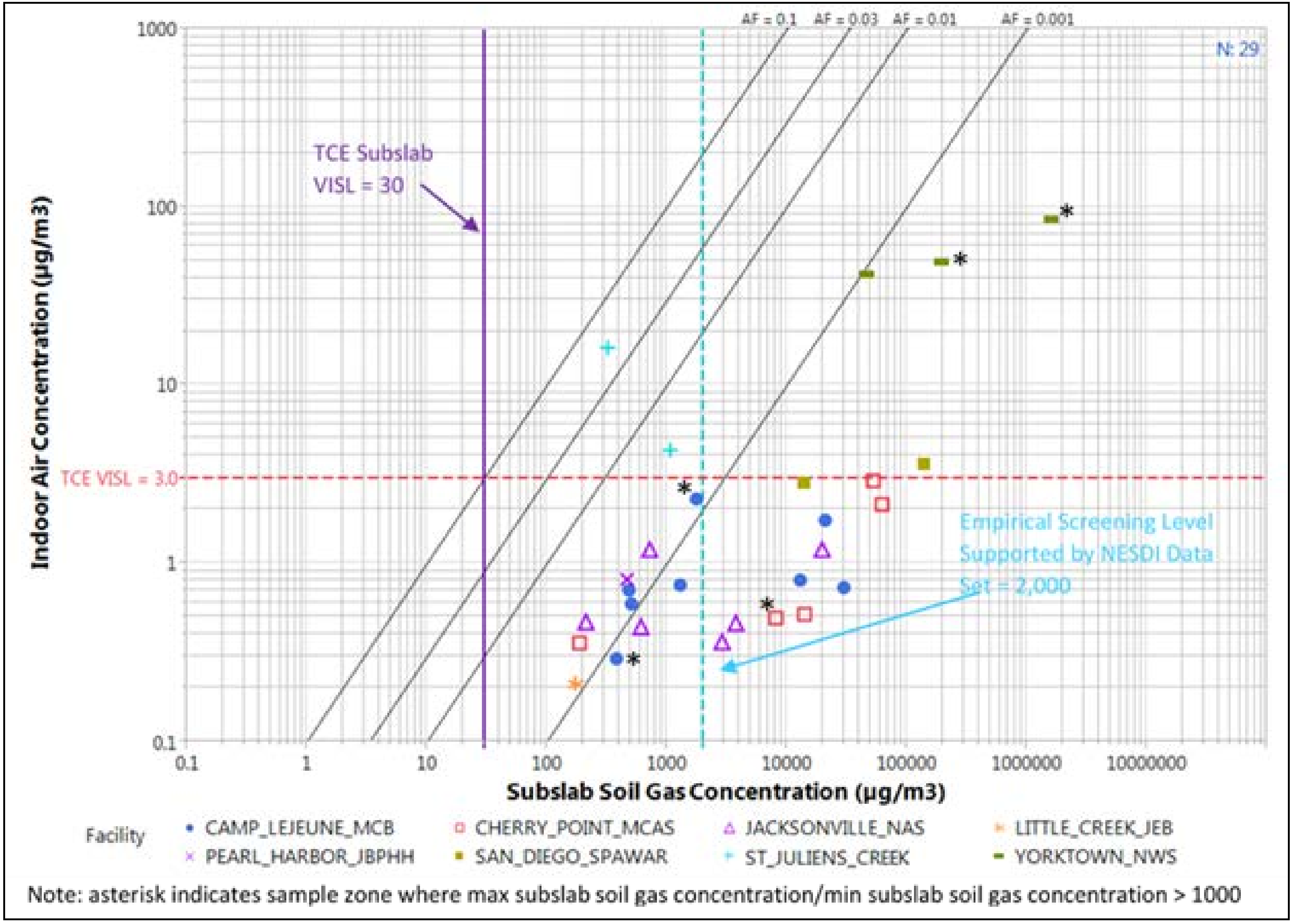


Figure 6-21. TCE Concentration in Sub-slab Soil Gas vs. Indoor Air
Sample Zone Averages with Nondetects Considered at Detection Limit
Baseline screen + Source strength screen + Preferential pathway=false
NESDI Project #476

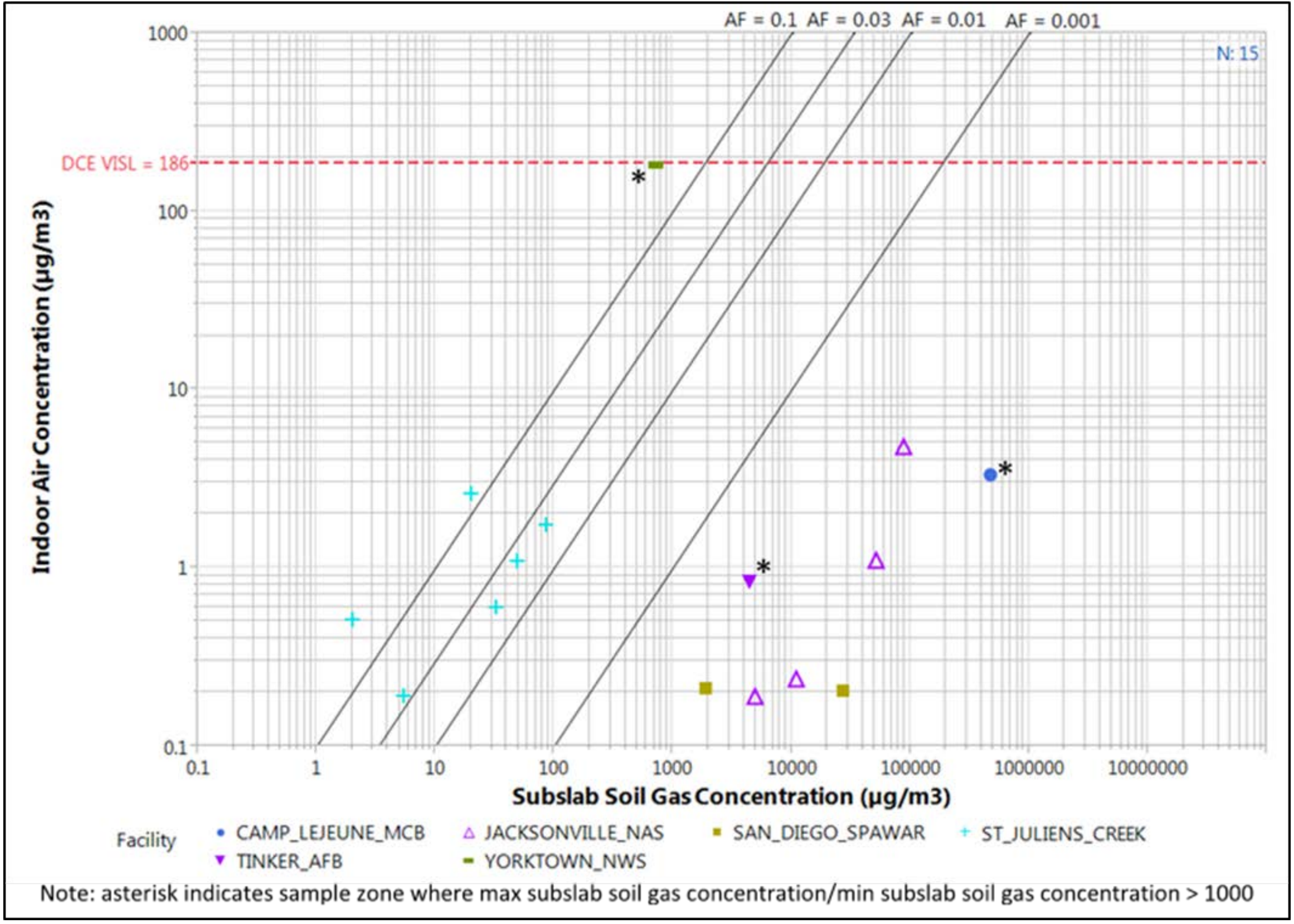


Figure 6-22. Cis-1,2-DCE Concentration in Sub-slab Soil Gas vs. Indoor Air
Sample Zone Averages; Detectable Data Only Included
Baseline screen + Source strength screen + Preferential pathway=false
NESDI Project #476

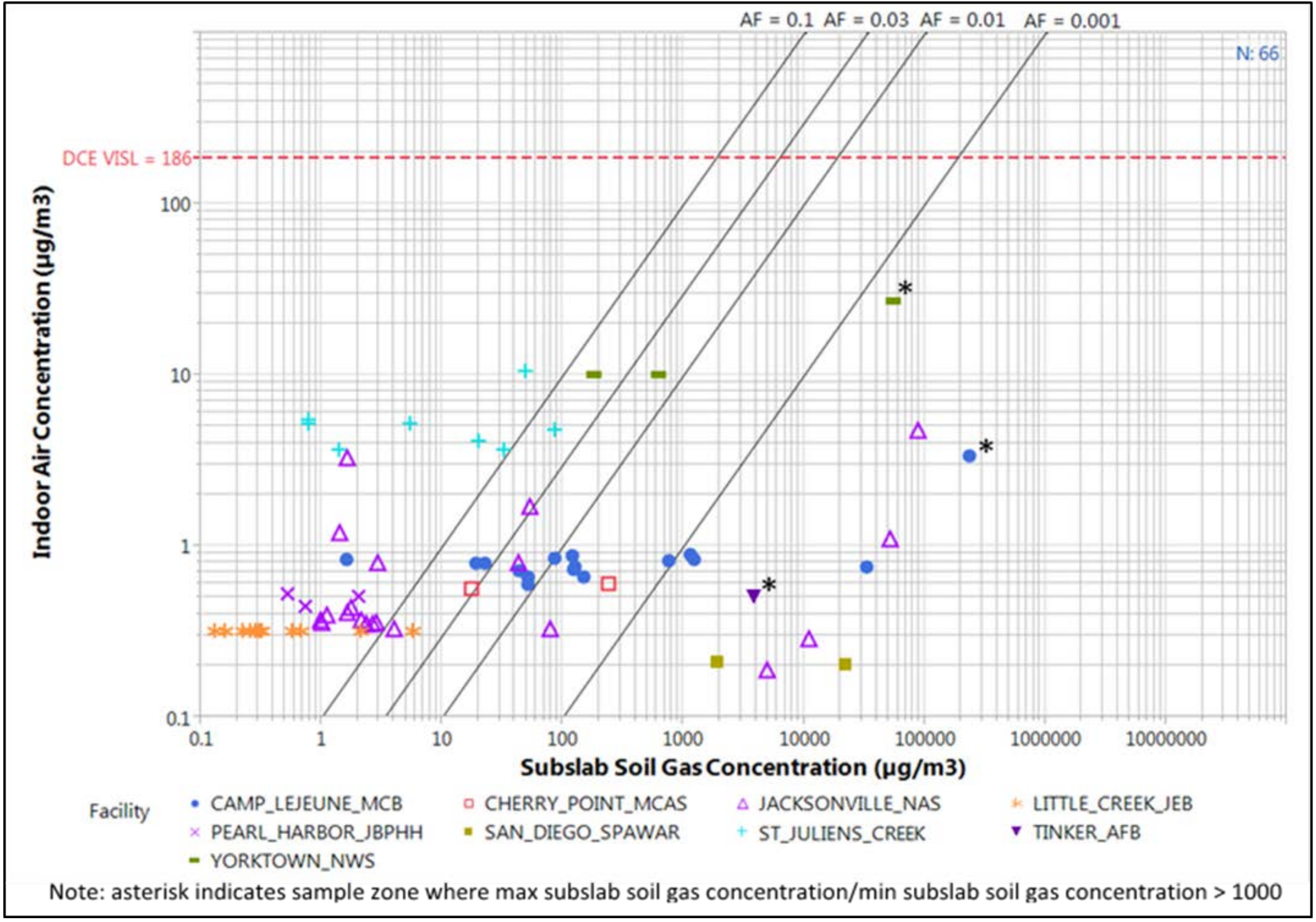


Figure 6-23. Cis-1,2-DCE Concentration in Sub-slab Soil Gas vs. Indoor Air
Sample Zone Averages with Nondetects Considered at Detection Limit
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NESDI Project #476

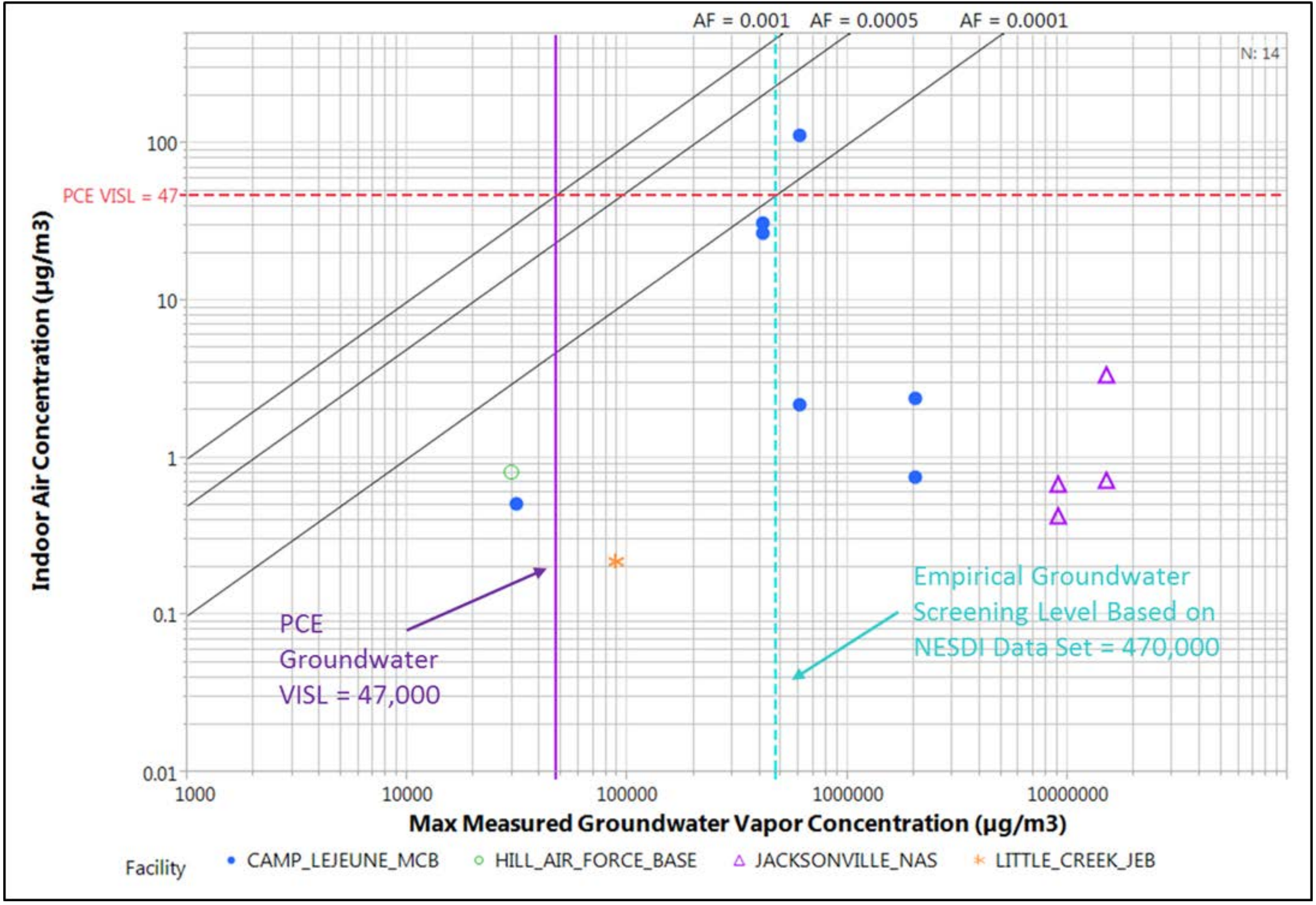

Figure 6-24. PCE Indoor Air Concentration vs. Groundwater Concentration
Sample Zone Averages; Detectable Data Only Included
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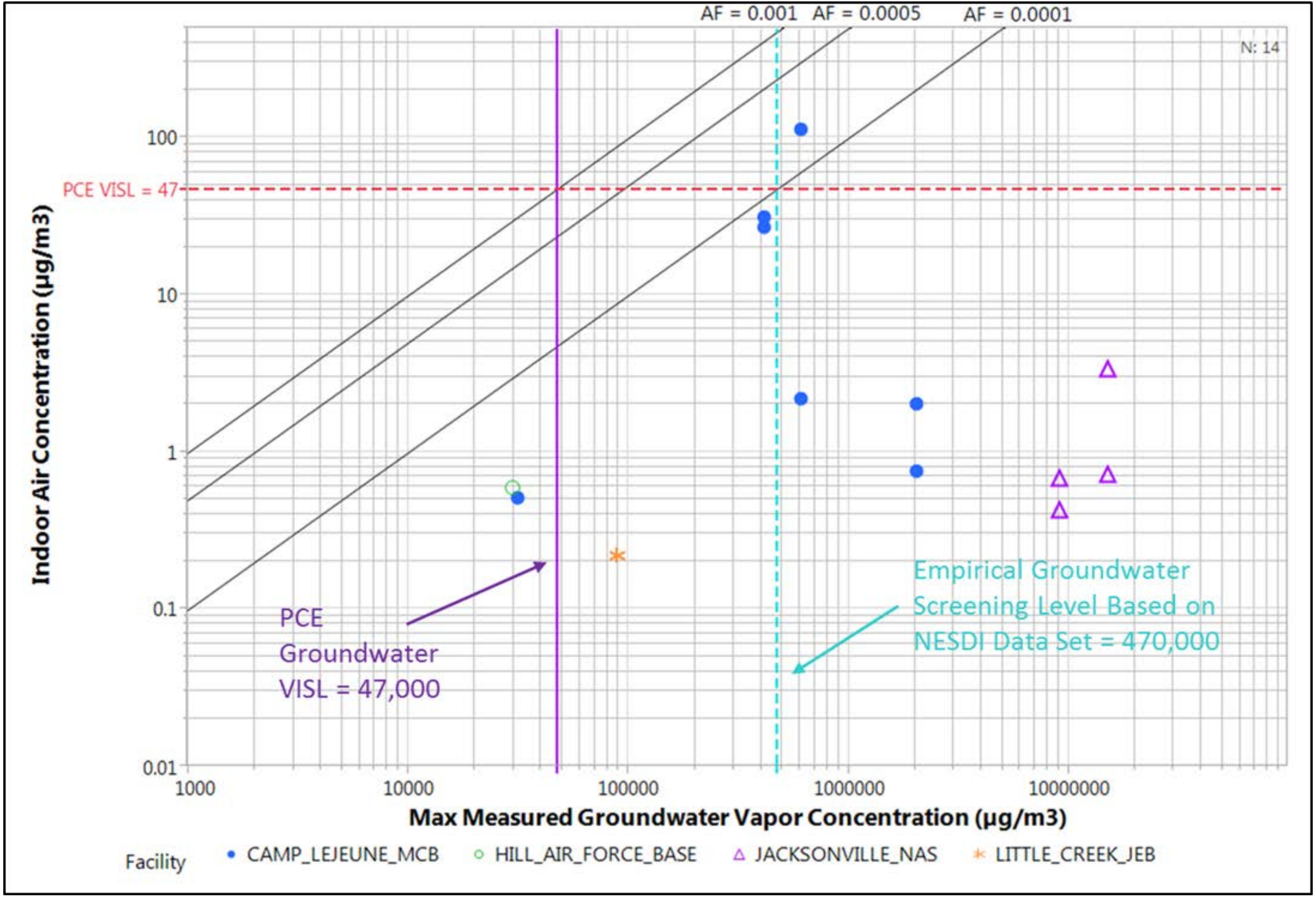

Figure 6-25. PCE Indoor Air Concentration vs. Groundwater Concentration
Sample Zone Averages with Nondetects Considered at Detection Limit
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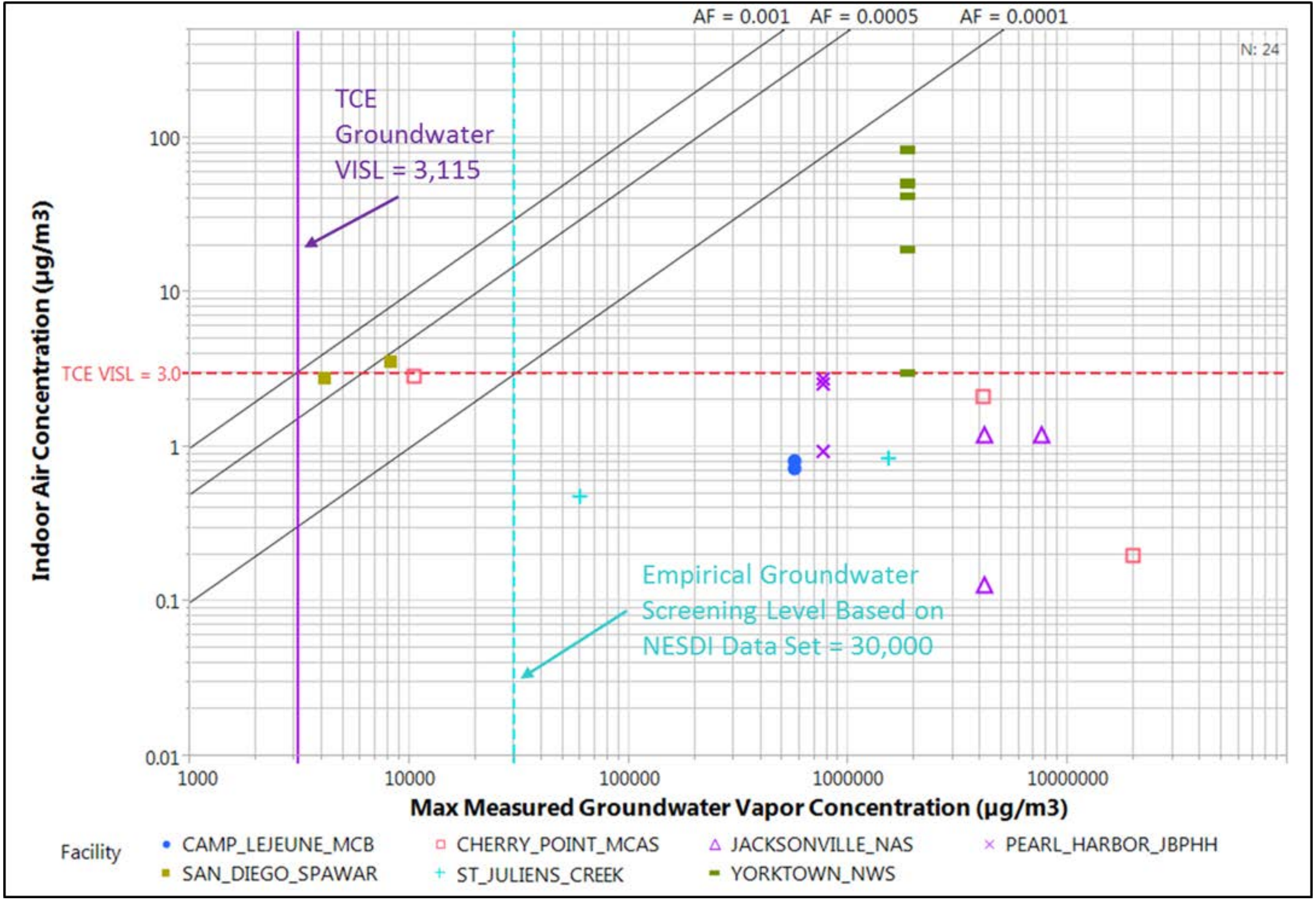

Figure 6-26. TCE Indoor Air Concentration vs. Groundwater Concentration
Sample Zone Averages; Detectable Data Only Included
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NESDI Project #476

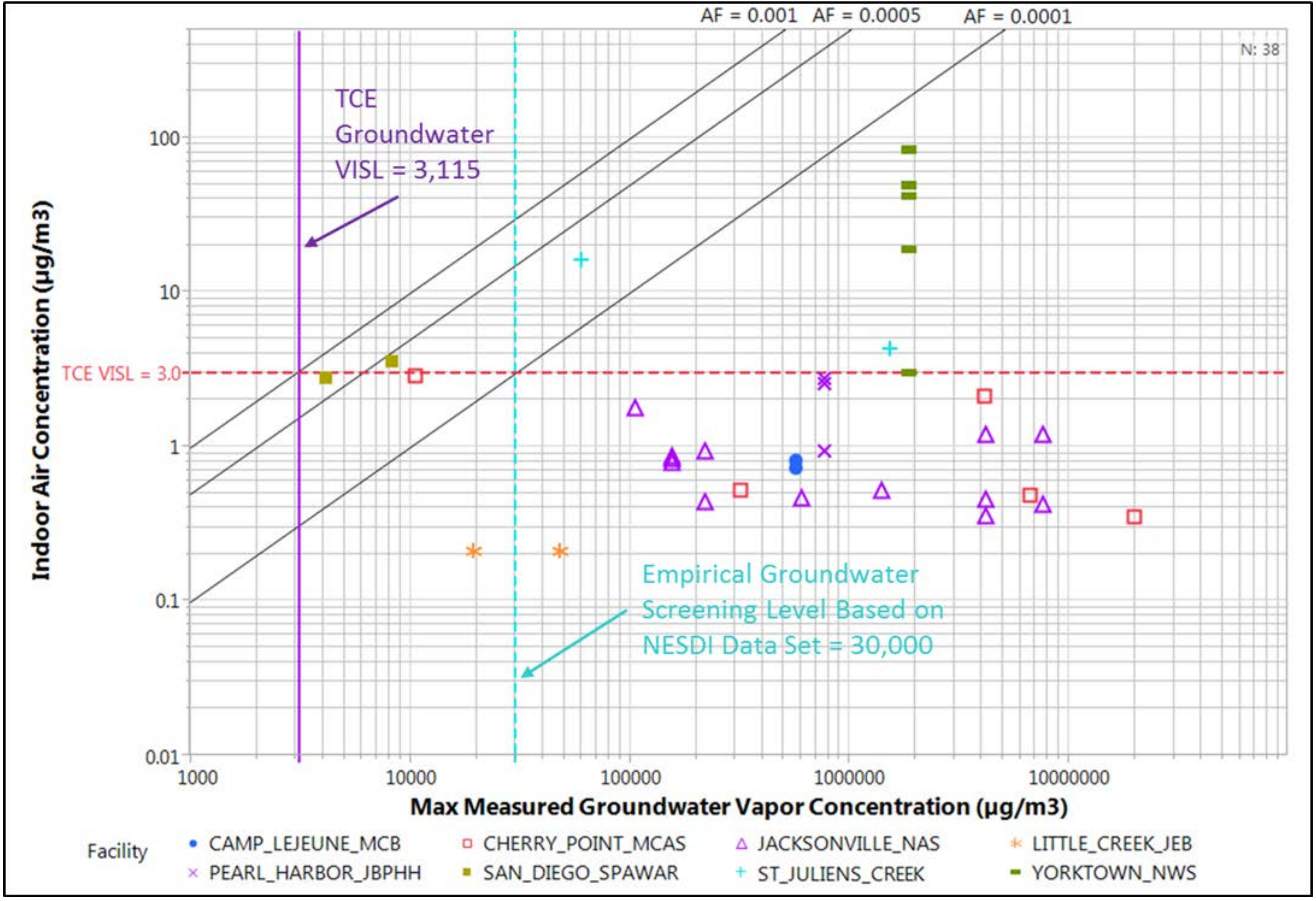

Figure 6-27. TCE Indoor Air Concentration vs. Groundwater Concentration
Sample Zone Averages with Nondetects Considered at Detection Limit
Baseline Screen + Source Strength Screen + Preferential Pathway=false
NESDI Project #476

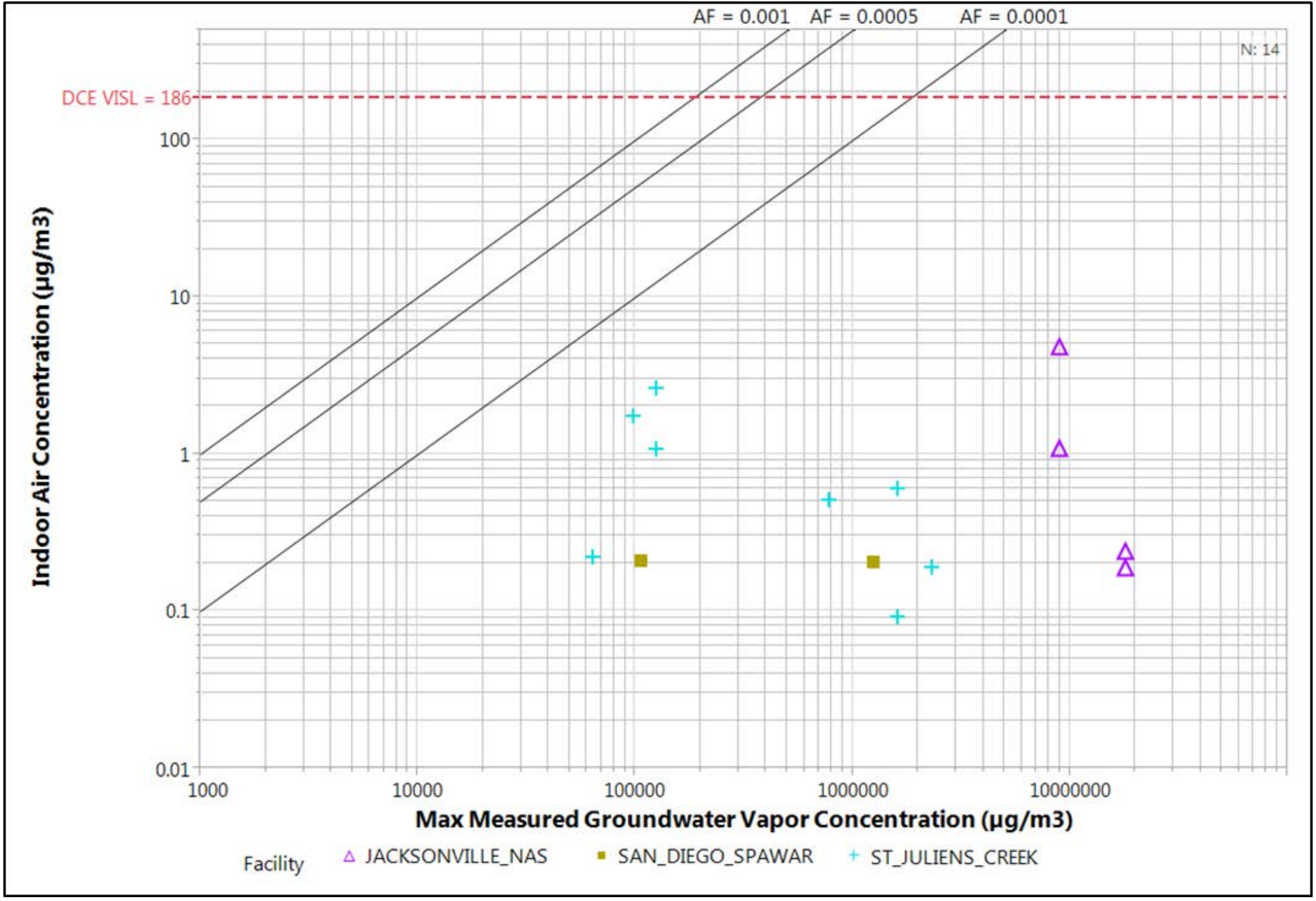

Figure 6-28. Cis-1,2-DCE Indoor Air Concentration vs. Groundwater Concentration
Sample Zone Averages; Detectable Data Only Included
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NESDI Project #476

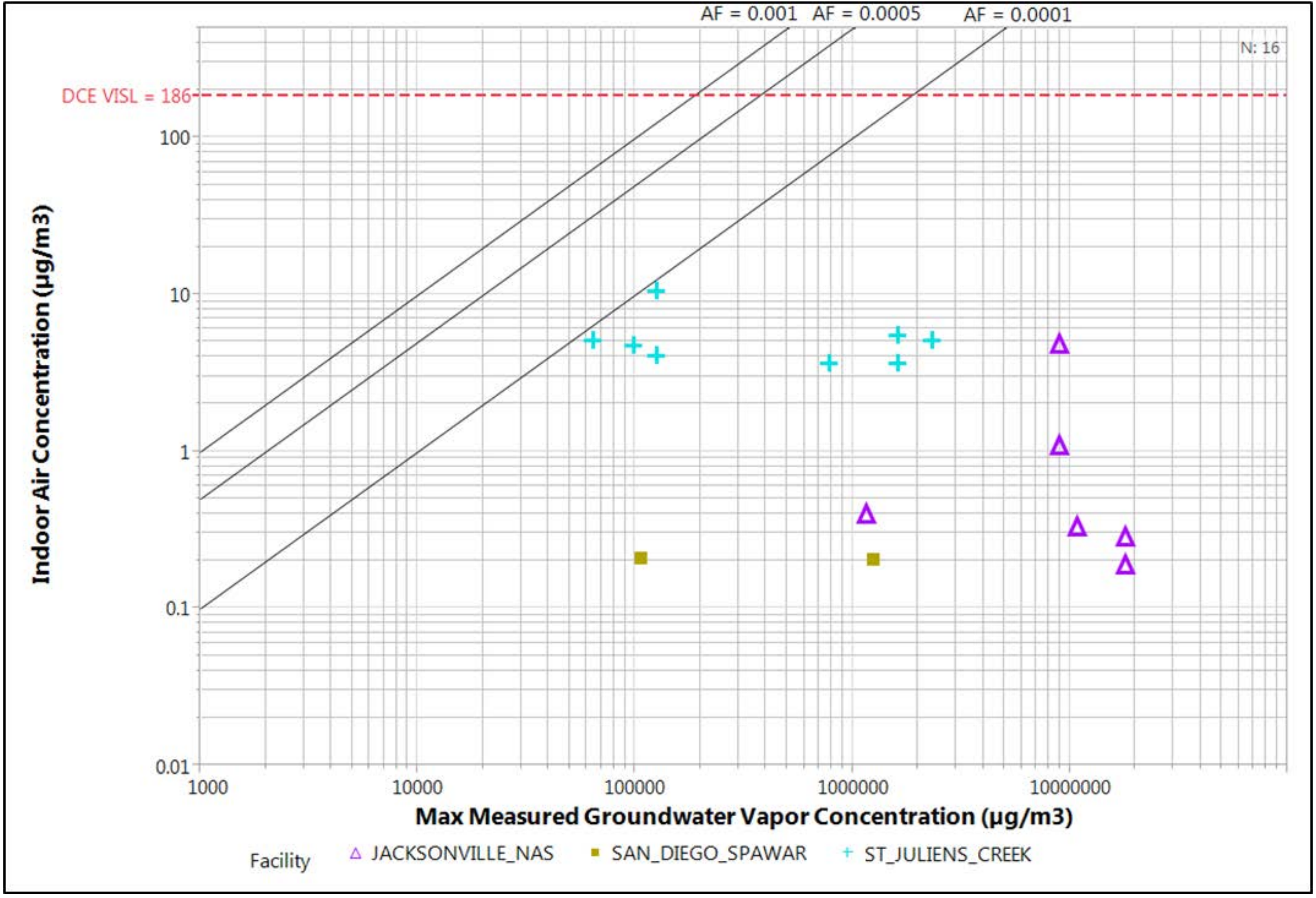

Figure 6-29. Cis-1,2-DCE Indoor Air Concentration vs. Groundwater Concentration
Sample Zone Averages with Nondetects Considered at Detection Limit
Baseline Screen + Source Strength Screen + Preferential Pathway=false
NESDI Project #476

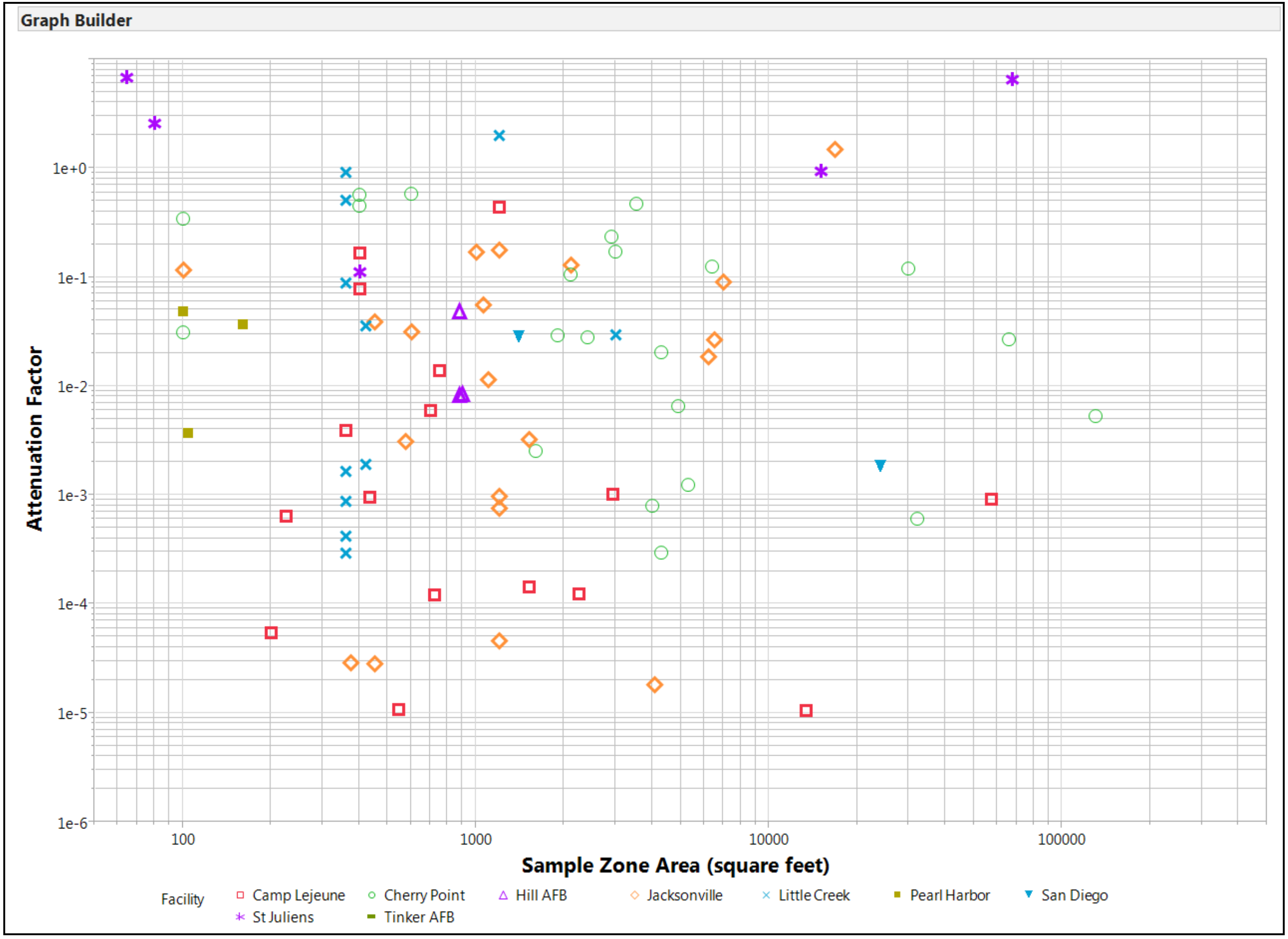

Figure 6-30. PCE Normalized Indoor Air Concentration vs. Sample Zone Area
Baseline Screen + Source Strength Screen + Preferential Pathway=false

NESDI Project #476

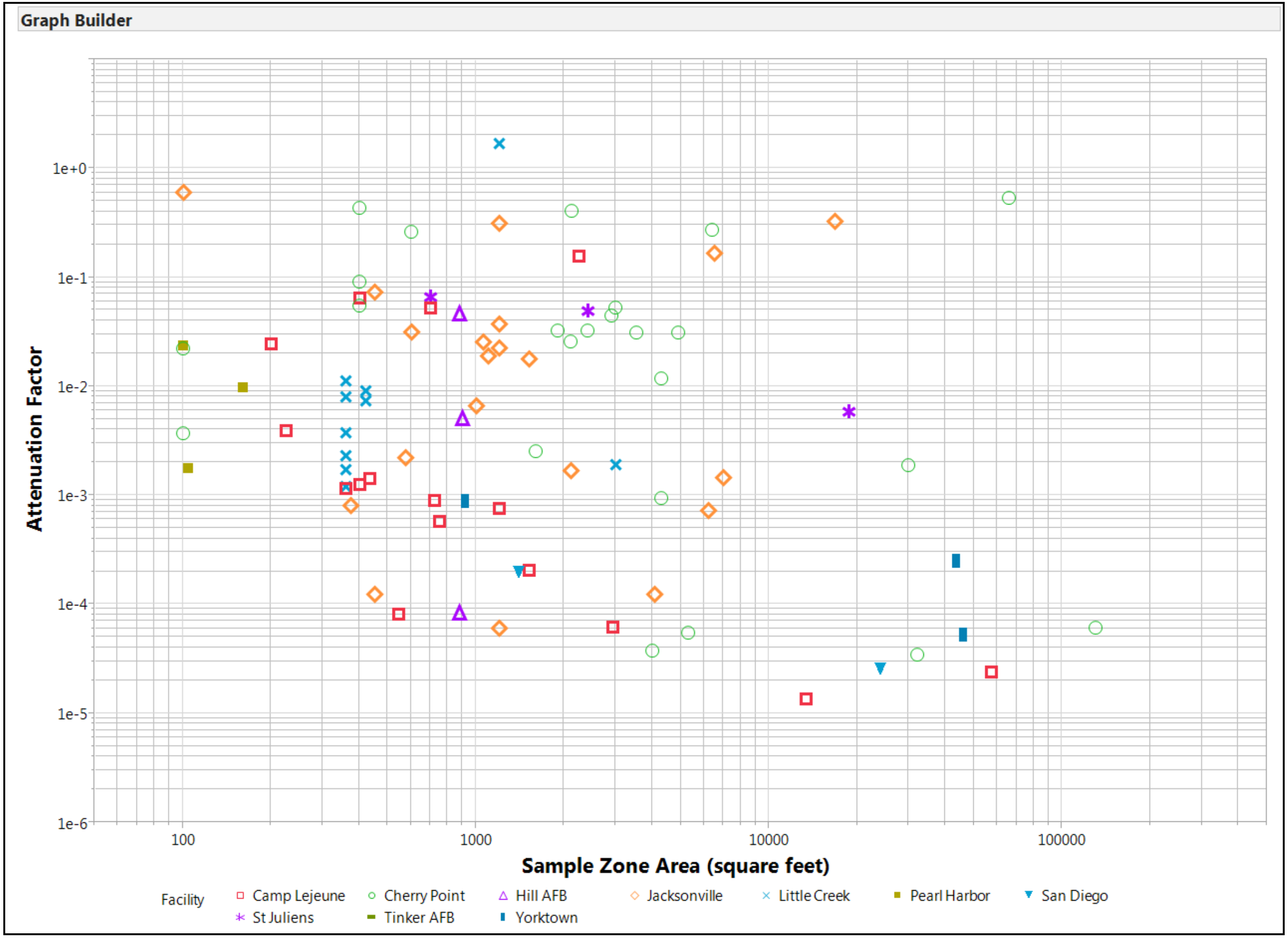

Figure 6-31. TCE Normalized Indoor Air Concentration vs. Sample Zone Area
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NESDI Project #476

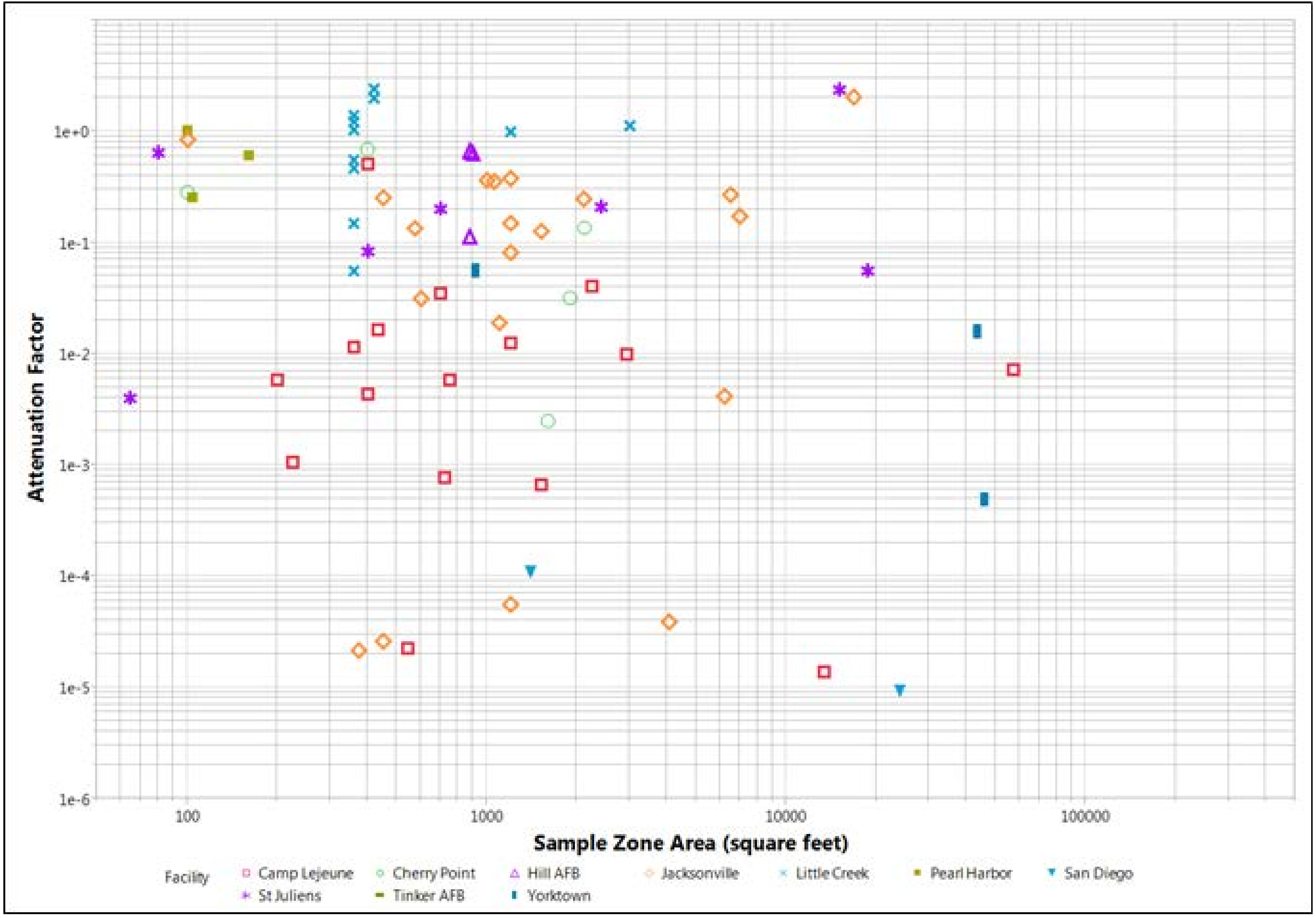

Figure 6-32. Cis-1,2-DCE Normalized Indoor Air Concentration vs. Sample Zone Area
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NESDI Project #476

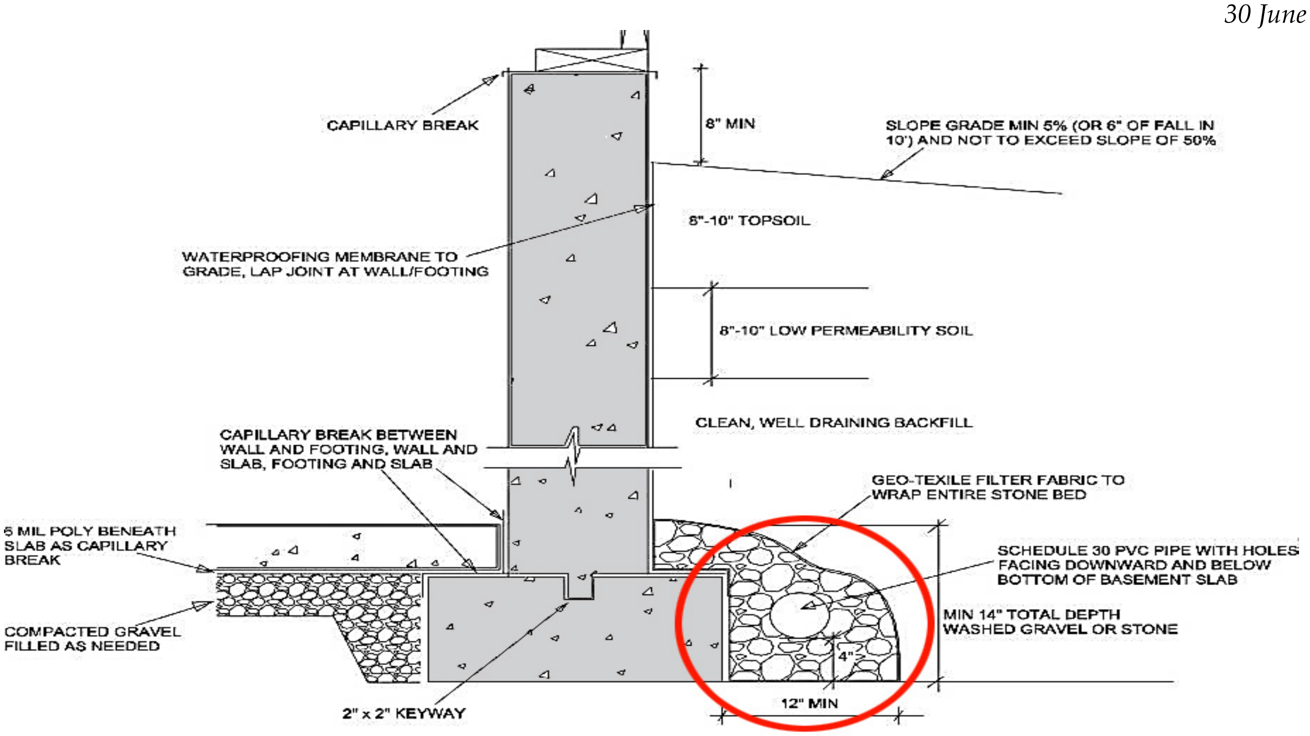

Figure reprinted from https://basc.pnnl.gov/sites/default/files/images/Drain%20Tile%20Cross-Section.jpg

Figure 6-33. Typical Cross-section of Foundation at Exterior Wall
NESDI Project #476

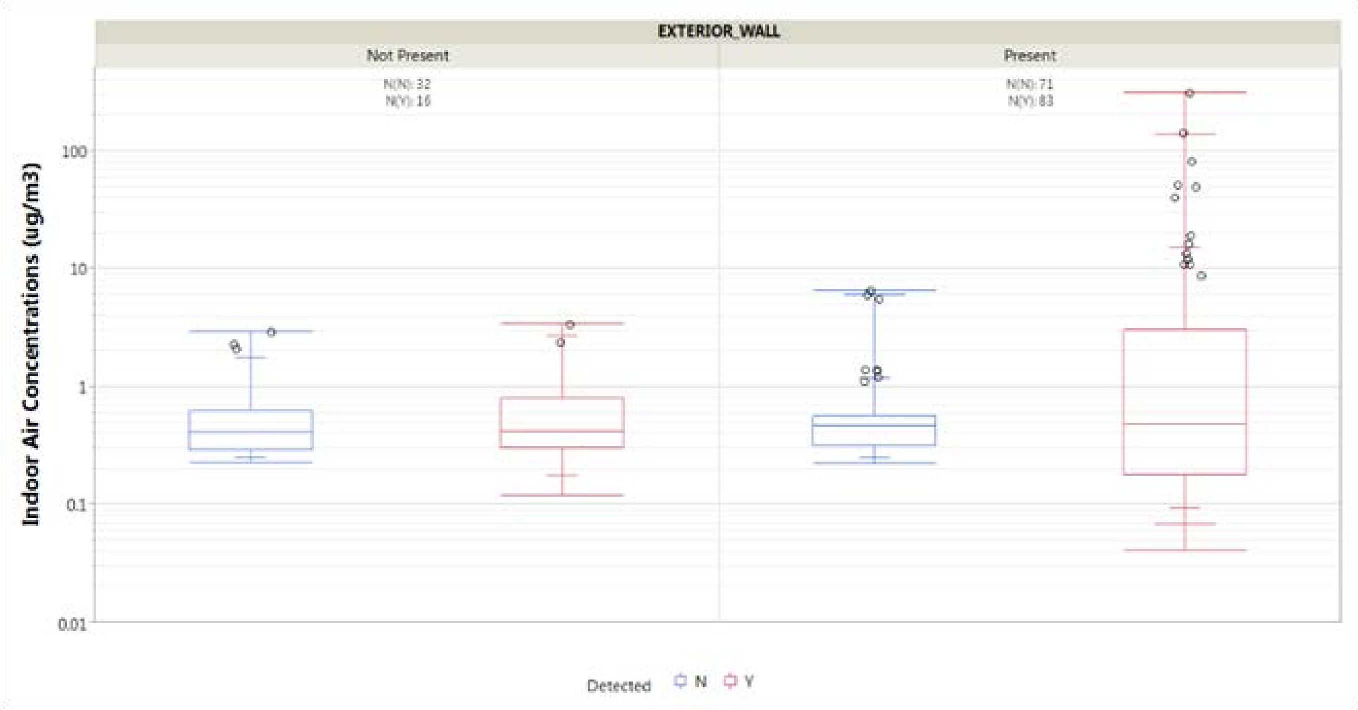

Figure 6-34. PCE Box and Whisker Plot of Indoor Air Concentration vs. Exterior Wall Presence in Sample Zone
NESDI Project #476

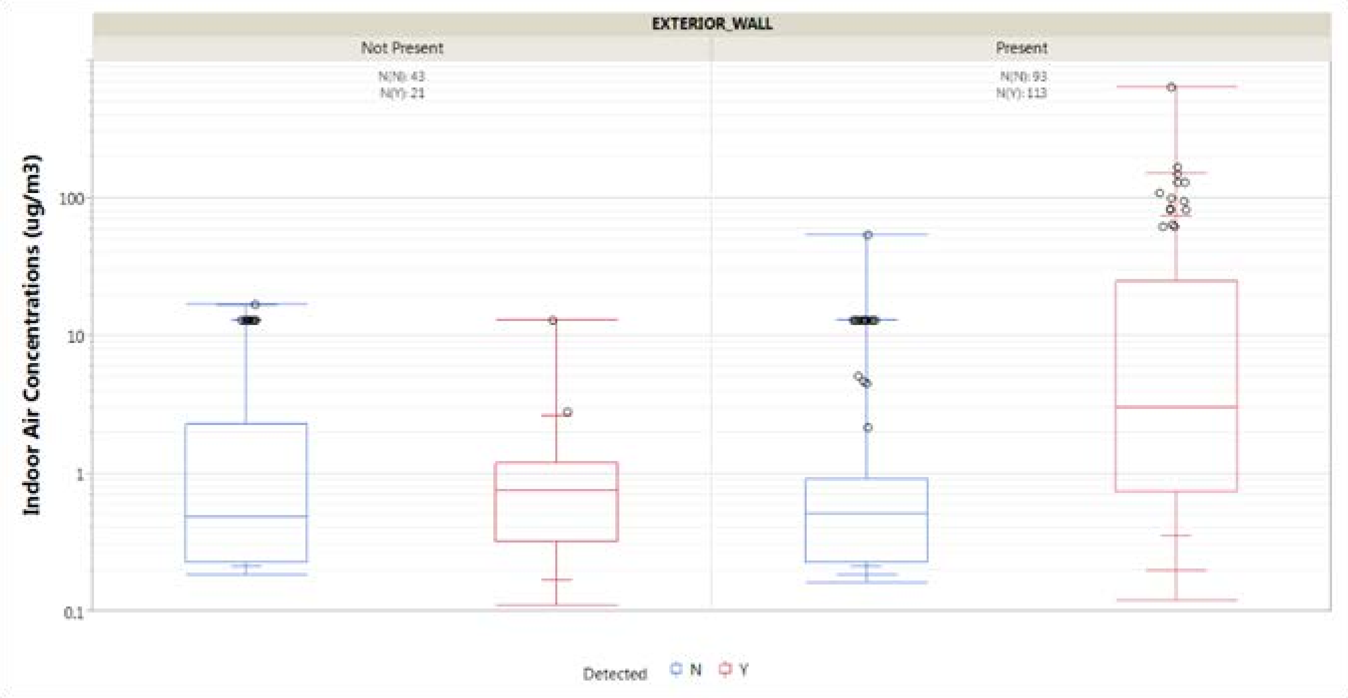

Figure 6-35. TCE Box and Whisker Plot of Indoor Air Concentration vs. Exterior Wall Presence in Sample Zone
NESDI Project #476

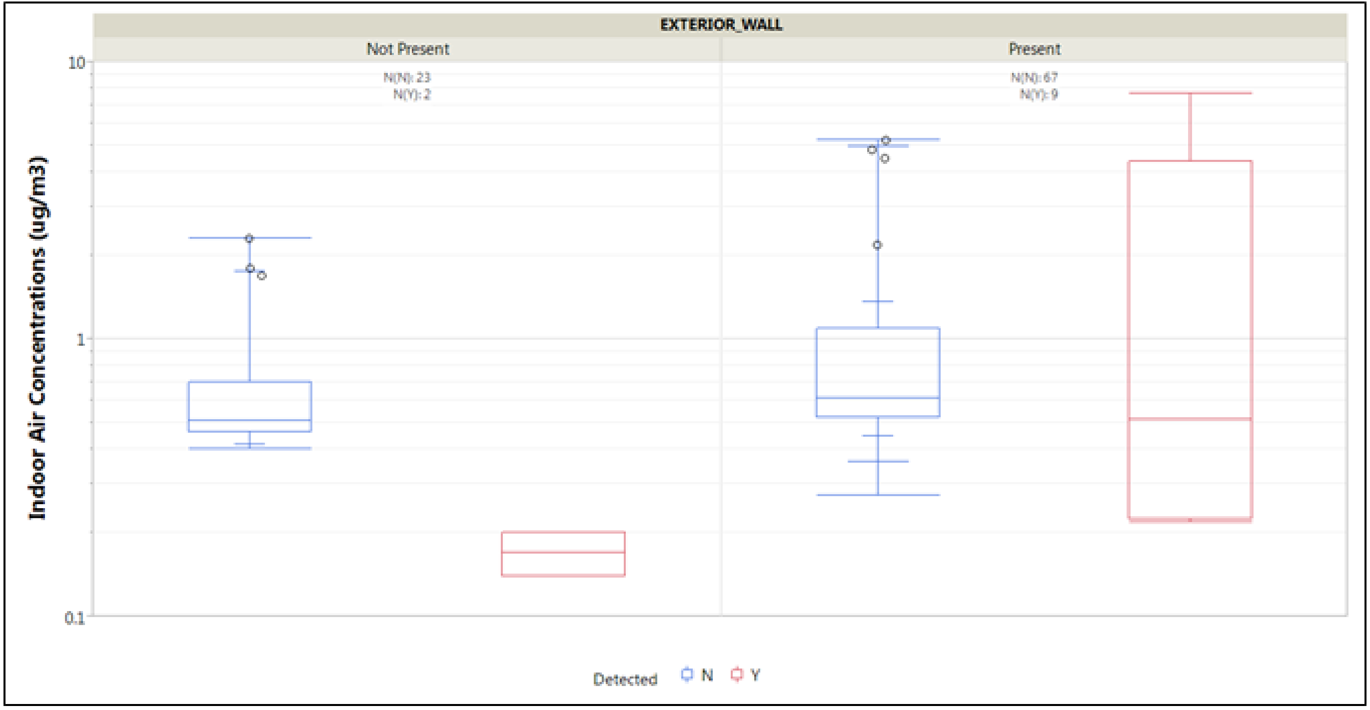

Figure 6-36. 1,1,1-TCA Box and Whisker Plot of Indoor Air Concentration vs. Exterior Wall Presence in Sample Zone
NESDI Project #476

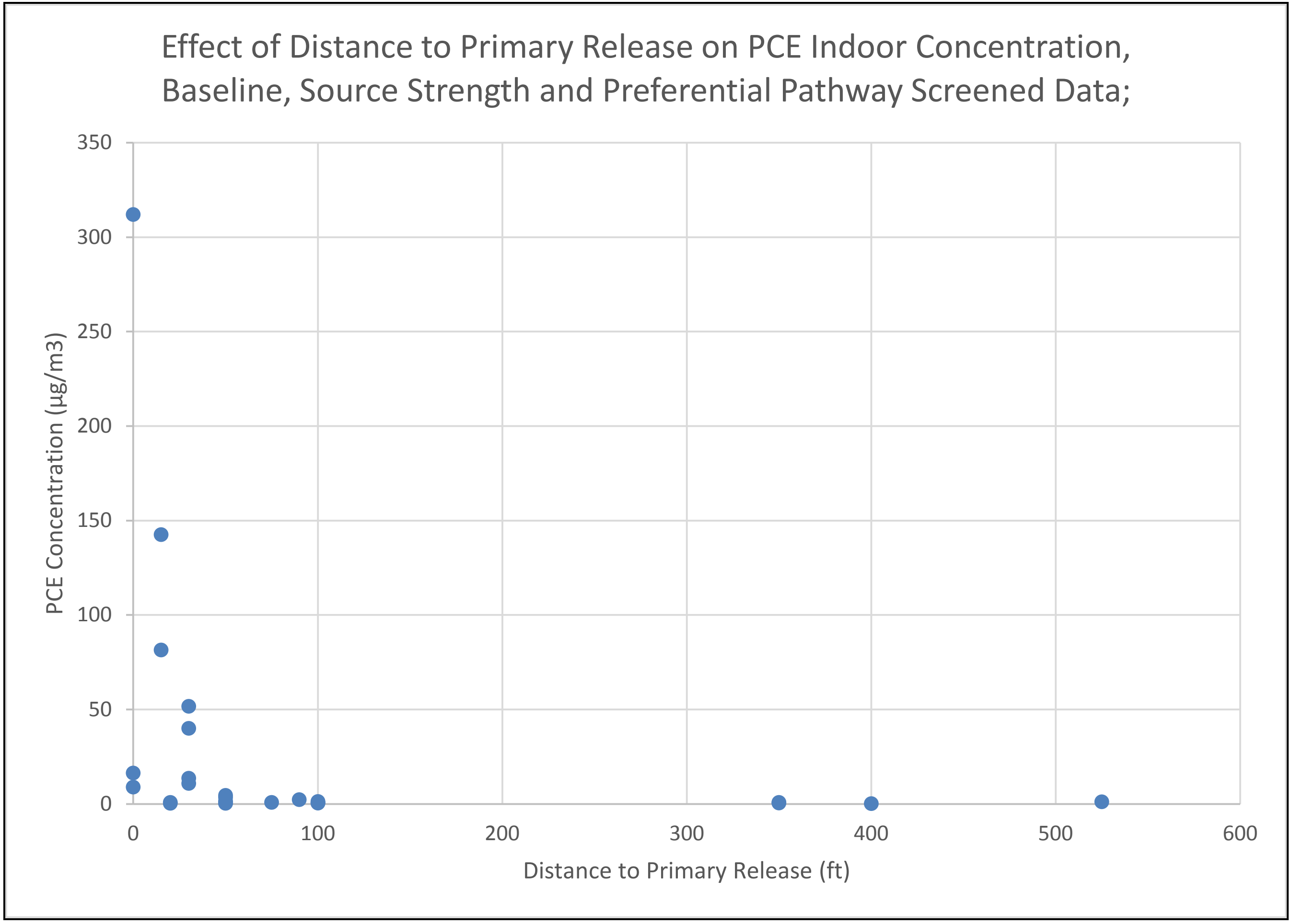

Figure 6-37. PCE Indoor Air Concentration vs. Distance to Primary Release
Baseline Screen + Source Strength Screen + Preferential Pathway=false

NESDI Project #476

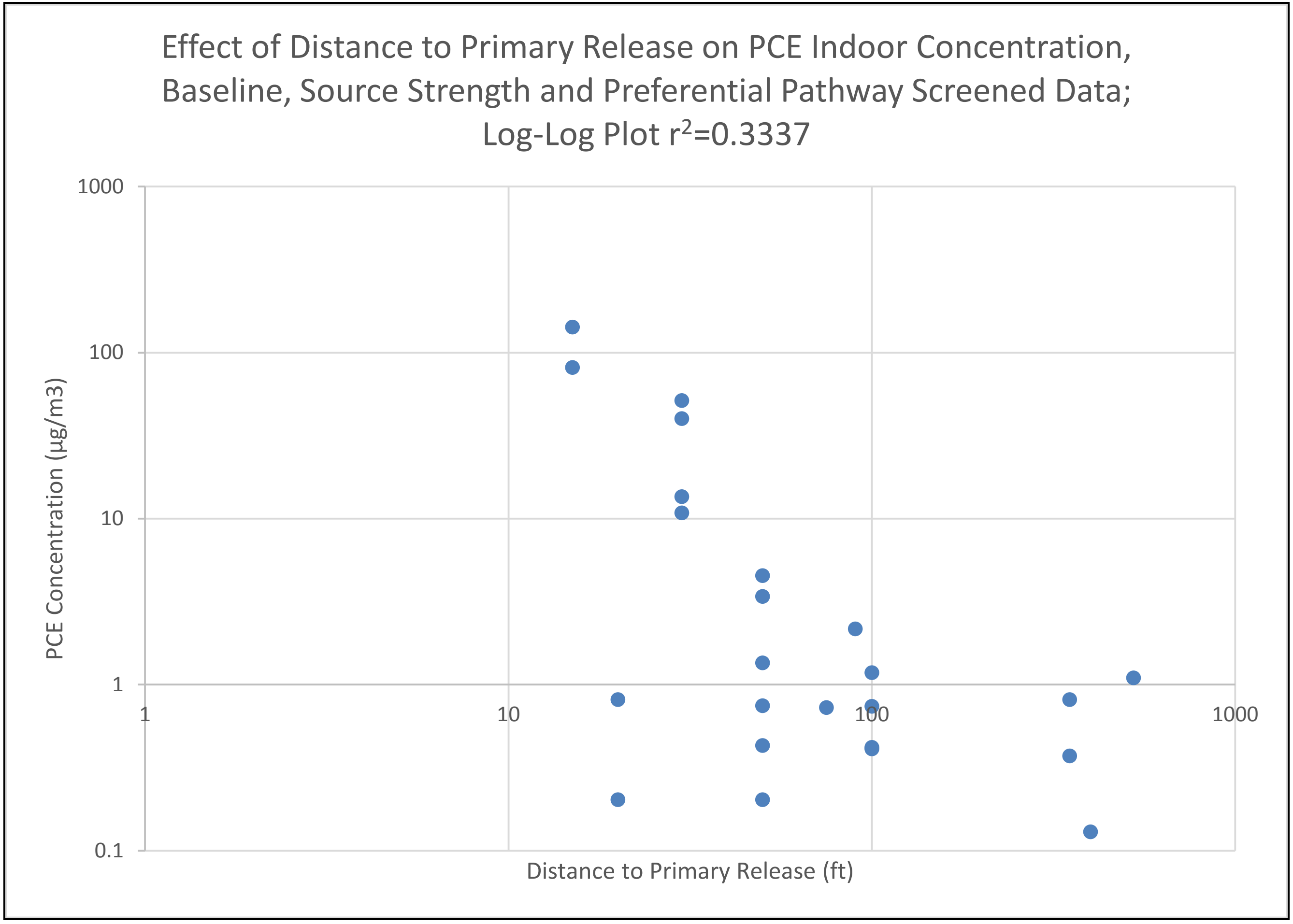

Figure 6-38. PCE Indoor Air Concentration vs. Distance to Primary Release Log-Log Plot
Baseline Screen + Source Strength Screen + Preferential Pathway=false

NESDI Project #476

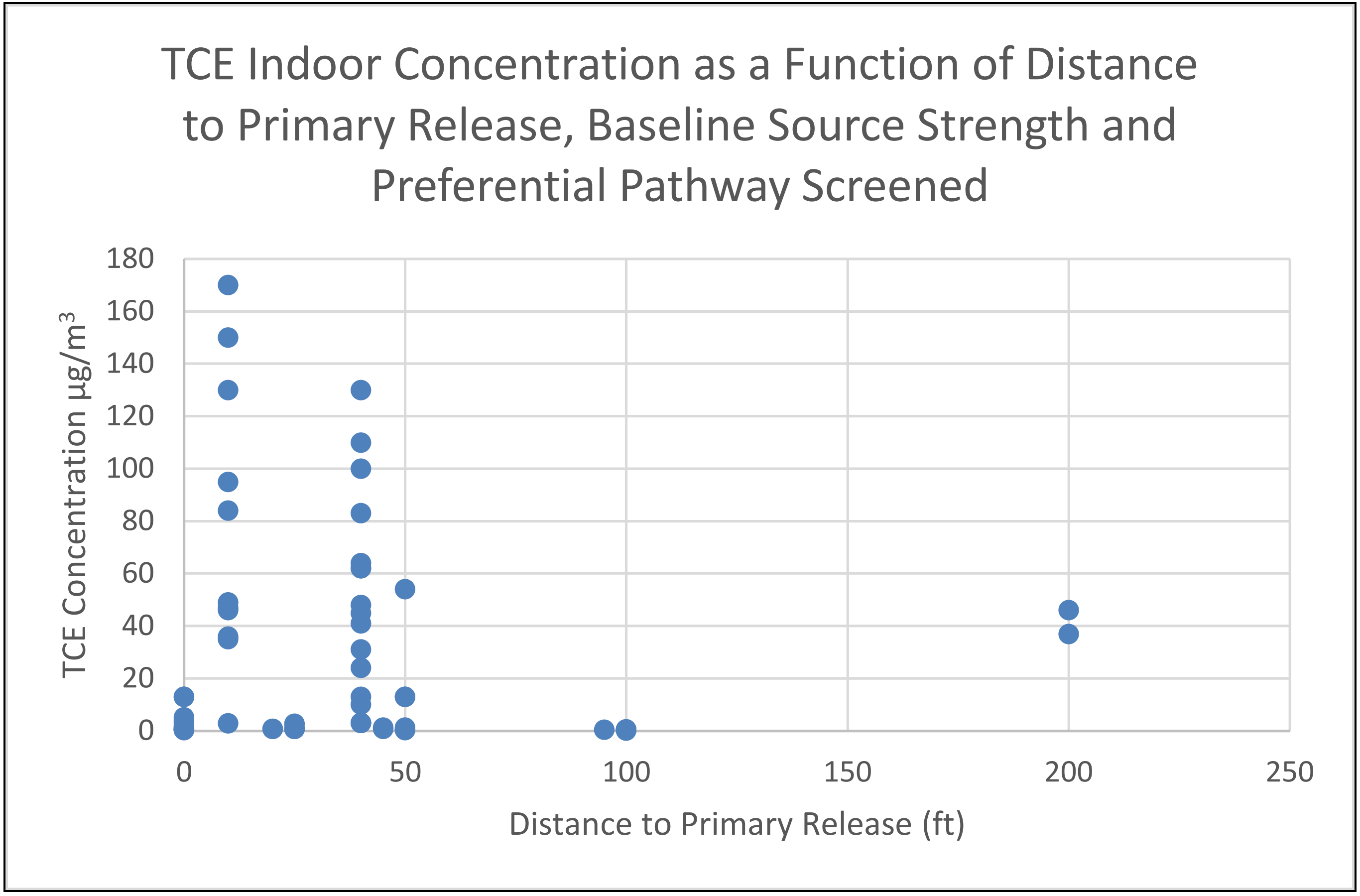

Figure 6-39. TCE Indoor Air Concentration vs. Distance to Primary Release
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NESDI Project #476

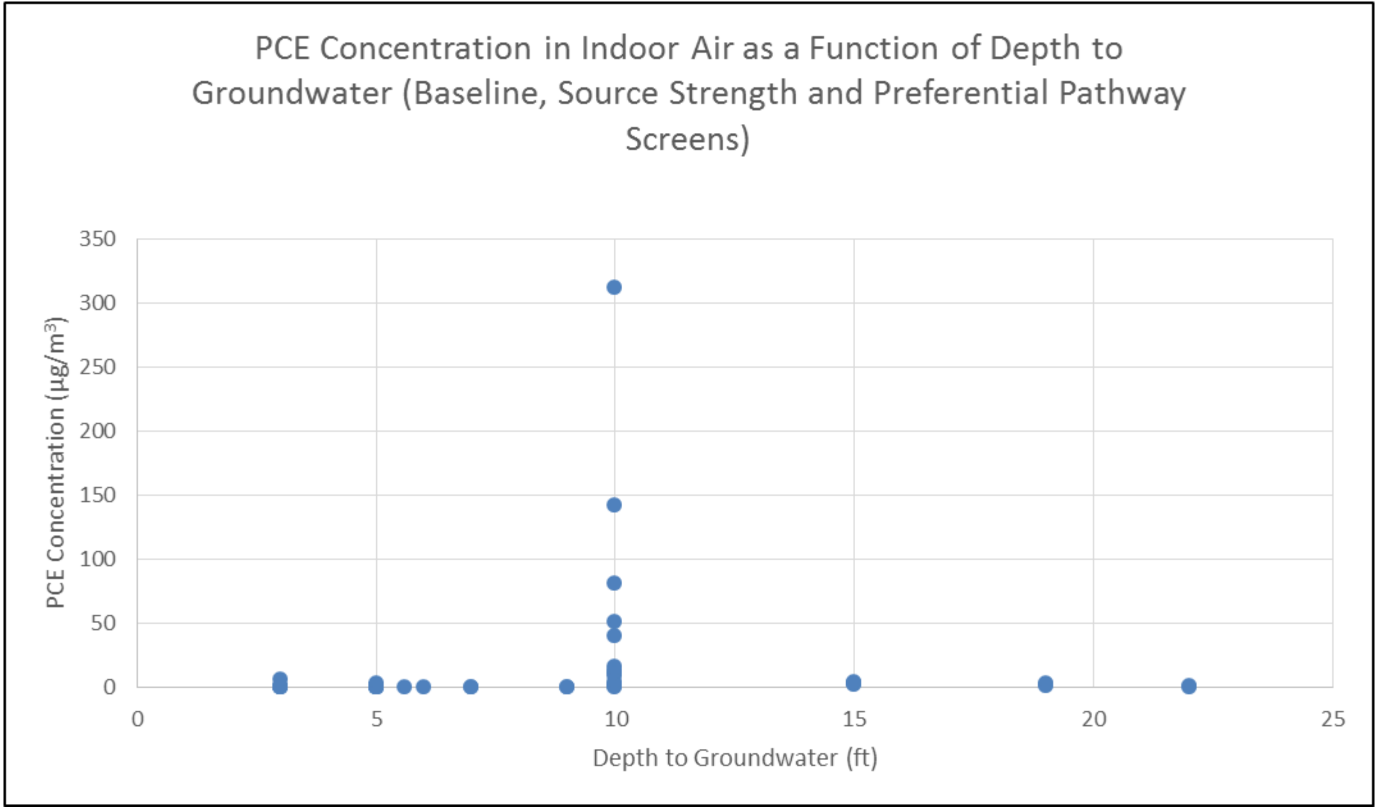

Figure 6-40. PCE Indoor Air Concentration vs. Depth to Groundwater
Baseline Screen + Source Strength Screen + Preferential Pathway=false

NESDI Project #476

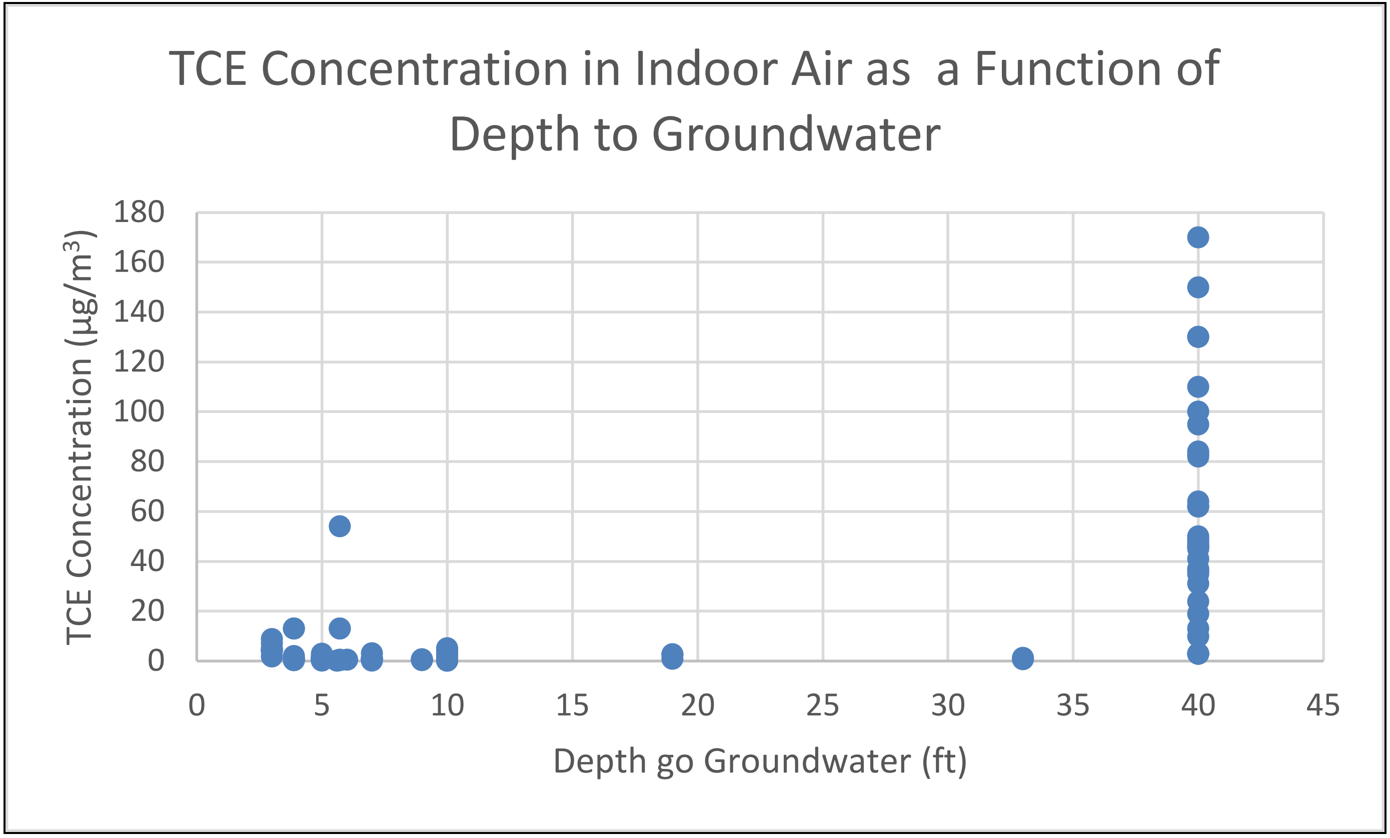

Figure 6-41. TCE Indoor Air Concentration vs. Depth to Groundwater
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NESDI Project #476

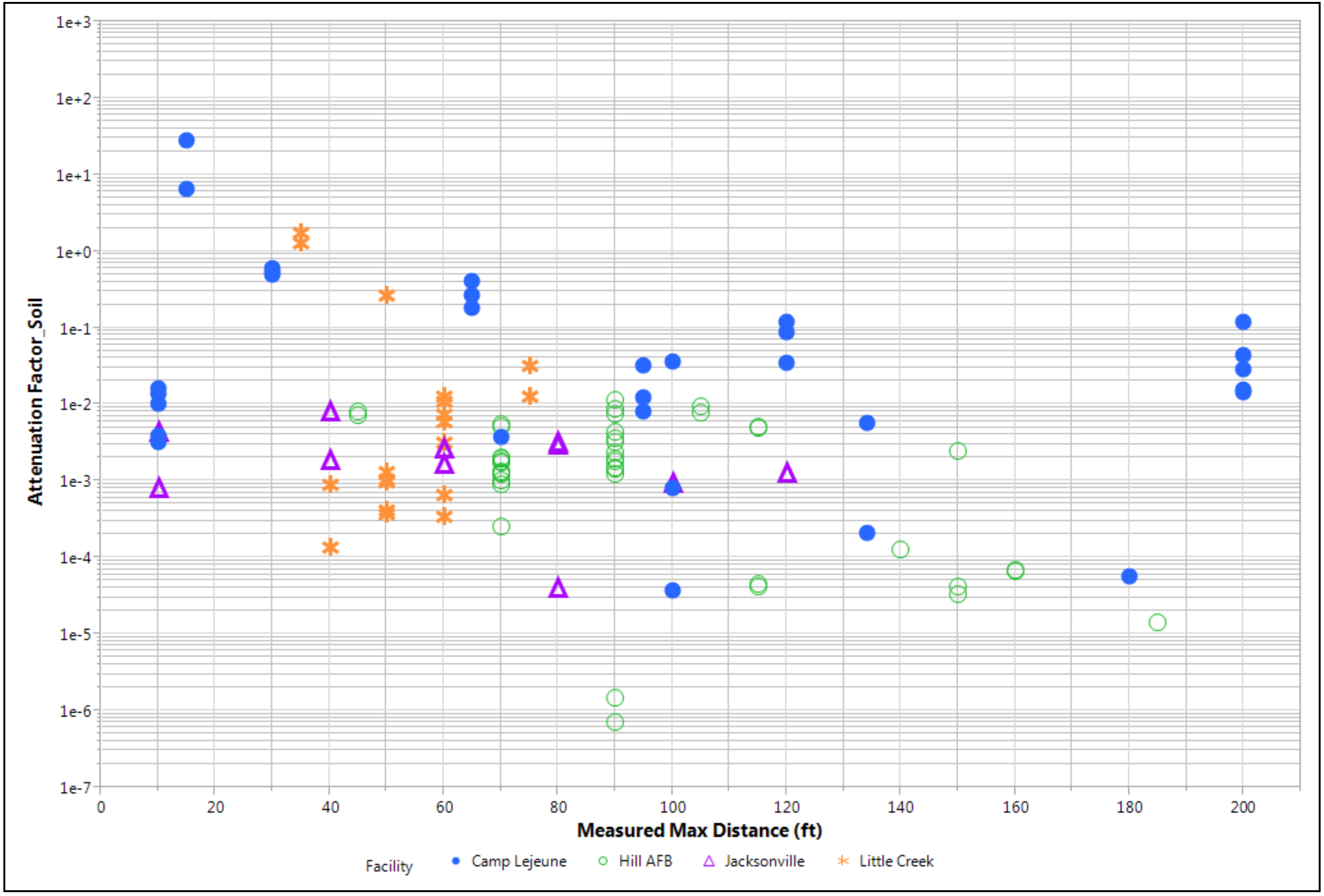

Figure 6-42, PCE Soil Attenuation Factor vs. Distance to Measured Maximum Groundwater Concentration
NESDI Project #476

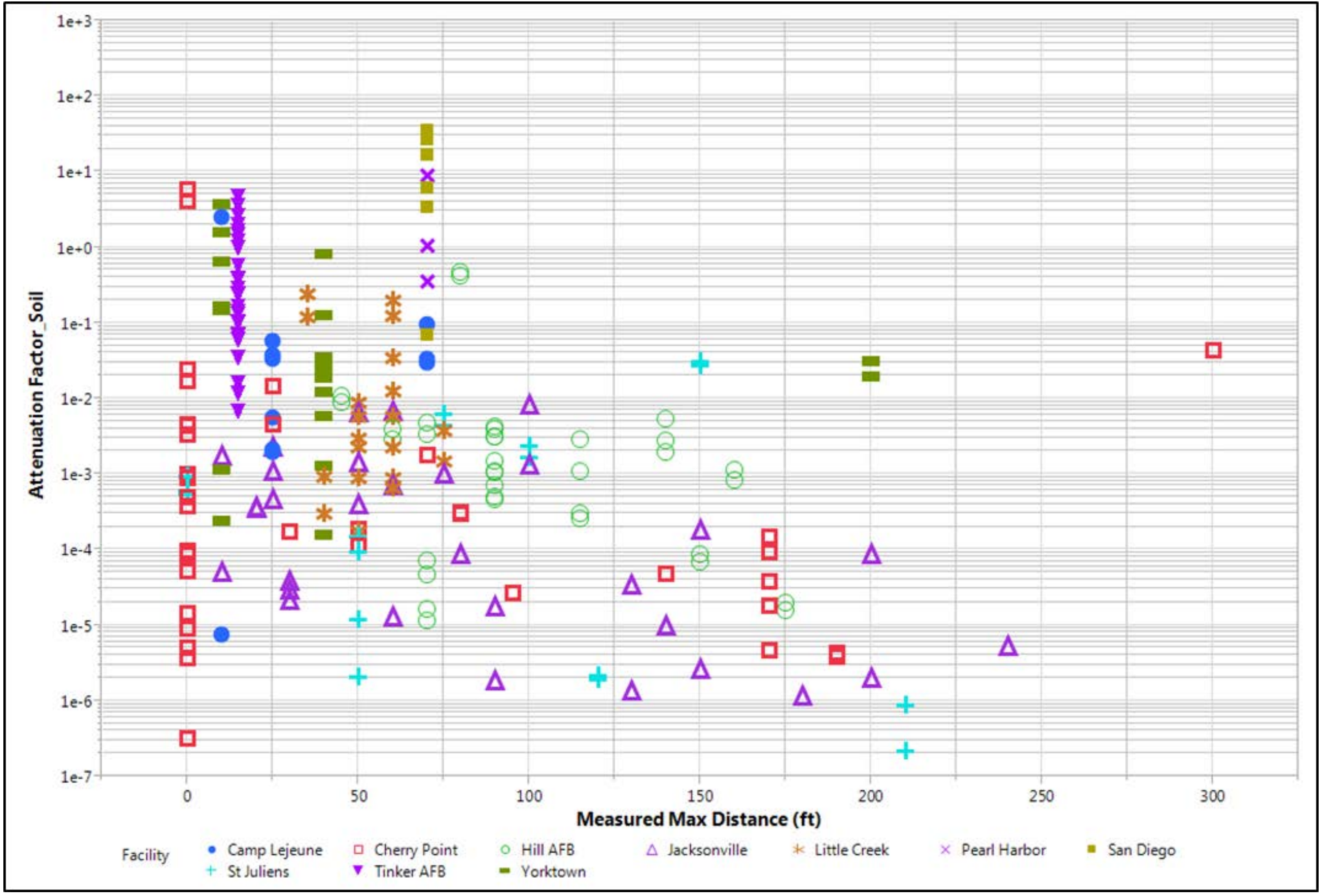

Figure 6-43, TCE Soil Attenuation Factor vs. Distance to Measured Maximum Groundwater Concentration
NESDI Project #476

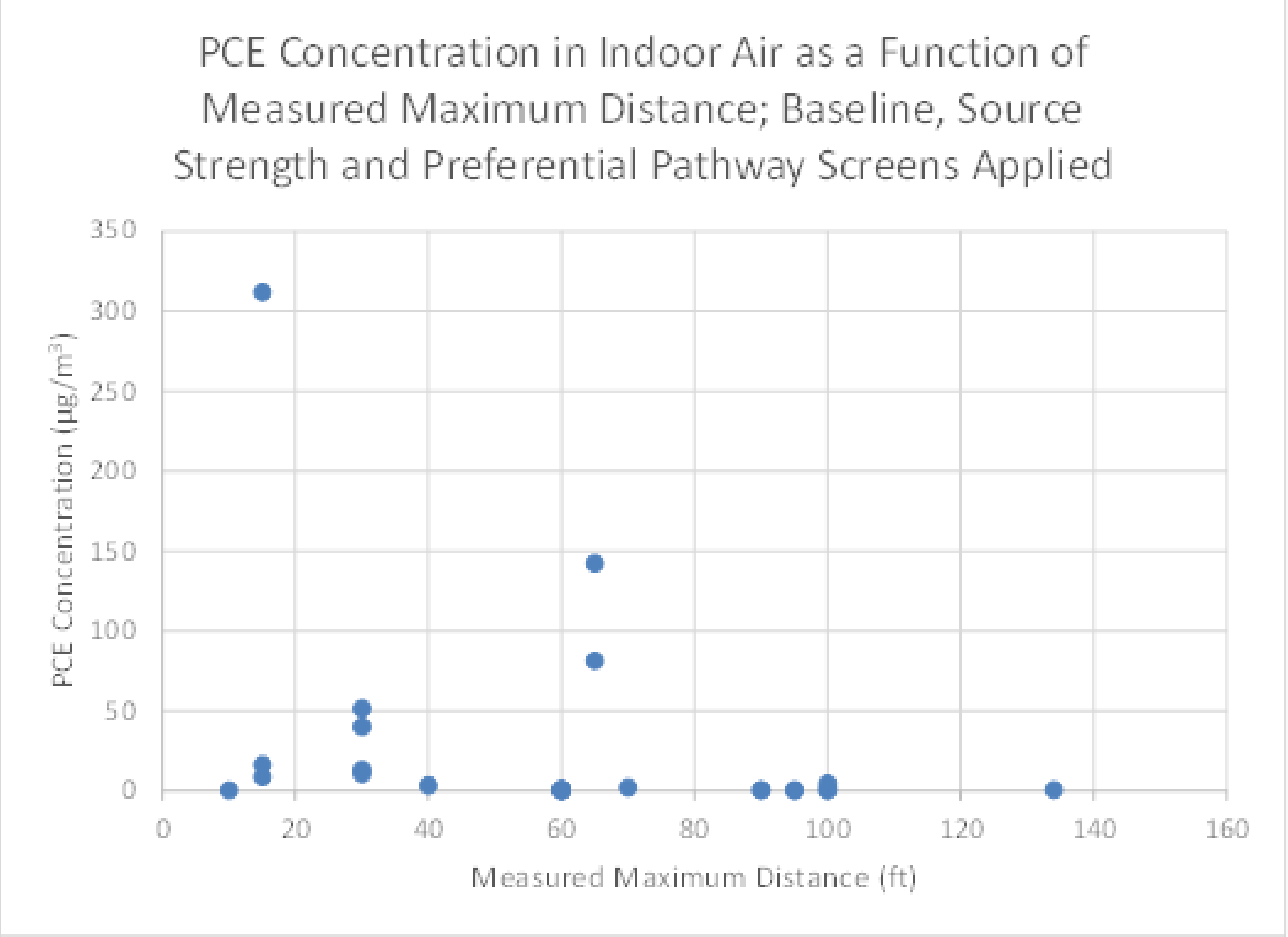

Figure 6-44, PCE Indoor Air Concentration vs. Distance to Measured Maximum Groundwater Concentration
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NESDI Project #476

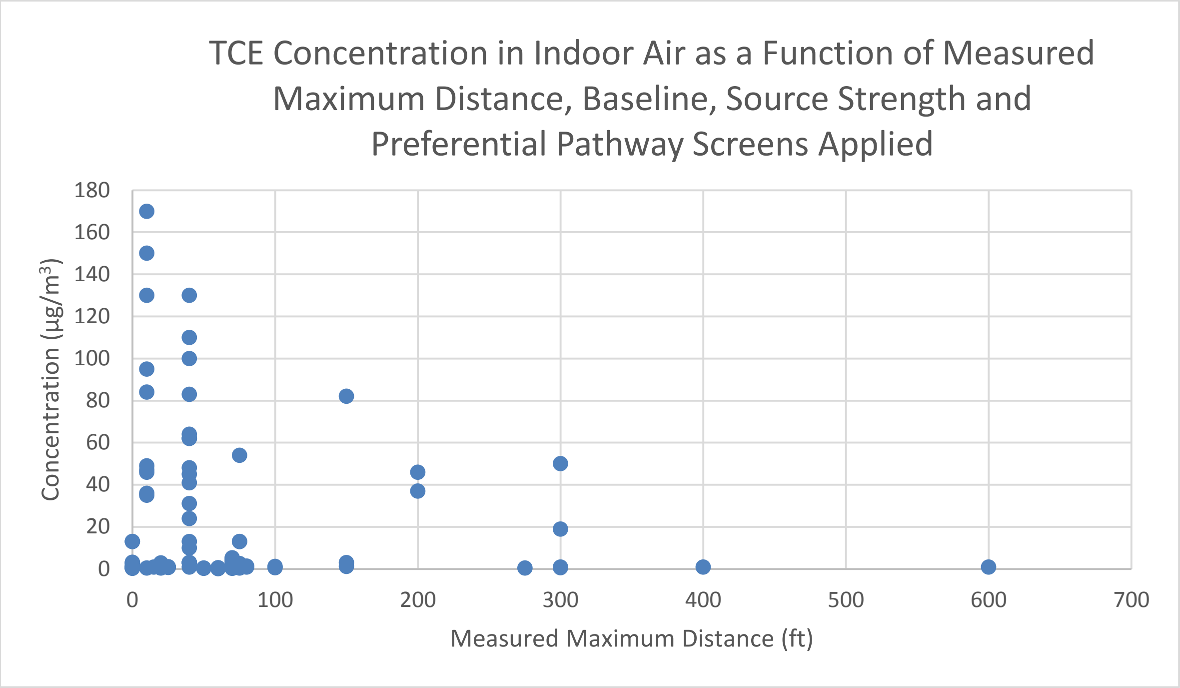


Figure 6-45, TCE Indoor Air Concentration vs. Distance to Measured Maximum Groundwater Concentration
Baseline screen + Source Strength Screen + Preferential Pathway=false

NESDI Project #476

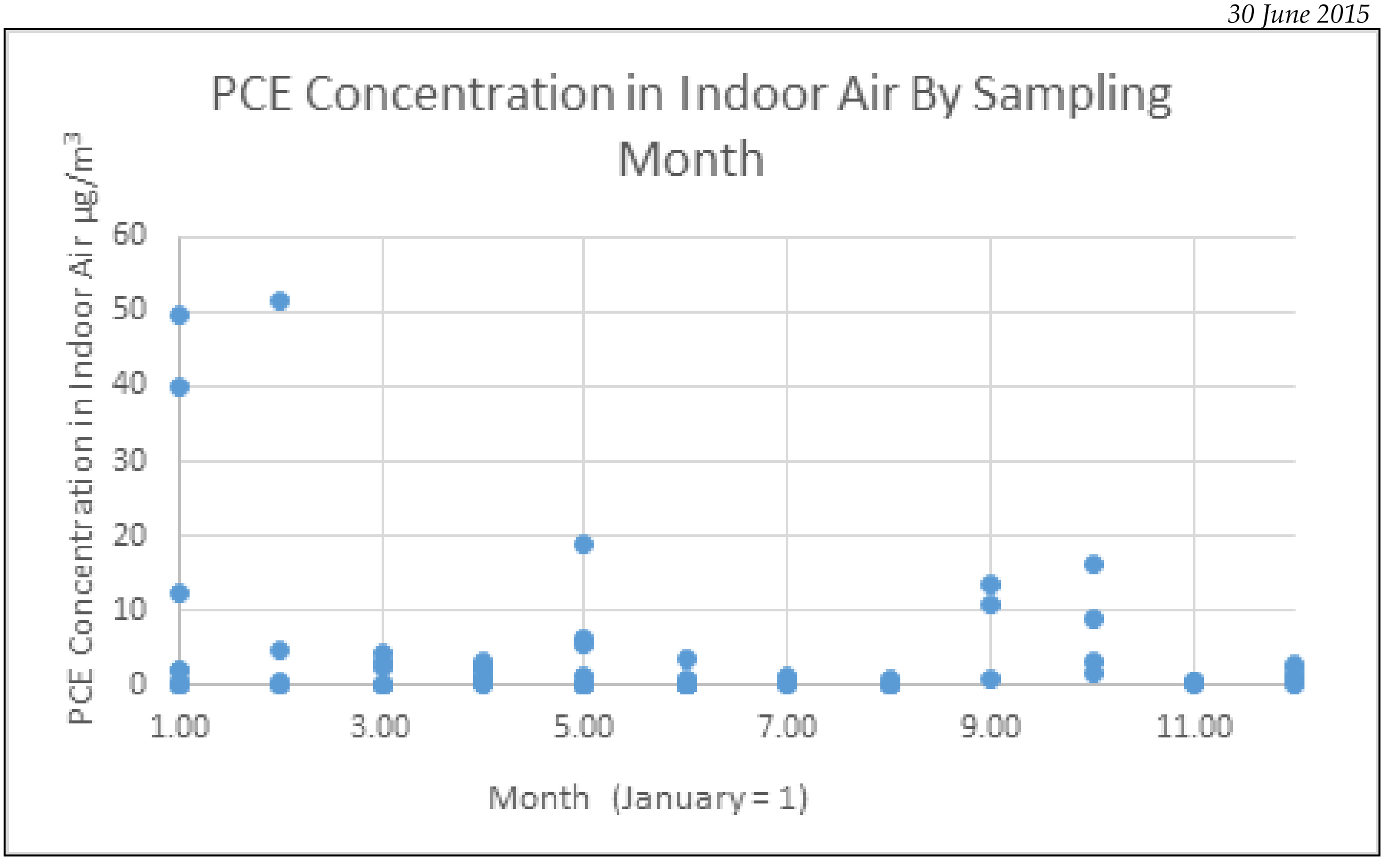


Figure 6-46. PCE Indoor Air Concentration vs. Sampling Month
NESDI Project #476

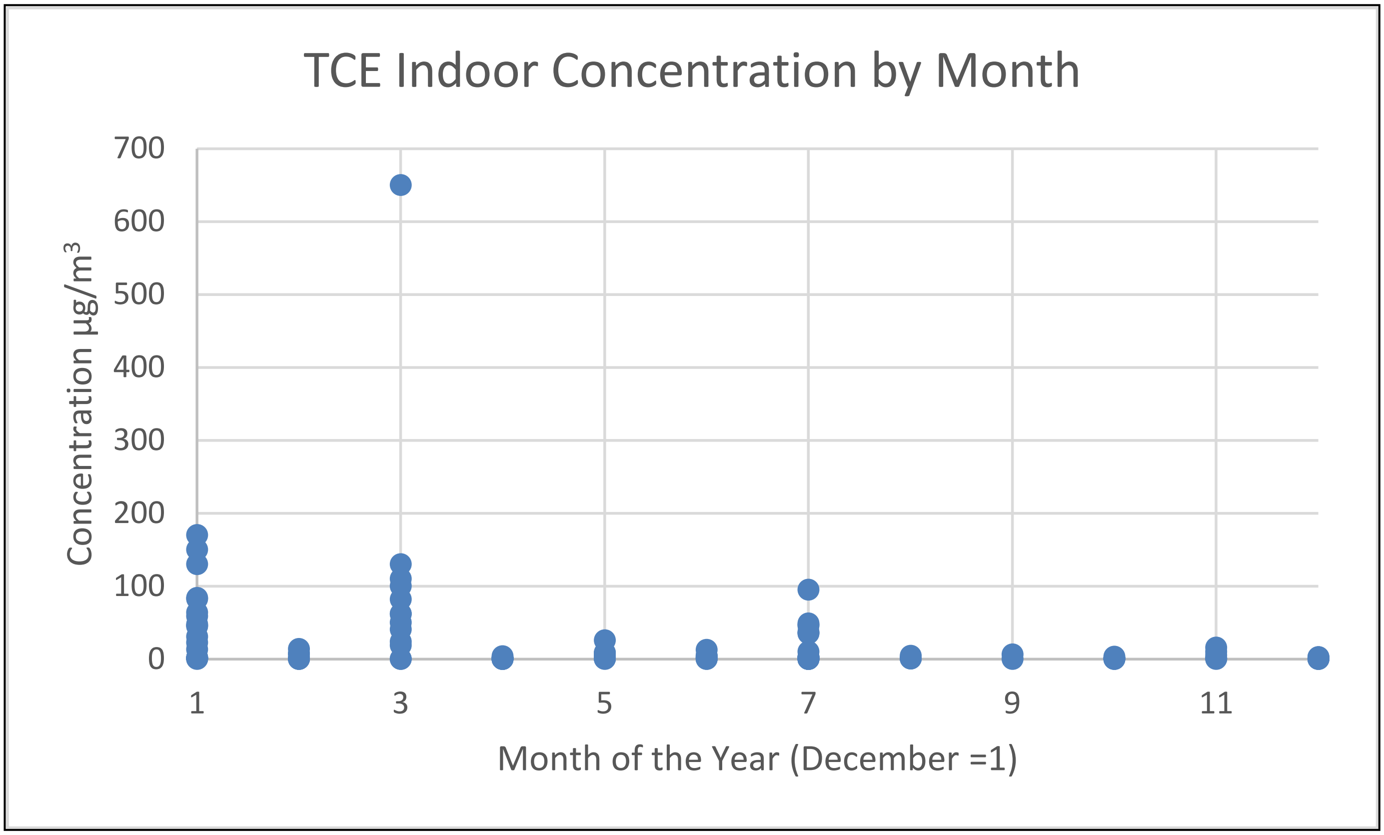
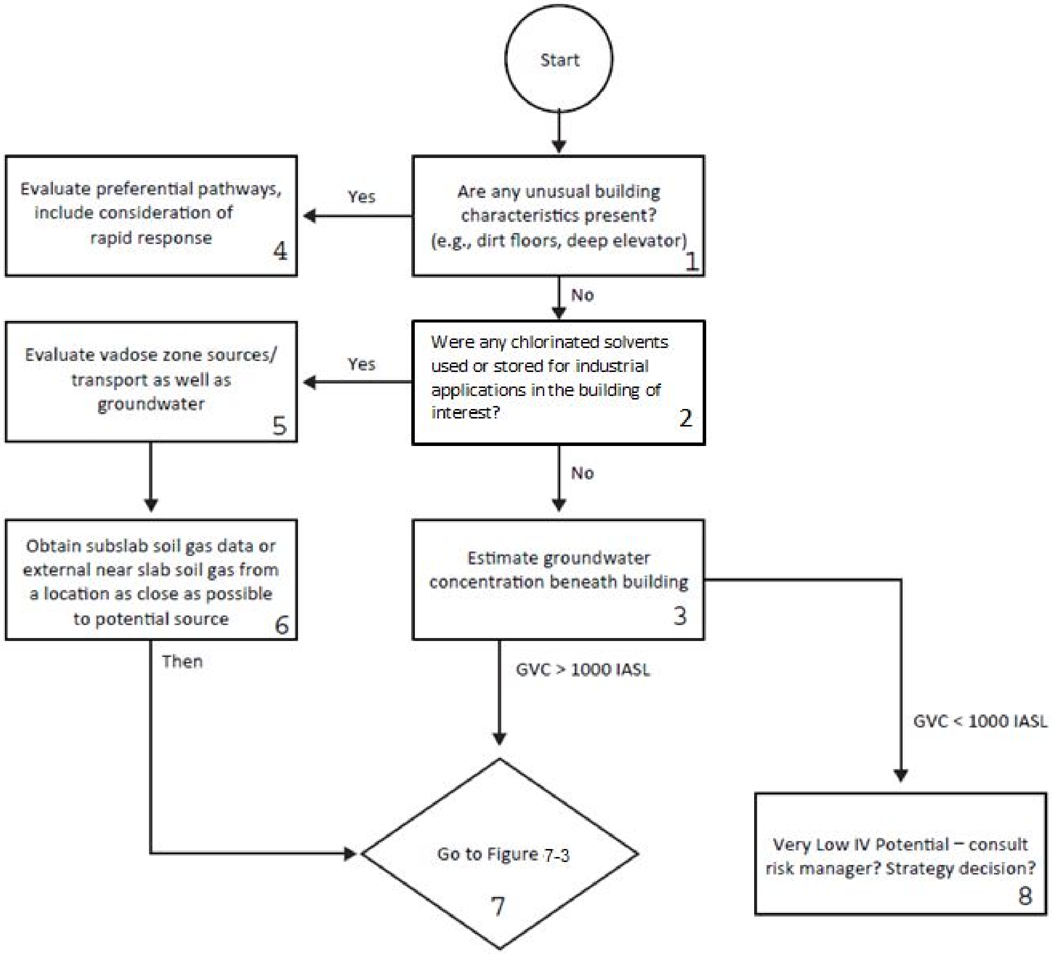


Figure 6-47. TCE Indoor Air Concentration vs. Sampling Month
NESDI Project #476



GVC = Groundwater Vapor Concentration (µg/m^3)
IASL = Indoor Air Screening Level (µg/m^3)

Figure 7-1. Quantitative Decision Framework – Groundwater Data Only
NESDI Project #476

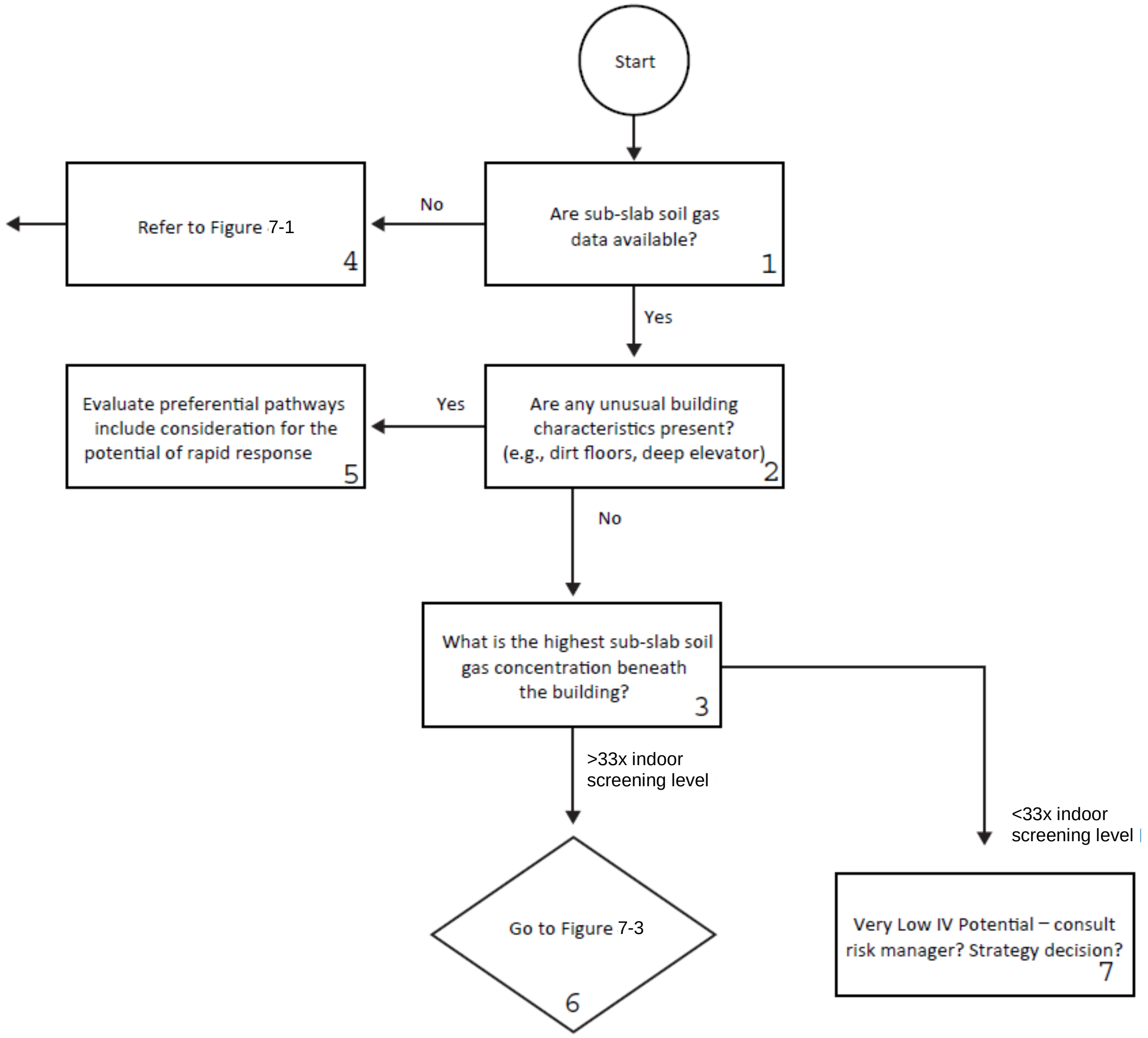
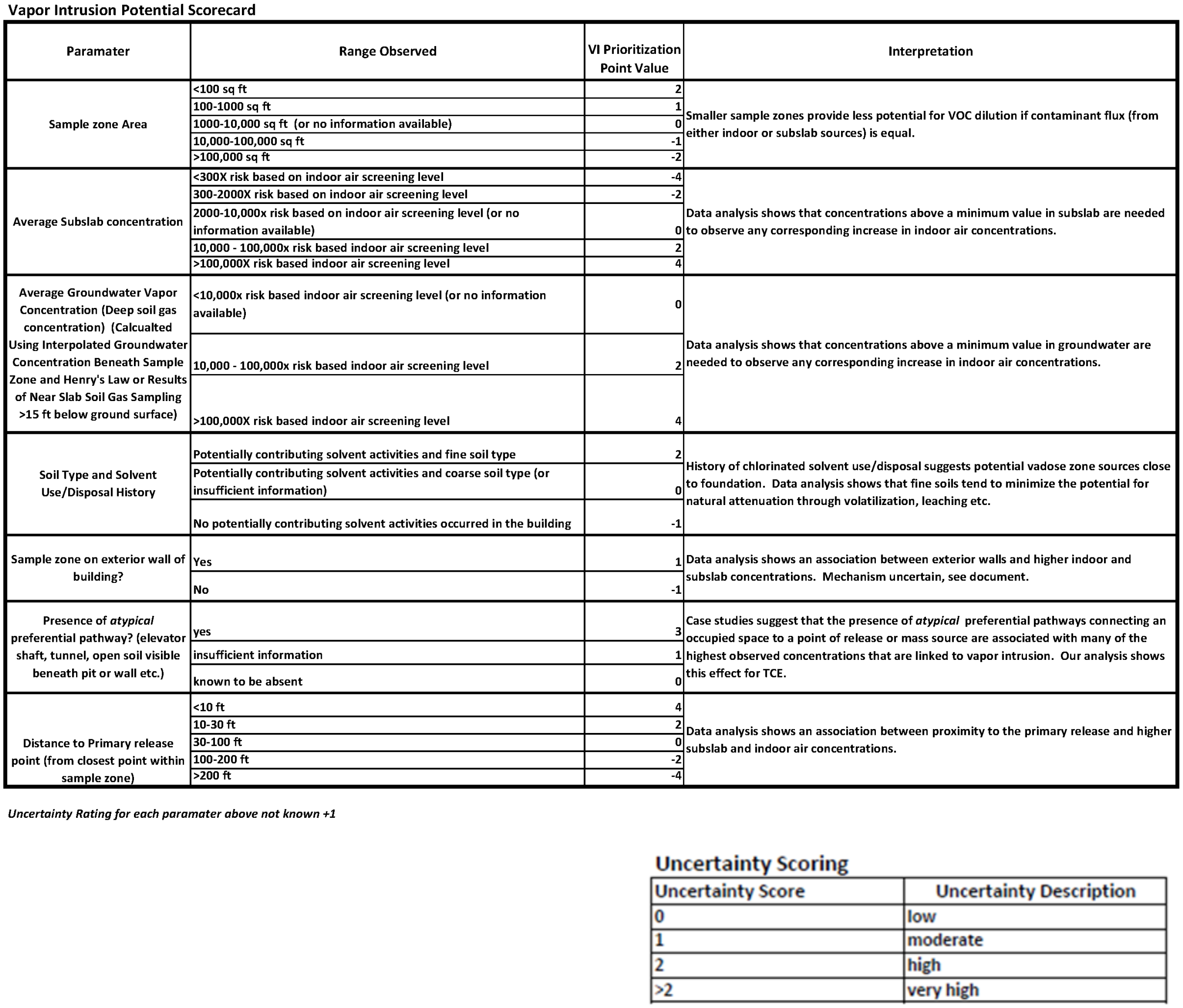


Figure 7-2. Quantitative Decision Framework – Sub-slab Soil Gas Data
NESDI Project #476



Vapor Intrusion Potential Scorecard

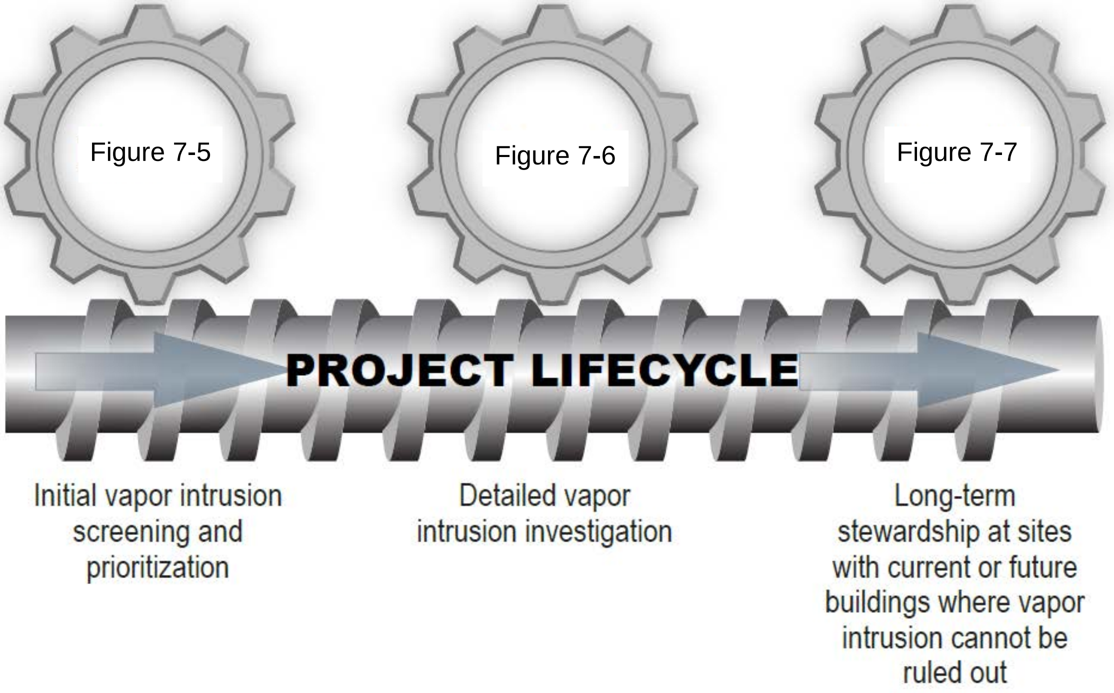
Paramater	Range Observed	VI Prioritization Point Value	Interpretation
Sample zone Area	<100 sq ft	2	Smaller sample zones provide less potential for VOC dilution if contaminant flux (from either indoor or subslab sources) is equal.
	100-1000 sq ft	1	
	1000-10,000 sq ft (or no information available)	0	
	10,000-100,000 sq ft	-1	
	>100,000 sq ft	-2	
Average Subslab concentration	<300X risk based on indoor air screening level	-4	Data analysis shows that concentrations above a minimum value in subslab are needed to observe any corresponding increase in indoor air concentrations.
	300-2000X risk based on indoor air screening level	-2	
	2000-10,000x risk based on indoor air screening level (or no information available)	0	
	10,000 - 100,000x risk based indoor air screening level	2	
	>100,000X risk based indoor air screening level	4	
Average Groundwater Vapor Concentration (Deep soil gas concentration) (Calcualted Using Interpolated Groundwater Concentration Beneath Sample Zone and Henry's Law or Results of Near Slab Soil Gas Sampling >15 ft below ground surface)	<10,000x risk based indoor air screening level (or no information available)	0	Data analysis shows that concentrations above a minimum value in groundwater are needed to observe any corresponding increase in indoor air concentrations.
	10,000 - 100,000x risk based indoor air screening level	2	
	>100,000X risk based indoor air screening level	4	
Soil Type and Solvent Use/Disposal History	Potentially contributing solvent activities and fine soil type	2	History of chlorinated solvent use/disposal suggests potential vadose zone sources close to foundation. Data analysis shows that fine soils tend to minimize the potential for natural attenuation through volatilization, leaching etc.
	Potentially contributing solvent activities and coarse soil type (or insufficient information)	0	
	No potentially contributing solvent activities occurred in the building	-1	
Sample zone on exterior wall of building?	Yes	1	Data analysis shows an association between exterior walls and higher indoor and subslab concentrations. Mechanism uncertain, see document.
	No	-1	
Presence of *atypical* preferential pathway? (elevator shaft, tunnel, open soil visible beneath pit or wall etc.)	yes	3	Case studies suggest that the presence of *atypical* preferential pathways connecting an occupied space to a point of release or mass source are associated with many of the highest observed concentrations that are linked to vapor intrusion. Our analysis shows this effect for TCE.
	insufficient information	1	
	known to be absent	0	
Distance to Primary release point (from closest point within sample zone)	<10 ft	4	Data analysis shows an association between proximity to the primary release and higher subslab and indoor air concentrations.
	10-30 ft	2	
	30-100 ft	0	
	100-200 ft	-2	
	>200 ft	-4	

Uncertainty Rating for each paramater above not known +1

Uncertainty Scoring

Uncertainty Score	Uncertainty Description
0	low
1	moderate
2	high
>2	very high

Figure 7-3. Vapor Intrusion Potential Scorecard
NESDI Project #476



** This scoring can be used through the lifecycle of the project*

Figure 7-4. Key to Scorecard Interpretation Graphs
NESDI Project #476

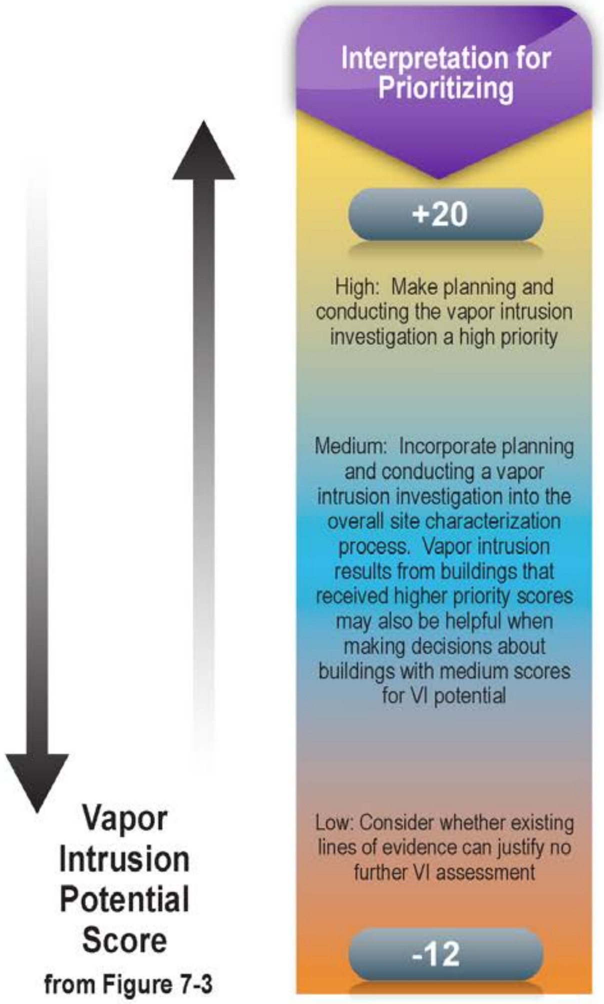
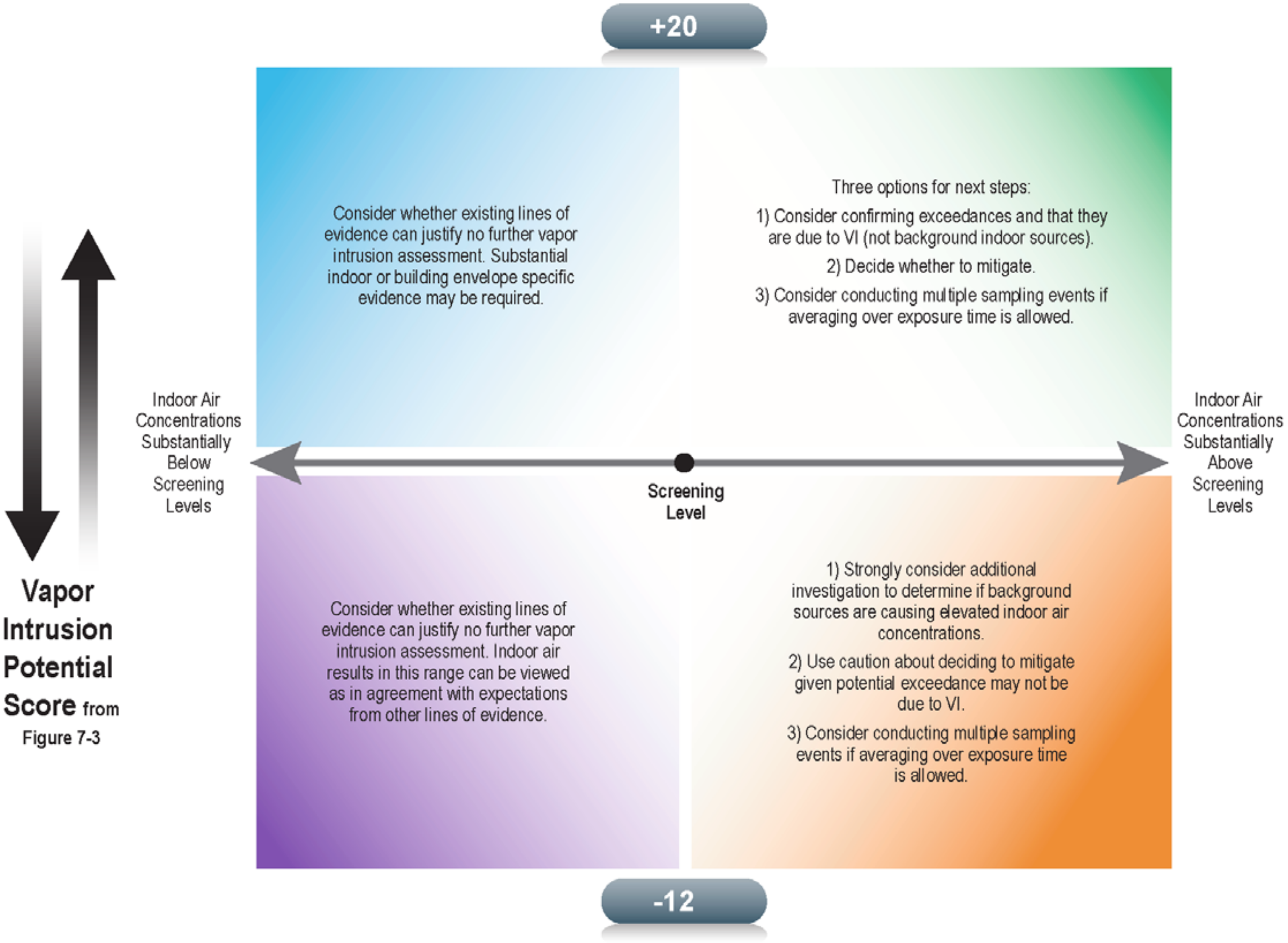


Figure 7-5. Interpretation of Total VI Potential Score for Prioritizing Initial Investigation Efforts
NESDI Project #476



Consider whether existing lines of evidence can justify no further vapor intrusion assessment. Substantial indoor or building envelope specific evidence may be required.

Three options for next steps:

1) Consider confirming exceedances and that they are due to VI (not background indoor sources).

2) Decide whether to mitigate.

3) Consider conducting multiple sampling events if averaging over exposure time is allowed.

Consider whether existing lines of evidence can justify no further vapor intrusion assessment. Indoor air results in this range can be viewed as in agreement with expectations from other lines of evidence.

1) Strongly consider additional investigation to determine if background sources are causing elevated indoor air concentrations.

2) Use caution about deciding to mitigate given potential exceedance may not be due to VI.

3) Consider conducting multiple sampling events if averaging over exposure time is allowed.

Figure 7-6. Interpretation of Scores for VI Potential at Sites with Indoor Air Data
NESDI Project #476

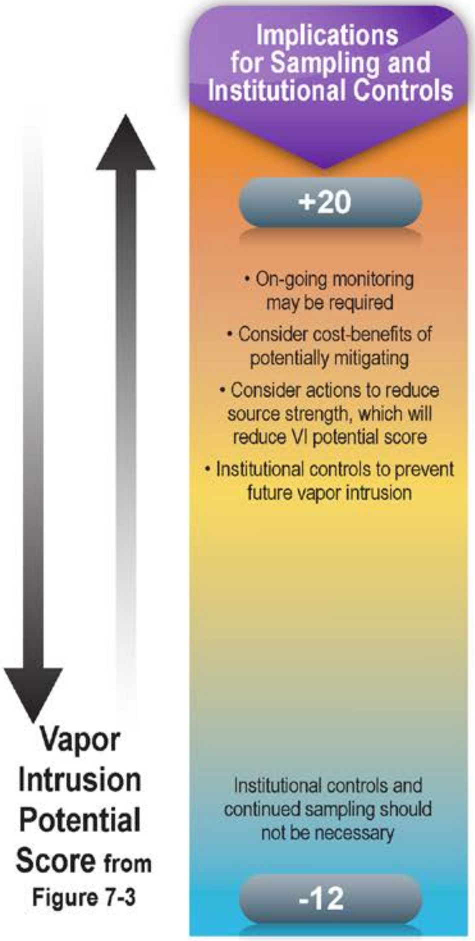


Figure 7-7. Interpretation of Total Score to Design Appropriate Long Term Stewardship
NESDI Project #476

Appendix A – Database Scope, Data Usability, Data Identification, Site/Building Selection & Data Gaps

NESDI Project #476, A Quantitative Decision Framework for Assessing Navy VI Sites- Database Scope, Data Usability, Data Identification, Site/Building Selection and Data Gaps

PREPARED FOR:	NAVFAC EXWC
COPY TO:	Keri Hallberg
PREPARED BY:	Michael Novak Loren Lund
DATE:	August 15, 2013
PROJECT NUMBER:	436747

The United States Naval Facilities Engineering Command (NAVFAC) Expeditionary Warfare Center (EXWC), NAVFAC Atlantic, and CH2M HILL are conducting the three-year research project titled, "*A Quantitative Decision Framework for Assessing Navy VI Sites-NESDI Project #476*." The work is being funded through the Navy's Environmental Sustainability Development to Integration (NESDI) program. This project involves developing and analyzing a database of empirical data from Navy sites where the potential for subsurface vapors related to historical releases of volatile organic compounds (VOCs) to migrate into buildings (i.e., vapor intrusion or "VI") has been investigated. The ultimate goal of the project is to develop a VI decision framework (relationships, decision rules, and other guidelines) and recommendations to incorporate into Navy VI guidance documents, training, or other evaluation tools.

This memorandum summarizes the findings from the following components of the project:

1. Establishing the scope of the Navy VI database, i.e., the analytical, subsurface and building-characteristics, and other data needed to support the subsequent data analysis
2. Developing and applying data usability criteria
3. Identifying sources of existing Navy VI and other Department of Defense data for use in populating the database
4. Identification and selection of sites and buildings
5. Identification of data gaps

Subsequent tasks for the project will involve developing, populating, and analyzing the database and empirical data, and developing the VI decision framework.

Potential Data Analysis Methods

Similar to the Data Quality Objectives framework used to define the data needs for environmental investigations, the first step in defining the data needs is to outline the project goals and analyses needed to support the goals. The goals and analyses described below resulted from an initial brainstorming session among the NESDI VI project team (CH2M HILL, 2013) and a subsequent conference call. It is likely that additional ideas will emerge as the project develops and the data suggest new lines of inquiry, which could result in supplementing the data analysis methods described herein. The primary goals for the project and potential analyses include:

1. Performing multivariable analysis of VI Factors and investigation outcomes and determining key factors and relationships between them.

   This process will begin with an exploratory data analysis (EDA) of a wide range of factors potentially influencing VI and then progress into more formal statistical analysis to test hypotheses suggested by the EDA. The following are some examples of the types of questions that could be asked:

- Is there a quantifiable relationship between the strength of a subsurface VOC source, the location of the building relative to that source, and the likelihood and magnitude of VI?
- Are there relationships between VI factors that support development of VI exclusion criteria? For example, could the United States Environmental Protection Agency's (USEPA, 2002) 100-foot distance between a VOC source and existing/future buildings be re-assessed for conditions typical of Navy industrial facilities and buildings?
- Are there differences in the likelihood and magnitude of VI between different regions of the US due to climatic factors and their impact in things such building construction and operation (e.g., leaving doors and windows open in warmer climates?
- Can buildings be categorized with respect to quantifiable characteristics (e.g., size and compartmentalization) and descriptive characteristic (e.g., condition, operation, and use) and the potential for VI?
- To what extent do geological characteristics, such as vadose zone thickness and soil texture, influence the potential (and magnitude) of VI at Navy industrial facilities.

2. Conducting an analysis of attenuation factors for industrial buildings using paired indoor/subsurface data and methods generally consistent with EPA (2012).

   Attenuation factors (which represent the reduction in vapor concentrations between the subsurface source and indoor air) underlie the risk-based, groundwater and soil gas VI screening levels frequently used during the initial screening phase of VI investigations. The current USEPA (2012) dataset of attenuation factors is based almost exclusively on data from residential structures. VI data collected from Navy and other industrial sites strongly support the hypothesis that USEPA's (2012) generic/default attenuation factors overestimate the potential for VI at Navy industrial buildings by orders of magnitude. The data incorporated into the Navy VI database and corresponding attenuation factors will be made available to Navy remedial project managers (RPMs) to provide support for use of more realistic (i.e., less conservative) industrial-based attenuations factors. This is likely to provide substantial improvements to the site screening process by supporting more representative VI screening levels for industrial buildings.

3. Evaluating non-VOC analytical parameters (e.g., moisture, radon, CO_2, and indoor/subslab differential pressures) to assess slab integrity and air mixing.

   The potential significance and usability of non-VOC analytical parameters in assessing VI have become more apparent in recent years (e.g., Johnson, et. al [2012], Lutes, et. al [2012]). Currently, building characteristics are predominantly characterized qualitatively with respect to factors such as slab and envelope integrity and other factors that potentially affect vapor entry and air mixing. Part of the NESDI VI project will assess whether there are parameters that can (1) be collected to lower cost and reduce impact to occupants and missions relative to typical VOC data collection, (2) provide a more quantitative basis for assessing vapor entry and air mixing, and (3) improve the site screening and building prioritization process for VI.

In addition to the above primary goals, the following secondary or supporting goals and questions are likely to be considered.

1. Does the aerobic degradation of vinyl chloride minimize its significance as potential VI contaminant of concern? Existing data from two Navy facilities, Marine Corps Installations East-Marine Corps Base Camp Lejeune (MCIEAST-MCB CAMLEJ) and Naval Air Station (NAS) Jacksonville, suggest a very low potential for VI of vinyl chloride even with relatively high groundwater source strengths.
2. Can the building prioritization process be improved and placed on a more scientific and defensible footing? Building prioritization has played a key role in optimizing allocation of investigation resources at sites with large numbers of buildings. At MCIEAST-MCB CAMLEJ for example, more than 1000 buildings lay within the regulatory site boundaries for sites with VOC contamination. A much reduced number of buildings was selected for data collection based on a prioritization process that considered factors such as subsurface VOC

source strength, building characteristics, occupancy and use, and distances between sources and buildings. The relative importance of these factors (i.e., there numerical weight) was further refined during a Phase 2 VI investigation at NAS Jacksonville (Davis, et. al, 2012). The VI data incorporated into the Navy VI database will be evaluated to assess whether this quantitative prioritization process can be further refined and justified, and thereby improving the site screening and building prioritization process.

3. Can additional "exclusion criteria" be developed for industrial sites? For example, are there some subsurface VOC concentrations or site/building characteristics for which significant VI has never been detected (or has less than 95-precent probability of detection).

Database Scope and Data Usability Criteria

Since one of the primary objectives of this project is to compile a database of factors that affect VI to support the analyses described above, following are the categories of factors that will be considered for use during the data evaluation phase:

1. Number of VOC sources (single or multiple), source type (e.g., soil, groundwater, and free product), and source strength
2. Source depths and lateral/vertical distances from buildings
3. Building characteristics/conditions (e.g., type of building, slab integrity and entry points, pressurization, air exchange rate, air flow/flux in and out of the building, building/compartment volume for mixing, use/history, compartmentalization)
4. Presence and impact of indoor or outdoor background VOC sources
5. Subsurface characteristics (e.g., moisture content in layered soils, heterogeneity, geologic barrier, etc.) and ground cover
6. Regional factors such as climate that may affect buildings construction or use in ways that could influence air exchange

Table 1 provides a detailed list of the types of data to be collected and compiled in the Navy VI database. **Table 1** also provides an initial assessment of data usability considerations related to issues such as data quality and uncertainties associated with inherent variability of some data types. This is an initial data assessment of data usability, which goes as far as identifying the key considerations. After the NESDI VI team reviews this technical memorandum and reaches consensus on the database scope and data usability considerations, some usability factors may be translated into numerical criteria. For example, **Table 1** currently indicates that adequate groundwater monitoring well spatial coverage is necessary if measured or interpolated groundwater VOC concentrations are to be assigned to a building. Subsequent revisions of **Table 1** may provide specific guidance on the numbers of wells, proximity of wells to buildings or other metrics related the representativeness of the groundwater data.

Site and Building Selection Process

A Navy "data call" conducted during the winter of 2012/2013 reported 144 sites where subsurface VOCs exist and the potential for VI has been considered to varying degrees. Two additional sites were identified for inclusion in the NESDI VI project after the data call was completed. The data that will be used to populate the Navy VI database will be selected from sites and buildings selected using structured process described below. It is possible that sites and building could be added or deleted during the subsequent database-population of the project.

The Microsoft Excel worksheets provided as **Attachment 1** contains the results of the recent data call, as well as worksheets related to the site and building selection process. A brief summary of the process used to select the sites for each step of the prioritization process and listed in these three worksheets are provided in the following bullets:

- Step 1: Based on the results of the data call, the "SiteSelection_Step1" worksheet contains formulas to select sites with indoor air data, industrial buildings, and chlorinated VOCs, which are the minimum criteria for inclusion in the Navy VI database. There is a column that allows users to override the automatic inclusion/exclusion process and document the rationale. For example, a user may have information about the availability of indoor air data that was not captured in the data call and could override the site selection determination.

- Step 2: The "SiteSelection_Step2" worksheet is used to select sites with subslab data, which is highly preferred but not necessarily a threshold criterion. For example, a site where groundwater is the only vapor source could be included without subslab data if there are other relevant and influencing VI factors.
- Step 3: Following steps 1 and 2, the sites that meet the basic data requirements are retained. The complexity of the site selection process increases in Step 3 because the goal is to select sites that represent a diversity of VI characteristics. There is no practical way to code the selection for diversity, so the purpose of step 3 is to provide detailed summaries of site characteristics to support professional judgment regarding site selection. Some of the necessary information that was provided in the data call is included in the "SiteSelection_Step3" worksheet. Other information will require compilation and review of site documents. The Step 3 worksheet contains cells for recording this information as well as a column for the final determination regarding site selection.
- Worksheets for Individual Sites: These worksheets contain similar information to the Step 1 through Step 3 worksheet but for specific buildings. Much of the information is provided in greater detail than in the site-selection spreadsheets. For example, the columns relating to analytical data provide information on what media were included in sampling, which specific VOCs were detected, their concentrations, and how these compare to screening levels and indoor-air background levels derived from a published report. This level of detail was necessary because (1) there is much variability in this information between buildings at a particular site, and (2) it aided selection of buildings that had sufficient data and, in aggregate, demonstrated diversity in site and building characteristics and VI outcomes. Each Individual Site worksheets contains as a column for the final determination regarding building selection.

With the exception of one barracks building at Joint Expedition Base Little Creek, the selected buildings are industrial, office or mixed industrial/office buildings. Within these general classifications, there is much diversity in the types of building uses. For example, industrial uses include operations ranging from laundry facilities to aircraft maintenance hangars. The "Tally" worksheet (in **Attachment 1**) provides a count of the number of selected buildings that exhibit certain key characteristics related to building characteristics, subsurface source strength, and VI outcome.

The analysis of VI outcome is more complex than many of the other characteristics. Based on the information contained the Individual Site worksheets, nine buildings had detectable VI. However, this assessment is largely based on the outcomes reported in the various site-specific documents. In many cases, these documents may have only noted whether indoor air VOC concentrations were above or below screening/action levels and did not consider lower VOC concentrations that could, or could not, be resulting from VI. This issue represents a current data gap (see following section), which will be addressed during the subsequent phase of the NESDI VI project.

The structured process for selecting buildings resulted in diverse geographies, building characteristics, VOC source type and strength, vadose zone characteristics, and degree of VI. These sites and buildings will provide a suitable basis for developing the Navy VI database.

Data Sources, Data Usability Assessment and Data Gaps

The data sources that will be used to develop the database are described in **Table 1**. In general terms, these may include:

- Analytical data
    - Data contained in the Navy Installation Restoration Information Solution (NIRIS). This will be the primary source for analytical data if the data have been loaded into NIRIS.
    - Results extracted from project documents in the case of non-Navy sites or at Navy sites where analytical data have not yet been loaded into NIRIS.
- Site/building characteristics data:
    - Information available from reliable public sources, for example, regional climate information available from National Weather Service websites or hydrogeological information from state or federal geological surveys
    - Information contained in project documents
    - Building-characteristic information contained in DOD document such as the Energy Audit Reports or the Internet Naval Facilities Assets Data Store (INFADS) database
    - Data developed specifically for the NESDI project through additional interviews or site reconnaissance

Attachment 2 presents a summary of the data sources considered during the site and building selection process which consist primarily of project-specific documents. This bibliography will continue to be updated as new sources of information are identified throughout the NESDI VI project.

Attachment 3 includes a Microsoft Excel workbook containing a worksheet for each site retained through the site/building selection process. For each data category and data type identified in **Table 1**, **Attachment 3** contains an assessment of the availability of such information, it usability and currently-identified data gaps. The following general observations were derived from the information and assessment in **Attachment 3**:

- Analytical data are generally available and usable. This is expected since the availability of sufficient data are a key part of the site/building selection process.
- Information on subsurface site characteristics is generally available and usable. This kind of information is commonly summarized in VI-specific reports or can be found in Remedial Investigation reports or other site documents.
- The availability and usability of information on building characteristics is variable. Information on building sizes and uses is more available, but information on such things as ventilation systems, slab integrity and compartmentalization has not been consistently documented.
- The assessment of VI outcome is available and usable in a limited number of cases, but in general, such determinations have not been made in a consistent manner directly usable in developing the Navy database. For example, many sites have information about whether or not indoor VOCs were above or below screening/action levels. However, the analysis of whether or not the detections were due to VI or background sources in not always complete.

The gathering and analysis of information pertaining to building characteristics and VI outcomes will be a significant component of developing the Navy VI database. As noted above, this may entail some additional research including interviews or site-reconnaissance. Such activities were anticipated and included during the scoping of this project.

Next Steps

This technical memorandum described potential data analyses and scope of the Navy VI database, identified data usability considerations, and described the site selection process and documented the initial evaluation of data availability and usability. The immediate next steps in this project include:

- Further refinement of the database scope and design. A draft database schema was submitted in May 2013 and will be updated as the project progresses.
- Conversion of the database schema into a Microsoft Access project database
- Commencement of the database population process

Feedback between these steps is expected and, for example, the database population process may provide insights that could result in further refinement of the database design.

As described in the Project Schedule (**Attachment 4**) a re-evaluation of data gaps will follow initial population of the Navy VI database, which may result in further data collection. The data analysis, decision framework and reporting components of the project will follow completion of the database population phase.

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TABLE 1

Database Scope and Data Usability Considerations

NESDI Vapor Intrusion Project - Database Scope, Data Usability, Data Identification Technical Memorandum

Data Category	Data Type	Data Source(s) and Availability	Data Usability Considerations
VOC concentration analytical data	Groundwater Exterior soil gas Subslab soil gas Indoor air Outdoor air	The Navy's NIRIS database will be the primary source of these data. Exceptions would occur (1) in cases of recent investigations where the data have not yet been submitted to NIRIS and (2) if non-Navy sites are included. In these cases, validated electronic data will be requested from project managers. If electronic data cannot be provided, results will be transcribed from project documents, but only as a last resort.	Minimum requirements for VOC analytical data include (1) analysis by a NELAP accredited laboratory for data analyzed using USEPA methods (e.g., TO-15) and (2) validation consistent with the Navy Installation Restoration Chemical Data Quality Manual (DON, 1999). Rejected ("R" flagged) data will be excluded. Exceptions to these minimum requirements will be considered on a case-by-case basis. More subjective considerations pertain to the representativeness of the data, particularly with respect to temporal and spatial variability. Datasets with multiple rounds of data are preferable, especially if they capture different site conditions (e.g., seasons and water table height). However, many sites will not have multiple rounds, especially for subslab and indoor air. The adequacy of spatial coverage will likely rely heavily on professional judgment. It will be important to document uncertainties related to data coverage so that that they can be integrated into data analysis and ultimately, the decision framework. Groundwater data would ideally only be used from wells that screen across the water table. Site specific exceptions could be considered, but only up to 10 feet below the water table. Data from deeper wells do not provide reliable characterization of a water table vapor source. With soil, subslab or exterior soil gas data, consideration should be given to sample collection procedures, particularly whether leak checks were performed and passed. Leaking soil gas probes can lead to non-representative results.
Radon concentration analytical data	Indoor radon data Outdoor radon data Subslab radon data	Radon data have only been collected at a few Navy facilities for the purpose of assessing radon as a natural soil gas tracer and supporting attenuation factor calculations. These data have not typically been reported to NIRIS. If available, electronic data will be requested from project managers. Otherwise, the data will be transcribed from	Most or all of the radon grab samples have been analyzed by a University of Southern California laboratory. There is no standard USEPA method for radon grab samples and the data have not been validated. The data will be considered usable unless information contained in associated reports suggest otherwise, e.g., a leaking probe or analytical issues

TABLE 1

Database Scope and Data Usability Considerations

NESDI Vapor Intrusion Project - Database Scope, Data Usability, Data Identification Technical Memorandum

Data Category	Data Type	Data Source(s) and Availability	Data Usability Considerations
		project documents, but only as a last resort.	noted by the laboratory.
Building characteristics data	Dimensions/volume (overall) Dimensions/volume (interior rooms) Qualitative and quantitative assessment slab integrity and indoor/outdoor air exchange Construction materials Subsurface structures HVAC presence and type Fenestrations (windows/doors) Use (e.g., office, manufacturing)	Most buildings where VI-specific data have been subject to a building survey where these types of characteristics are documented to varying degrees. The level of detail typically increases along with the stage of the vapor intrusion assessment mitigation process from screening -> building-specific data collection -> mitigation. For many buildings at Navy facilities, high-quality and detailed information are also available through Energy Audit Reports. When available, these should be used as a primary data source for many of the building characteristics data needed for the Navy VI database.	Some of the building characteristics, such as size, are easily ascertained and data from most sources will be reliable and usable. Many of the characteristics such as qualitative evaluations of slab integrity or air exchange are based on more subjective assessments. This was anticipated during the scoping of the project and it is expected that NESDI VI project staff will acquire new building-characteristics data and conduct additional assessments to achieve consistency in the data. In addition, the NESDI VI project will evaluate more objective methods for evaluating building characteristics, such as using radon, carbon dioxide, differential pressures and other measurements to quantify air exchange.
Subsurface characteristics	Depth of water table Groundwater flow direction Vadose zone soil types Soil moisture	This type of information is usually readily available through vapor intrusion reports, other site investigation reports and long-term monitoring reports.	“Raw” data such as water levels are typically reliable and useable. Careful review is warranted for interpretive characteristic such groundwater flow directions since the quality of interpretation varies. For example, tidal affects and vertical gradients are not always considered when developing potentiometric surface maps leading to less useful interpretations.
Source characteristics	Type (soil, dissolved, free product) Distance from building	This type of information is often readily available through vapor intrusion reports, other site investigation reports and long-term monitoring reports. In some cases, it may be necessary to infer the type and geometry of primary releases from analytical data, plume geometry and historical records.	The extent and quality of source characterization at VOC-contaminated sites vary greatly. Ascertaining the availability of information regarding VOC sources will be a key consideration in selecting sites for populating the Navy VI database, with preference given to sites with more comprehensive and higher quality information.
Other site characteristics	Climate	Climate data are readily available through regional and local sources.	Climate data are typically derived from reliable sources such as National Weather Service databases and will be usable for this project.
Background sources	Nearby point/non-point air emission sources inventories	Some investigation reports will contain explicit discussion of background VOCs, but this is not typical.	Being able to ascertain indoor VOC results coming from background sources and filter them from the dataset will be critical to the data analyses.

Data Category	Data Type	Data Source(s) and Availability	Data Usability Considerations
	Site/building chemical inventories Building specific, background focuses analytical data (e.g., real-time GC/MS)	Evaluation of indoor, subslab and outdoor air results can be used to assess the source of indoor VOCs, i.e., vapor intrusion versus a background source.	The quality and extent of information related to background VOC sources, building specific chemical inventories for example, vary widely. Data analysis to support background evaluations also range from nonexistent to high quality. Sites with information deemed more reliable or with sufficient information to support calculations by the NESDI VI team will receive higher priority in the site-selection process.
Reported VI determination	Outcome • No-detectable VI • Detectable VI - Indoor VOCs above VI screening/action levels - Indoor VOCs below VI screening/action levels	Many reports will contain explicit statements regarding the occurrence and significance of vapor intrusion. More commonly, however, this information will need to be ascertained based on analytical data and other supporting information.	The reliability of VI determinations will vary widely and the way investigation outcomes are reported will be inconsistent. For example, it is common for detected concentrations below screening/action levels to be reported as "VI not occurring" when, in fact, it could be occurring but the results are not significant with respect to human health. For consistency in the Navy VI database, the NESDI VI team will need to reassess outcomes for most sites.

Notes and Abbreviations:
CSM – Conceptual Site Model
GC/MS – Gas chromatography / mass spectroscopy
NELAP - National Environmental Laboratory Accreditation Program
NIRIS - Navy Installation Restoration Information Solution
VI – Vapor Intrusion

Attachment 1

Available to Navy RPMs upon request.

Attachment 2

Available to Navy RPMs upon request.

Attachment 3

Available to Navy RPMs upon request.

Attachment 4

Available to Navy RPMs upon request.

Appendix B – Work Plan for Additional Building and Other Data Collection Activities

NESDI Project #476, A Quantitative Decision Framework for Assessing Navy VI Sites – Work Plan for Additional Building and Other Data Collection Activities Potentially Affecting Vapor Intrusion Potential

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DATE:	December 13, 2013
PROJECT NUMBER:	436747

The United States Naval Facilities Engineering Command (NAVFAC) Expeditionary Warfare Center (EXWC), NAVFAC Atlantic, and CH2M HILL are conducting the 3-year research project titled, "*A Quantitative Decision Framework for Assessing Navy VI Sites-NESDI Project #476*." The work is being funded through the Navy's Environmental Sustainability Development to Integration (NESDI) program. This project involves developing and analyzing a database of empirical data from Navy sites where the potential for subsurface vapors related to historical releases of volatile organic compounds (VOCs) to migrate into buildings (i.e., vapor intrusion or "VI") has been investigated. The ultimate goal of the project is to develop a VI decision framework (relationships, decision rules, and other guidelines) and recommendations to incorporate into Navy VI guidance documents, training, and/or other evaluation tools.

This Technical Memorandum (TM) summarizes the plan for implementing additional data collection of building characteristics and other physical information for up to five additional sites (up to five buildings each). This effort will fill potential data gaps on building characteristics (e.g., building volume, mechanical and natural ventilation, occupancy status, chemical usage, and potential background sources) that have the potential to affect VI. This TM is intended to be a living document and addition detail, including specific buildings, data to be collected, and field procedures, will be added following additional data analyses in order to target sites/buildings which will provide the maximum amount and most useful data within the existing budget.

Figure 1 is a flow chart illustrating a process starting with the initial database population (completed), going through a quality control (QC) process, and ending with data gap identification and rectification. The following sections describe this process in detail.

Current Data Identification, Collection, and Analysis

The current data identification, collection, and analysis effort, leading to the identification of data gaps, is summarized below.

- *Site and building selection:*

  A Navy "data call" conducted during the winter of 2012/2013 reported 144 sites where subsurface VOCs exist and the potential for VI has been considered to varying degrees. Three additional sites were identified for inclusion in the NESDI VI project after the data call was completed and include data from Air Force and Army sites. As outlined in the Database Scope, Data Usability, Data Identification, Site/Building Selection, and Data Gaps TM, a prioritization process was used to select 60 buildings for which VI data will be populated into a Navy VI database. Each site was selected based upon factors that affect VI in order to support the following primary goals for the project and potential analyses:

  1. Multivariable exploratory data and/or statistical analyses of VI factors and investigation outcomes and determining key factors and relationships between them.

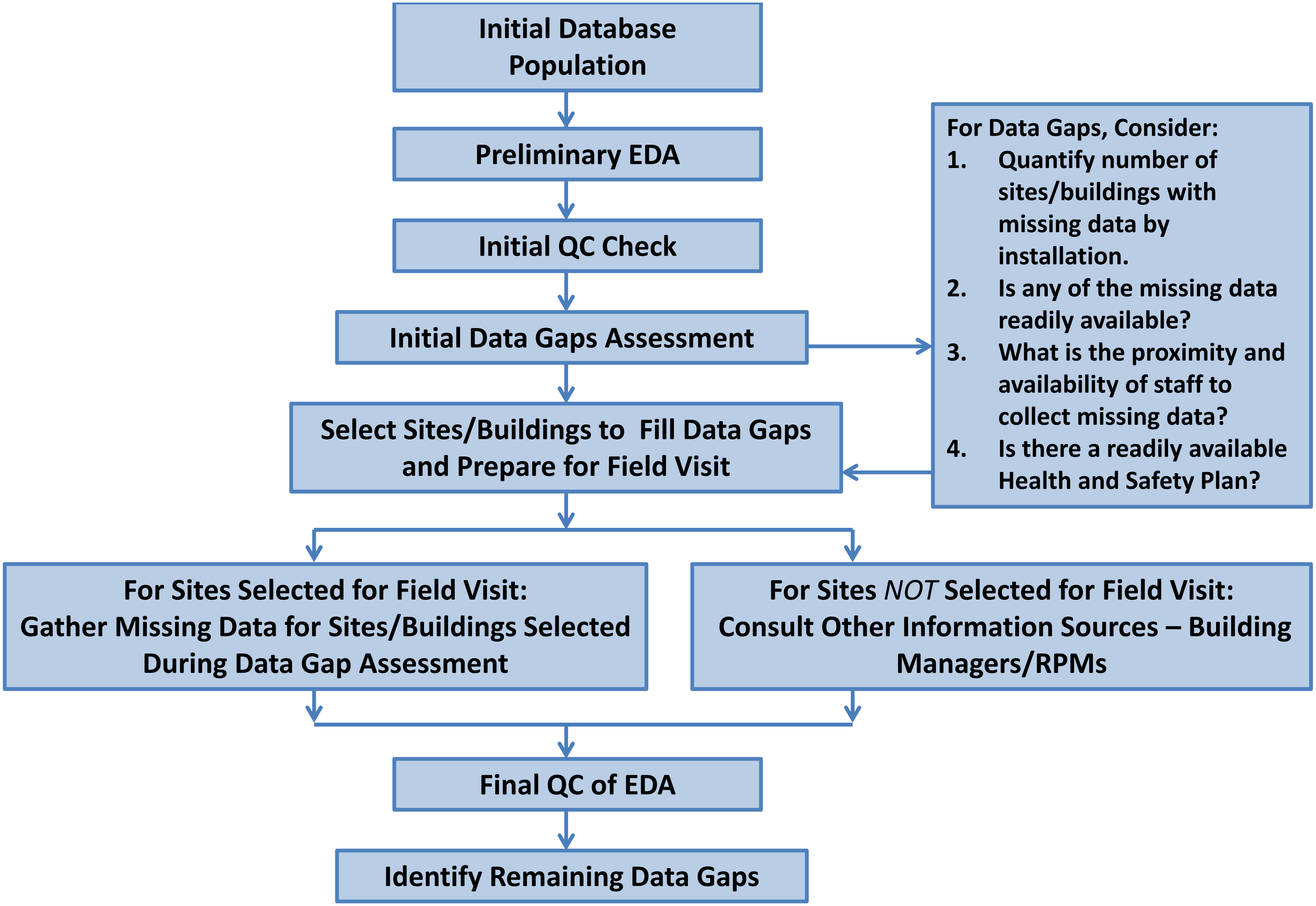

Figure 1
Data Gap Identification Process Flow Chart
NESDI Vapor Intrusion Project

2. Analysis of attenuation factors for industrial buildings using paired indoor/subsurface data and methods generally consistent with U.S. Environmental Protection Agency (EPA, 2012).
3. Evaluation of non-VOC analytical parameters (e.g., moisture, radon, carbon dioxide (CO_2), and indoor/subslab differential pressures) to assess slab integrity and air mixing.

To achieve the primary project goals and conduct the analyses described above, the following are the categories of factors that were used to select the sites for use during the data evaluation phase:

1. Number of VOC sources (single or multiple), source type (e.g., soil, groundwater, and free product), and source strength.
2. Source depths and lateral/vertical distances from buildings.
3. Building characteristics/conditions (e.g., type of building, slab integrity and entry points, pressurization, air exchange rate, air flow/flux in and out of the building, building/compartment volume for mixing, use/history, and compartmentalization).
4. Presence and impact of indoor or outdoor background VOC sources.
5. Subsurface characteristics (e.g., moisture content in layered soils, heterogeneity, geologic barrier, etc.) and ground cover.
6. Regional factors such as climate that may affect building construction or use in ways that could influence air exchange.

- *Database design and development:*

  The VI data incorporated into the Navy VI database will be evaluated to assess whether the building prioritization process can be further refined and justified, thereby streamlining the standard site screening process currently used during VI investigations conducted at Department of Defense (DoD) facilities. As described above, the prioritization process considers factors such as subsurface VOC source strength, building characteristics, occupancy and use, and distances between sources and buildings. These factors were used to design and develop the database. The data dictionary, which summarizes the database design, is included as **Attachment A**.

- *Initial database population*

  Two primary data sources were used to populate the initial database. In general terms, these include:

  1. Analytical data:
     a. Data contained in the Naval Installation Restoration Information Solution (NIRIS). This is the primary source for analytical data that have been loaded into the NESDI VI database.
     b. Results extracted from project documents in the case of non-Navy sites or at Navy sites where analytical data have not yet been loaded into NIRIS.
  2. Site/building characteristics data:
     a. Information available from reliable public sources, such as regional climate information from National Weather Service websites or hydrogeological information from state or federal geological surveys.
     b. Information contained in project documents.
     c. Building-characteristic information contained in DoD document such as the Energy Audit Reports or the Internet Naval Facilities Assets Data Store (INFADS) database.

  A data entry tool was developed to standardize site and building characteristic data for database population. The tool allows users to enter the data through a macro, which then converts the entered data into a database-friendly format for easy loading to the formal database.

Exploratory data analysis

A preliminary exploratory data analysis (EDA) of the available data initially loaded into the VI database was conducted to provide potential insight into factors that may influence the outcome of VI investigations. This was done so that such factors could be more closely scrutinized to identify potential data gaps or new types of data which the preliminary EDA indicated may influence VI and could be assimilated into the VI database.

The analysis discussed below is meant only to yield potential insights regarding potential data or data-analysis gaps. It is truly preliminary since:

1. It is based on a database that is incomplete and has not undergone QC.
2. Issues that are likely to have a significant impact on the results and conclusions, e.g., the effect of background VOC sources, have been addressed in only a cursory fashion.
3. Insights were gleaned only from informal observations of graphical EDA methods, and assessment of statistical significance was not considered.

Dot plots with overlain Box-Whisker plots were used as the primary visualization tool during the preliminary EDA. The plots were created using JMP software (SAS Institute, Version 11). A Dot plot presents all values of a single variable (e.g., indoor air VOC concentrations) on the Y axis and broken down by different categories on the X axis. The left-to-right position of the dots is not significant; it results from the “dithering” process, wherein points collocated on the Y axis are spread out instead of placed one atop the other.

The Box-Whisker plots show nonparametric summary statistics, including quartiles (25th percentile, 50th percentile or median, and 75th percentile). Coloring of the dots adds a third dimension to the analysis, allowing further categorization of the data.

This type of visualization was selected because (1) users can see all values of a given variable in addition to the nonparametric summary statistics and (2) it is easy to explore the effects of a single categorization variable (e.g., building size) or multiple categorization variables (e.g., building size and flooring type) at the same time.

As with any initial data exploration effort used to identify whether correlations exist, it important to note that correlation does not imply causation and to be cautious of drawing conclusions based on apparent relationships that could, in fact, be illustrating something else or could be based on insufficient data. For example, consider a hypothetical example where indoor air concentration appeared to be generally higher for buildings with bare floors versus carpeted floors. It would be important to ask whether carpeted space, which might typically be offices, could be smaller on average than shops or warehouses that may be larger and would have more floor space/potential vapor entry points. It would also be important to assess the corresponding subsurface source strength and separation distances for each type of floor covering and whether the carpeted spaces were from enough sites so that preliminary generalizations would be supportable. Further data exploration and relationship evaluation will be conducted as part of the next phase of the project.

The plots (**Attachment B**) show both the indoor and subslab concentrations on the Y axis with dot colors corresponding to whether an analytical result was a detected or non-detected value. Non-detected values were plotted at the method detection limit. To simplify the analysis as this stage of the process, a single analyte (trichloroethene) was selected for review.

Subsequent data analysis for this project will include calculated subslab-to-indoor-air attenuation factors (AFs), which are the ratio of measured indoor-air VOC concentration to measured subslab VOC concentrations. An initial attempt to do this during the preliminary EDA identified a number of confounding factors. Consequently, preliminary graphical analysis would not yield useful insights at this stage.

Table 1 summarizes observations from the preliminary EDA and   provides considerations related to possible data gaps or data QC.

Table 1: Preliminary EDA Summary

Grouping Variable	**Observations**
Vapor Intrusion Sample Type	This plot was done to see if the data looked as expected, namely, that subslab concentration were higher than indoor-air concentrations, which was the case. Indoor air concentrations show a high fraction of nondetected results. The high number of nondetected indoor air results will be a confounding factor during analysis of attenuation factors during later stages of the project.
Building Volume	Both indoor and subslab concentrations increase with building volume. There is no obvious basis for assuming this is a causational relationship.
Sample Zone Volume	As above
Exterior Wall	The Exterior Wall database field records whether the sample zone has as least one wall located along the exterior of the building (coded as “1”) or not (coded as “0”). The zones without an exterior wall have a somewhat higher median subslab concentration and somewhat lower indoor air concentration. This suggest, counterintuitively, potentially higher attenuation for the all interior spaces. However, there were few sample zone coded “0”. Given the small sample size, further evaluation of potential confounding factors is warranted.
Flooring Type	The floor types other than “bare concrete” have lower subslab and indoor air concentrations. This is a challenging comparison because the “bare concrete” sample zones had subslab concentrations up to 4 orders of magnitude greater than in the zones with the other flooring material. A second plot was prepared with subslab concentrations capped at 10,000 μg/m^3. This plot also suggest higher indoor air concentration for the “bare concrete” sample zones. A potential causational relationship could result from floor covering reducing advective and diffusive vapor transport across the slab.
HVAC Type	The “Engineered HVAC” type had a high proportion of nondetected results in the indoor air relative to the “None” and “Zone Specific” types. However, the latter two types also had subslab concentrations. The high proportion of sample zones with “None” HVAC type is potentially significant data gap, which will need to be resolved before drawing conclusions about this factor.
Preferential Pathways	The sample zones with Preferential Pathways indicated as present (coded “1”) had higher indoor air concentration but also higher subslab concentrations than those without preferential pathways noted (coded “0”). The concentration data will need to be normalized to attenuation factors before this factor can be further assessed.
Zone Air Exchange	Sample zones that were open to other zones had higher indoor and subslab concentration. The concentration data will need to be normalized to attenuation factors before this factor can be further assessed.

Grouping Variable	**Observations**
Distance from Primary Release	The lowest subslab concentrations were observed farthest from the primary release, which is expected. The relationship for indoor air is less clear. The concentration data will need to be normalized to attenuation factors before this factor can be further assessed. Furthermore, this criterion requires significant interpretation of data to determine the position of a primary release. The quality control discussion below addresses uncertainties associated with this factor.
Groundwater Source Strength	Both indoor and subslab concentrations increased along with groundwater source strength, which is expected. This criterion requires significant interpretation of data to assess the groundwater source strength beneath a sample zone. The quality control discussion below addresses uncertainties associated with this factor.

Data QC Plan

Developing defensible conclusions and recommendations from the data and data analysis depends on an understanding of the quality of information included in the database, along with an understanding of the level of consistency in the interpretation of the parameters that have been entered in the database. While effort was made to accomplish this during the initial population, data assessment and entry were performed by multiple individuals based on underlying data sources of various quality and detail. Therefore, a QC review is recommended to evaluate and improve the defensibility and quality of the database.

There are four primary types of uncertainties (or errors) potentially introduced during initial database population. The first is data that are missing, either because the information was not available or the data inadvertently were not entered. The second is the mis-entry of data from an original source. An example would be a flooring type entered as tile when a building-survey form identified the flooring as bare concrete.

The third type of error or uncertainty results from incomplete information in the original data source, which in turn results in the need to estimate or infer a value. An example would be reports or field forms that lack information about the dimensions of a building or sample zone. In such cases, the lengths and areas may have been estimated based on a map or drawing, with heights being estimated based on a photograph or a qualitative written description.

The fourth type of error or uncertainty relates to the more interpretive types of data included in the database. The two primary types of interpretive data include the following:

1. The estimated VOC concentrations in groundwater beneath a sampling zone (in the case of interpolated plumes).
2. The location(s) of primary VOC releases and the distance between a sampling zone and the primary release(s).

In the case of groundwater VOC concentrations, monitoring wells are rarely located within a building and concentrations may vary by orders of magnitude over the scale of a building. Thus, estimating the range of groundwater VOC concentrations under a sampling zone requires interpolation and professional judgment. The locations of primary release are spelled out in many cases, i.e., the location of a solvent storage tank, but in other cases the primary release was unknown. Such cases required inference of the release location based on the geometry of the resulting groundwater VOC plume.

Table 2 identifies the types of data included in the VI database and the type of potential uncertainties (or errors). The process for conducting a QC evaluation of the current database will vary according to the type of potential uncertainties (or errors), as described below:

- **Missing Data.** A database analyst will prepare a list of missing data. The teams inputting data for each installation will be tasked with finding and entering the missing data.
- **Data Entry Errors**. The NESDI VI database team will be divided into two groups. Since the Navy and CH2M HILL team members generally input data for different sites, this is a natural division for establishing the groups. Navy members will review CH2M HILL data and *vice versa*. A minimum of 25% of individual database records for each type identified in **Table 2** will be randomly selected and the review teams will check for accuracy against the original source(s) of the data. If errors are found for a particular type of data, the errors will be corrected and further QC review will be conducted, including up to 100% review for those types of data.

  In contrast to the site and building characteristics data, the subslab, indoor, and outdoor air analytical results were, in most cases, derived from an established database with QC requirements enforced throughout the data lifecycle. The NIRIS database was the source of the majority of these records. Records from the Air Force's Environmental Restoration Program Information Management System (ERPIMS) database were also used as the data source for the two Air Force installations included. A database analyst will conduct a completeness and integrity check for these data to determine whether indoor, outdoor, and subslab VOC data were imported and properly assigned to the correct sampling matrix. Generally, the data for one sampling zone for each installation will be checked and additional zones will be checked only when issues are identified.

There were a few cases where analytical data were not available from the NIRIS or ERPIMS database and analytical results were provided in various Microsoft Excel tabular formats. Due the data manipulation needed to prepare the data for import, there was a higher potential for error. Thus, a minimum of 25% of such analytical results will be traced back to the original report or other data source to assess accuracy and completeness. Further evaluation will be conducted for specific datasets where systematic issues are identified.

- **Estimation Uncertainties**. Individual team members will be asked to identify sites or buildings where they found that estimation was necessary. The same review teams described above will review 100% of the identified data. An example of a supportable basis for estimation is a ceiling height estimate from a photograph with some kind of reference point (e.g., a standard doorway) evident. An estimate of ceiling height based only on a description of use (e.g., office) would require further evaluation.
- **Interpretation Uncertainties**. There are three main types of data that require specialized expertise to populate in the database: (1) groundwater VOC concentrations under a sampling zone when co-located groundwater analytical data are not available, (2) the location of and distance to primary releases, and (3) the presence of potential background (indoor or outdoor) VOC sources. Each of these data types typically requires analysis of multiple lines of evidence and an understanding of the strengths and limitations of the evidence and analyses. For example, the potential presence of a background VOC source can include evaluation of outdoor air VOC data, chemical inventories, real-time analytical data, ratios of indoor to subslab VOC concentrations, and other lines of evidence. When assessing even a relatively straightforward line of evidence, like outdoor air data, it is necessary to consider multiple factors such as the contemporaneousness of the results with indoor data, the location of the outdoor samples relative to HVAC intake vents, and the potential influence of strong subsurface VOC sources and VOC remediation systems on outdoor air. Because of the greater complexity of the interpretation uncertainties relative to data entry or estimation errors/uncertainties, the QC process will start with a review of database entries and source information by a subject matter expert in hydrogeology and VI. This person will review the pertinent data from a minimum of two buildings from each Navy installation included in the VI database to assess questions, including:

    1. To what extent are the groundwater VOC data and data interpretations (e.g., concentration interpolations) sufficient to support estimation of concentrations under the building? Were the data and interpolations based on wells that screen across the water table or have a top of screen no deeper than 10 feet below the water table? To what extent are the estimates of groundwater VOC concentrations under the building defensible?
    2. Was the location of the primary release identified and, if so, is it supportable based on the available information? Was the distance from the building to the primary release appropriately estimated?
    3. Was the potential presence of background sources considered? Were the data sufficient to support the analysis and were the data interpreted appropriately?

    Based on an initial review of the database, few cases of background VOC sources were identified. This reflects the lack of such information in the underlying reports. It is common to see potential background sources evaluated only in cases where an indoor air VOC concentration exceeded a risk-based screening level and even then evaluations may be sporadic and of varying quality. It is critical that indoor air VOC concentrations used in data analysis during later stages of the project be the results of VI. Thus, the lack of consistent assessment of potential background VOCs represents a significant data- analysis gap (discussed further below).

Errors or uncertainties that can be rectified based on existing information will be corrected in the database. Those requiring further data or data analysis will be addressed as data gaps or data-analysis gaps (see below).

Data Gap Identification and Work Plan

Field data and data-analysis gaps will be identified through the QC process described above. Some gaps have already been identified through a preliminary review of the dataset and the EDA process. This section describes the process for: (1) documenting the status of each type of data for each installation, building, and sampling zone, (2) specifying the step(s) needed to rectify data gaps, and (3) verifying when the data are deemed sufficient for the final database.

Table 3 presents a matrix containing a cell for each type of data in the VI database for each sampling zone. One of the following task descriptions is included in each cell to document the requirement. Other information pertinent to completing the process may also be included, as beneficial. The letters in brackets next to the descriptions are codes used in **Table 3** to capture the requirements.

1. Site and building characteristics data
    a. Data missing [M]
    b. Data entry QC [QCe]
    c. Data estimation QC [QCs]
    d. Data interpretation QC [QCi]
    e. Records Review [RR]
    f. Field observation [FO]
    g. Data review complete [C]
2. Subslab and indoor air VOC data
    a. Data missing [DM]
    b. Data analyst QC check [QCa]
    c. 25% data source review [QCr]
    d. Data review complete [C]

It is expected that most of the currently identified data gaps and those identified through the QC process will be addressed through identification and review of existing documents and data sources. If the information is found to be unavailable or unreliable for some reason, field observations may be necessary.

It is currently expected that sample zones listing carpet as the flooring type may require field observation to assess if other flooring types (e.g., tile or vinyl) underlay the carpet. This was observed at the Hill AFB building, where carpet was laid over vinyl asbestos tiles. The vinyl tiles are presumably less gas-permeable than the carpet and thus, could affect the occurrence and magnitude of potential VI compared with carpet.

The assessment of indoor or outdoor background VOC sources is a prevalent data-analysis gap and is one that is important to adequately address if reliable inferences and conclusions are to be drawn from indoor air results. The Navy's *Interim Final Guidance for Environmental Background Analysis, Volume IV: Vapor Intrusion Pathway* (Background Guidance) (Battelle, et. al., 2011) discusses multiple methods for assessing the potential presence of background VOC sources. Some of these methods require special sampling or analysis at the time indoor VOC samples are collected. Since the purpose of the background assessment for this project is to evaluate whether existing indoor air VOC results may be affected by background sources, methods using existing information will be used, primarily including:

1. Methods examining the ratios of VOC concentration in the indoor air and subslab soil gas.
2. Comparison of indoor air VOC concentrations with those in outdoor air.
3. Review of documentation, such as building survey forms and chemical product inventories.
4. Use of radon data where available.

Indoor air VOC results suspected to be influenced by background sources will be flagged in the database and will not be used for most of the data analyses planned for this project.

References

Battelle, CH2M HILL, and Newfields. 2011. User's Guide UG-2091-ENV. *Interim Final Guidance for Environmental Background Analysis, Volume IV: Vapor Intrusion Pathway.* April.

United States Environmental Protection Agency, 2012. Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings. March.

Table 2: Types of Quality Control Evaluations Needed for Database Fields

Table	Data Field	Data Entry Errors	Estimation Uncertainties	Interpretation Uncertainties
BUILDING	BUILDING NUMBER	X		
	BUILDING NAME	X		
	BUILDING NOTES	X		
	DATA SOURCE	X		
BUILDING CHARACTERISTICS	BUILDING AREA	X	X	
	CEILING HEIGHT MIN	X	X	
	CEILING HEIGHT MAX	X	X	
	BUILDING VOLUME	X	X	
	CONSTRUCTION DATE	X		
	DESIGN CCN	X		
	PRIMARY USE CCN	X		
	NUMBER OF FLOORS	X		
ENV INSTALLATION	INSTALLATION NAME	X		
ENV SITE	SITE NAME	X		
SAMPLE ZONE	SAMPLE ZONE NUMBER	X		
	SAMPLE ZONE NAME	X		
SAMPLE ZONE BACKGROUND SOURCE	ANALYTE	X		
	ANALYTE PREFERRED	X		
	BACKGROUND SOURCE NAME	X		
SAMPLE ZONE CHARACTERISTICS	SAMPLE ZONE AREA	X	X	
	SAMPLE ZONE HEIGHT MIN	X	X	
	SAMPLE ZONE HEIGHT MAX	X	X	
	SAMPLE ZONE VOLUME	X	X	
	HVAC TYPE	X		X
	PRIMARY USE CCN	X		
	SUBGRADE STRUCTURES	X		X
	PREFERENTIAL PATHWAY	X		X
	DEPTH TO GROUNDWATER	X		X
	SOIL TYPE	X		X
	EXTERIOR WALL	X		X
	FLOORING TYPE	X		
	ZONE AIR EXCHANGE	X		X
SAMPLE ZONE DATA	All fields	X		
SAMPLE ZONE GROUNDWATER	ANALYTE	X		
	INTERPOLATED MIN	X		X

Table	Data Field	Data Entry Errors	Estimation Uncertainties	Interpretation Uncertainties
	INTERPOLATED MAX	X		X
	MEASURED MIN	X	X	
	MEASURED MAX	X	X	
	MEASURED MAX DISTANCE	X	X	
SAMPLE ZONE LOCATIONS	LOCATION ID	X		
	VI SAMPLE TYPE	X		
SAMPLE ZONE PRIMARY RELEASE	ANALYTE	X		
	PRIMARY RELEASE SOURCE NAME	X		
	DISTANCE TO PRIMARY RELEASE	X		X

Table 3 available to Navy RPMs upon request.

Attachment A

Attachment A: Data Dictionary

Module	ObjectType	ObjectSubType	Object Conceptual Name	ObjectName	ElementName	DataType	ElementDescription	dBDataType	FieldSize	Format	Required	Key	ValidValue	Example	BusinessRule	VVSourceName	VVSourceType	Notes
Vapor_Intrusion	Table	Data Table	Installation	ENV_INSTALLATION	INSTALLATION_ID	Autonumber	Unique ID for Navy Environmental Installaiton	int	6		Yes	PK	Yes	1				Consider changing to SITE_ID
Vapor_Intrusion	Table	Data Table	Installation	ENV_INSTALLATION	Installation Name	Text	Unique identifier for installation associated with the location	char(20)			Yes		Yes	Whidbey				Convention for non-Navy sites will need to be developed.
Vapor_Intrusion	Table	Data Table	Site	ENV_SITE	SITE_ID	Autonumber	Unique ID for Navy Environmental Site	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Site	ENV_SITE	INSTALLATION_ID	Number	Unique ID for Navy Environmental Installaiton	int	6		Yes	FK	Yes	1		ENV_INSTALLATION	Table	
Vapor_Intrusion	Table	Data Table	Site	ENV_SITE	NIRIS_SITE_ID	Number	Unique ID for Navy Environmental Site	int	6		Yes	PK	Yes	1		NIRIS ENV_Site	Table	
Vapor_Intrusion	Table	Data Table	Site	ENV_SITE	Site Name	Text	Unique identifier for site associated with the location	char(20)			Yes			OU 1				Convention for non-Navy sites will need to be developed.
Vapor_Intrusion	Table	Data Table	Building	BUILDING	BUILDING_ID	Autonumber	Unique integer ID for a Navy building	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Building	BUILDING	SITE_ID	Number	Unique ID for Navy Environmental Site	int	6		Yes	FK	Yes	1		ENV_SITE	Table	
Vapor_Intrusion	Table	Data Table	Building	BUILDING	Building Number	Text	Commonly used building reference number	char(10)	10		Yes			103				
Vapor_Intrusion	Table	Data Table	Building	BUILDING	Building Name	Text	Commonly use building name	char(35)	35		No			Public Works Maintenance Shop				
Vapor_Intrusion	Table	Data Table	Building	BUILDING	Building Notes	Text	Additional information about a building	char(255)	255		No							
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	BUILDING_CHAR_ID	Autonumber	Unique ID for a Navy building's charateristics	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	BUILDING_ID	Number	Unique integer ID for a Navy building	int	6		Yes	FK	Yes	1		BUILDING	Table	
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Building Area	Number	Floor area of building (square feet)	int	7		No			12000				
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Min Ceiling Height	Number	Shortest ceiling height within building (feet)	int	2		No			12				
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Max Ceiling Height	Number	Tallest ceiling height within building (feet)	int	2		No			25				
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Building Volume	Number	Air volume within building (cubic feet)	int	9		No			257000				
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Construction date	Date	Date on which the building was constructed (remodels not included)	Date/Time	8	YYYYMMDD	No			19560214				
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Design CCN	Text	Design CCN as provided in InFADS	Char(100)	100		No		Yes	610-10 - ADMINISTRATIVE OFFICE		D_CCN	Table	
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Primary Use CCN	Text	Primary Use CCN as provided in InFADS	Char(100)	100		No		Yes	610-10 - ADMINISTRATIVE OFFICE		D_CCN	Table	
Vapor_Intrusion	Table	Data Table	Building Characteristics	BUILDING_CHARACTERISTIC	Number of Floors	Number	Number of floors present in the building	float(3)	3	3,1	No			1.5				
Vapor_Intrusion	Table	Data Table	Sample Zone	SAMPLE_ZONE	SAMPLE_ZONE_ID	Autonumber	Unique integer ID for a sample zone within a Navy building	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Sample Zone	SAMPLE_ZONE	BUILDING_ID	Number	Unique integer ID for a Navy building	int	6		Yes	FK	Yes	1		BUILDING	Table	
Vapor_Intrusion	Table	Data Table	Sample Zone	SAMPLE_ZONE	Sample Zone Number	Number	Number assigned by NESDI project to a sample zone within a building	int	6		Yes							
Vapor_Intrusion	Table	Data Table	Sample Zone	SAMPLE_ZONE	Sample Zone Name	Text	Name assigned by NESDI project to a sample zone within a building	char(50)	50		No			Paint Shop				
Vapor_Intrusion	Table	Data Table	Sample Zone	SAMPLE_ZONE	Sample Zone Notes	Text	Additional information about a sample zone within a building	char(255)	255		No							
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	SAMPLE_ZONE_CHAR_ID	Autonumber	Unique record ID	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	SAMPLE_ZONE_ID	Number	Unique integer ID for a sample zone within a Navy building	int	6		Yes	FK	Yes	1		SAMPLE_ZONE	Table	

Module	ObjectType	ObjectSubType	Object Conceptual Name	ObjectName	ElementName	DataType	ElementDescription	dBDataType	FieldSize	Format	Required	Key	ValidValue	Example	BusinessRule	VVSourceName	VVSourceType	Notes
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Sample Zone Area	Number	Floor area of sample zone (square feet)	int	7		No			12000				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Sample Zone Height Min	Number	Shortest ceiling height within sample zone (feet)	int	2		No			12				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Sample Zone Height Max	Number	Tallest ceiling height within sample zone (feet)	int	2		No			25				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Sample Zone Volume	Number	Air volume within sample zone (cubic feet)	int	9		No			257000				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	HVAC Type	Text	Type of HVAC system in sample zone	Char(35)	35		No		Yes	Engineered HVAC		D_HVAC_TYPE	Table	
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Primary Use CCN	Text	Primary Use CCN of sample zone as provided in InFADS	Char(100)	100		No		Yes	610-10 - ADMINISTRATIVE OFFICE		D_CCN	Table	
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Use Notes	Text	Additional information about use of a sample zone	Char(255)	255		No			Re-painting of buddy store fuel tanks				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Subgrade Structures	Text	Boolean indicator of the presence of subgrade structures	Boolean	3		No			Yes				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Subgrade Structures Notes	Text	Description of subgrade structures	Char(255)	255		No			Steam utility vault with dirt floor				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Preferential Pathway	Text	Boolean indicator of the presence of preferential pathways for the sample zone	Boolean	3		No			Yes				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Preferential Pathway Notes	Text	Additional information about preferential pathways	Char(255)	255		No			Utility conduit unlays sample zone				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Depth to Groundwater	Number	Depth to top of water table beneath sample zone (feet)	float(5)	5	5,2	No			62.45				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Soil Type	Text	Generalized description of vadose zone soil type	char(35)	35		No		Yes			D_SoilType	Table	
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Exterior Wall	Text	Boolean indicator of the presence of an exterior wall in the sample zone	Boolean	3		No			Yes				
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Flooring Type	Text	Generalized description of flooring in sample zone	Char(50)	50		No		Yes	Vinyl tile or sheet		D_FLOORING_TYPE		
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Zone Air Exchange within Building	Text	Generalized description of sample zone air exchage with the building	Char(35)	35		No		Yes	Open to Other Zones		D_ZONE_AIR_EXCHANGE		
Vapor_Intrusion	Table	Data Table	Sample Zone Characteristics	SAMPLE_ZONE_CHAR	Zone Air Exchange Notes	Text	Additional information about zone air exhange	Char(255)	255		No			Sample zone is a bathroom with exhaust fans				
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	PRIMARY_RELEASE_ID	Autonumber	Unique record ID for the primary release for a sample zone	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	SAMPLE_ZONE_ID	Number	Unique integer ID for a sample zone within a Navy building	int	6		Yes	FK	Yes	1		SAMPLE_ZONE		
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	Primary Release Source Name	Text	Name assigned by NESDI project to a primary release source associated with a sample zone	char(50)	50		Yes			Site 14 - TCE				
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	ANALYTE_ID	Text	Unique Analyte ID assigned for the analysis parameter obtained from the accompanying Navy lookup-domain table.	char(20)	20		Yes		Yes	127-18-4		D_Analyte_ID	Table	

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Module	ObjectType	ObjectSubType	Object Conceptual Name	ObjectName	ElementName	DataType	ElementDescription	dBDataType	FieldSize	Format	Required	Key	ValidValue	Example	BusinessRule	VVSourceName	VVSourceType	Notes
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	Analyte	Text	Analyte associated with the primary release source for the sample zone	char(35)	35		Yes		Yes	Trichloroethylene				
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	ANALYTE_NAME_PREFERRED	Text	Analyte associated with the primary release source for the sample zone	char(35)	35		Yes		Yes	Trichloroethylene				
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	Distance to Primary Release (feet)	Number	Horizontal distance from the sample zone to the primary release source	int	3		No			56				
Vapor_Intrusion	Table	Data Table	Sample Zone Primary Release	SAMPLE_ZONE_PRIMARY_RELEASE	Primary Release Notes	Text	Additional information about primary release for the sample zone	char(255)	255		No			Primary release occurred in 1944				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	ZONE_DATA_ID	Autonumber	Unique record ID	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	SAMPLE_ZONE_ID	Number	Unique integer ID for a sample zone within a Navy building	int	6		Yes	FK	Yes	1		SAMPLE_ZONE		
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	ZONE_DATA_SOURCE_ID	Number	Unique ID corresponding to standardized data source names	int	6		6					D_DATA_SOURCE		
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	LOCATION_NAME	Text	Unique name of a sampling location	char(35)	35		Yes			MW-2R				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	VI_SAMPLE_TYPE	Text	A data code that describes the original and intended purpose of the sampling location as selected from a list of valid values.	char(16)	16		Yes		Yes	AIR		D_LOCATION_TYPE	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	SAMPLE_NAME	Text	Unique sample name	char(50)	50		Yes			B103-IA-02				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	SAMPLE_MATRIX	Text	A code identifying a sample matrix	char(16)	16		Yes		Yes	AA		D_SAMPLE_MATRIX	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	COLLECT_DATE	Date/Time	Date on which the sample was collected. Format for date is YYYYMMDD (i.e., September 15, 1994 = 19940915)	Date/Time	8		Yes			19940915				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	COLLECT_TIME	Text	Time of day (24-hour clock) at which the sample was collected. Format for time is HH:MM:SS. Use the standard 24 hour clock	Date/Time	8		No			13:15:30				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	ANALYTICAL_METHOD	Text	Analytical Method ID defined in accompanying domain-lookup table	char(20)	20		No		Yes	TO-15		D_Analytical_Method	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	ANALYTE_ID	Text	Unique Analyte ID assigned for the analysis parameter obtained from the accompanying Navy lookup-domain table.	char(20)	20		Yes		Yes	127-18-4		D_Analyte_ID	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	ANALYTE_NAME	Text	Common name for the analysis parameter derived from the DESCRIPTION field in the D_Analyte_ID lookup table	char(50)	50		Yes		Yes	tetrachloroethene		D_Analyte_ID	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	ANALYTE_NAME_PREFERRED	Text	Common name for the analysis parameter derived from the DESCRIPTION field in the D_Analyte_ID lookup table	char(50)	50		Yes		Yes	tetrachloroethene		D_Analyte_ID	Table	

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Module	ObjectType	ObjectSubType	Object Conceptual Name	ObjectName	ElementName	DataType	ElementDescription	dBDataType	FieldSize	Format	Required	Key	ValidValue	Example	BusinessRule	VVSourceName	VVSourceType	Notes
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	RESULT_VALUE	Number	This field represents the final corrected analyte concentration value generated after a sample has been analyzed or a test performed.	float(18)	18	18,10	Yes			23				
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	RESULT_UNITS	Text	Unit of measure for the analyte value.	char(16)	16		Yes		Yes	UG_M3		D_Result_Units	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	FINAL_QUALIFIER	Text	Final qualifier code assigned to the result.	char(16)	16		No		Yes	J		D_Final_Qualifier	Table	
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	DETECTED	Text	Y-N field designating if the final result is a detect (Y) or non-detect (N).	char(1)	1		Yes		Yes	Y	If LAB_QUALIFIER or VALIDATOR_QUALIFIER contains a 'U', then DETECTED must			
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	DETECTION_LIMIT	Number	Reported Detection Limit	float(18)	18	18,10	Yes							
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	MDL	Number	Method Detection Limit	float(18)	18	18,10	Yes							
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	QC_NARRATIVE	Text	A description or other unique information concerning the subject item, limited to 120 characters.	char(120)	120		No							
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	NESDI_NOTES	Text	NESDI project-specific notes related to an analytical results	char(255)	255		No							
Vapor_Intrusion	Table	Data Table	Analytical Data	SAMPLE_ZONE_DATA	NESDI_COLOCATION	Text	NESDI project-specific association of co-located sample locations. Contains Location_Name entry for a co-located sample, e.g., a subslab location associated with an indoor air sample.	char(35)	35		No							
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	BACKGROUND_SOURCE_ID	Autonumber	Unique integer ID for a background VOC source associated with a zone	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	SAMPLE_ZONE_ID	Number	Unique integer ID for a sample zone within a Navy building	int	6		Yes	FK	Yes	1		SAMPLE_ZONE		
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	Background Source Name	Text	NESDI project name assigned to a background VOC source	char(35)	35		Yes							
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	ANALYTE_ID	Text	Unique Analyte ID assigned for the analysis parameter obtained from the accompanying Navy lookup-domain table.	char(20)	20		Yes		Yes	127-18-4		D_Analyte_ID	Table	
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	Analyte	Text	Common name for the analysis parameter derived from the DESCRIPTION field in the D_Analyte_ID lookup table	char(50)	50		Yes		Yes	tetrachloroethene		D_Analyte_ID	Table	
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	ANALYTE_NAME_PREFERED	Text	Common name for the analysis parameter derived from the DESCRIPTION field in the D_Analyte_ID lookup table	char(50)	50		Yes		Yes	tetrachloroethene		D_Analyte_ID	Table	
Vapor_Intrusion	Table	Data Table	Background Sources	BACKGROUND_SOURCE	Background Source Notes	Text	Additional information related to	char(255)	255		No		Yes	Source discovered by JM				
Vapor_Intrusion	Table	Data Table	VI Outcome	ZONE_OUTCOME	ZONEOUTCOME_ID	Number	Unique record ID	int	6		Yes							
Vapor_Intrusion	Table	Data Table	VI Outcome	ZONE_OUTCOME	BUILDING_ZONE_ID	Number	Unique integer ID for a zone within a Navy building	int	6		Yes	FK	Yes	1		BuildingZone	Table	

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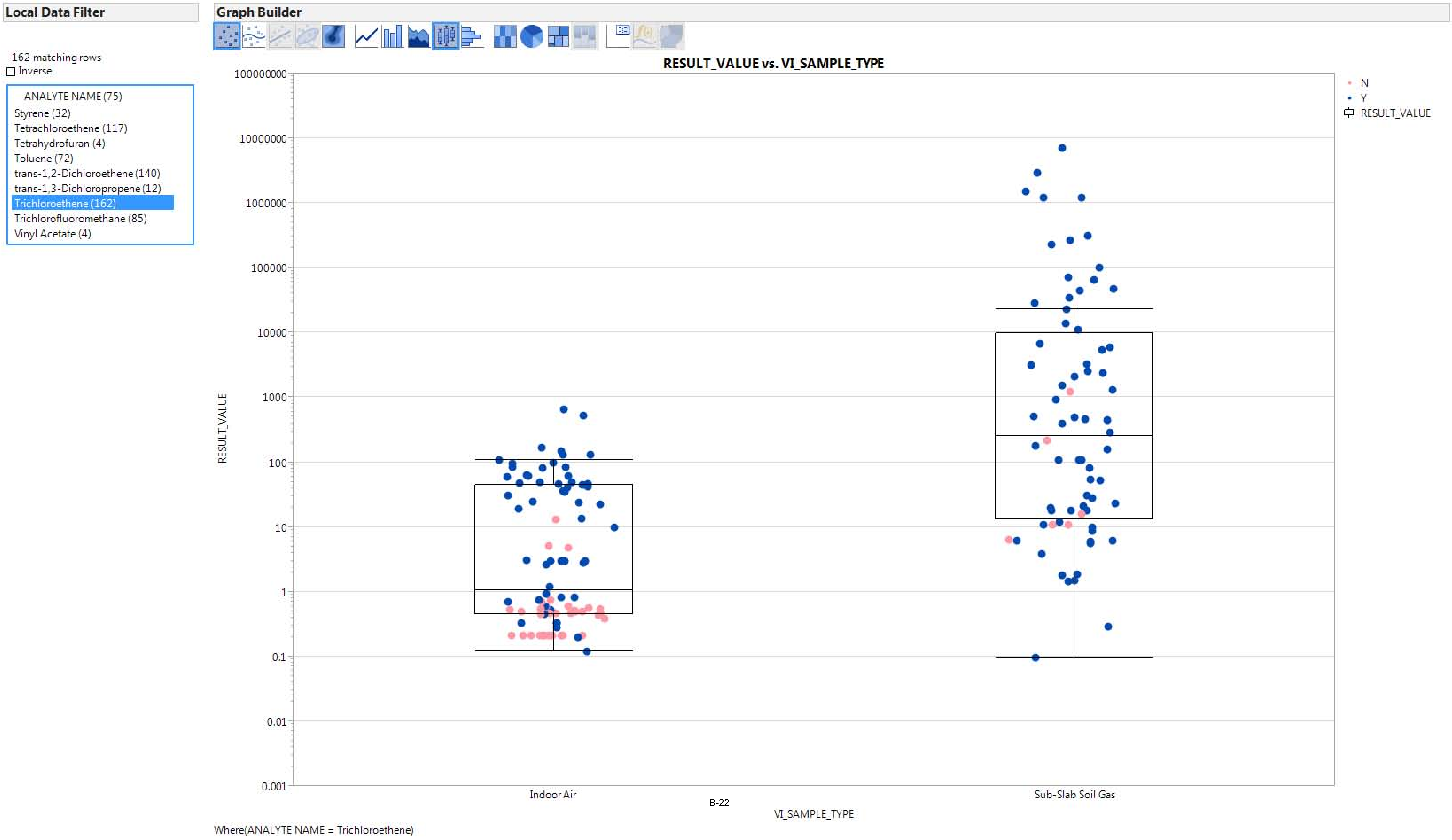
Module	ObjectType	ObjectSubType	Object Conceptual Name	ObjectName	ElementName	DataType	ElementDescription	dBDataType	FieldSize	Format	Required	Key	ValidValue	Example	BusinessRule	VVSourceName	VVSourceType	Notes
Vapor_Intrusion	Table	Data Table	VI Outcome	ZONE_OUTCOME	ZONE_OUTCOME	Text	Description of vapor intrusion investigation outcome for building zone	char(10)	10		Yes		Yes	VI_NotSig		D_Outcome	Table	
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	SAMPLE_ZONE_GROUNDWATER_ID	Autonumber	Unique record ID	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	SAMPLE_ZONE_ID	Number	Unique integer ID for a sample zone within a Navy building	int	6		Yes	FK	Yes	1		SAMPLE_ZONE		
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	ANALYTE_ID	Text	Unique Analyte ID assigned for the analysis parameter obtained from the accompanying Navy lookup-domain table.	char(20)	20		Yes		Yes	127-18-4		D_Analyte_ID	Table	
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Analyte	Text	Analyte associated with the groundwater for the sample zone	char(35)	35		Yes		Yes	Trichloroethylene		D_ANALYTE_ID		
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	ANALYTE_NAME_PREFERRED	Text	Analyte associated with the groundwater for the sample zone	char(35)	36		Yes		Yes	Trichloroethylene		D_ANALYTE_ID		
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Interpolated Min Under Zone	Text	Minimum interpolated groudwater concentration under the sample zone for the specific analyte (ug/L)	char(10)	10		No			ND				
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Interpolated Max Under Zone	Text	Maximum interpolated groudwater concentration under the sample zone for the specific analyte (ug/L)	char(10)	10		No			100000				
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Measured Min	Number	Minimum measured groudwater concentration coresponding to the sample zone for the specific analyte (ug/L)	float(18)	18	18,10	No			0.12				
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Measured Max	Number	Maximum measured groudwater concentration in the nearest water table well coresponding to the sample zone for the specific analyte (ug/L)	float(18)	18	18,10	No			12340				
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Measured Max Location ID	Text	Location ID corresponding to the measured maximum for the sample zone	char(15)	15		No			OU1-16GW08				
Vapor_Intrusion	Table	Data Table	Sample Zone Groundwater	SAMPLE_ZONE_GROUNDWATER	Measured Max Distance (feet)	Number	Distance from the sample zone to the measured max location	int	3		No			36				
Vapor_Intrusion	Table	Data Table	Sample Zone Location ID	SAMPLE_ZONE_LOCATIONS	SAMPLE_ZONE_LOCATION_ID	Autonumber	Unique record ID	int	6		Yes	PK		1				
Vapor_Intrusion	Table	Data Table	Sample Zone Location ID	SAMPLE_ZONE_LOCATIONS	SAMPLE_ZONE_ID	Number	Unique integer ID for a sample zone within a Navy building	int	6		Yes	FK	Yes	1		SAMPLE_ZONE		
Vapor_Intrusion	Table	Data Table	Sample Zone Location ID	SAMPLE_ZONE_LOCATIONS	Location ID	Text	Location ID associated with the sample zone	char(15)	15		Yes			OU1-16GW08				
Vapor_Intrusion	Table	Data Table	Sample Zone Location ID	SAMPLE_ZONE_LOCATIONS	Sample Type	Text	Sample matrix associated with the location ID	char(35)	35		Yes			Indoor Air				
Vapor_Intrusion	Table	Data Table	Sample Zone Location ID	SAMPLE_ZONE_LOCATIONS	NIRIS ID	Text	Boolean indicator of the presence of the location ID in the NIRIS database	Boolean	3		No			Yes				

Attachment A: Data Dictionary

Module	ObjectType	ObjectSubType	Object Conceptual Name	ObjectName	ElementName	DataType	ElementDescription	dBDataType	FieldSize	Format	Required	Key	ValidValue	Example	BusinessRule	VVSourceName	VVSourceType	Notes
Vapor_Intrusion	Table	Data Table	Sample Zone Location ID	SAMPLE_ZONE_LOCATIONS	Report Reference	Text	Report reference for the location ID	Char(255)	255		No			OU 10 Remedial Investigation Report, CH2M HILL, 2013				

Attachment B



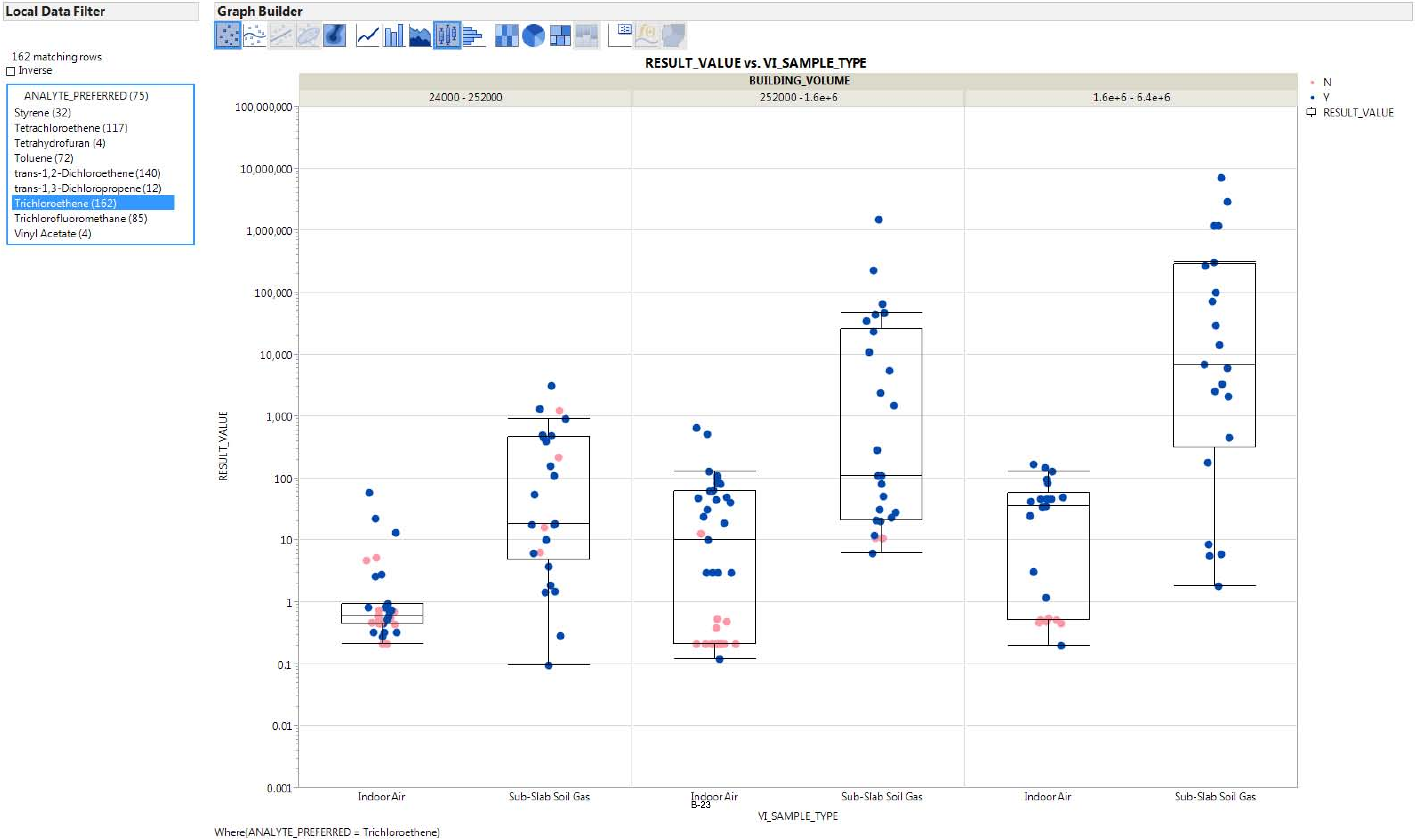
Local Data Filter

162 matching rows
☐ Inverse

ANALYTE NAME (75)
- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)
- Vinyl Acetate (4)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



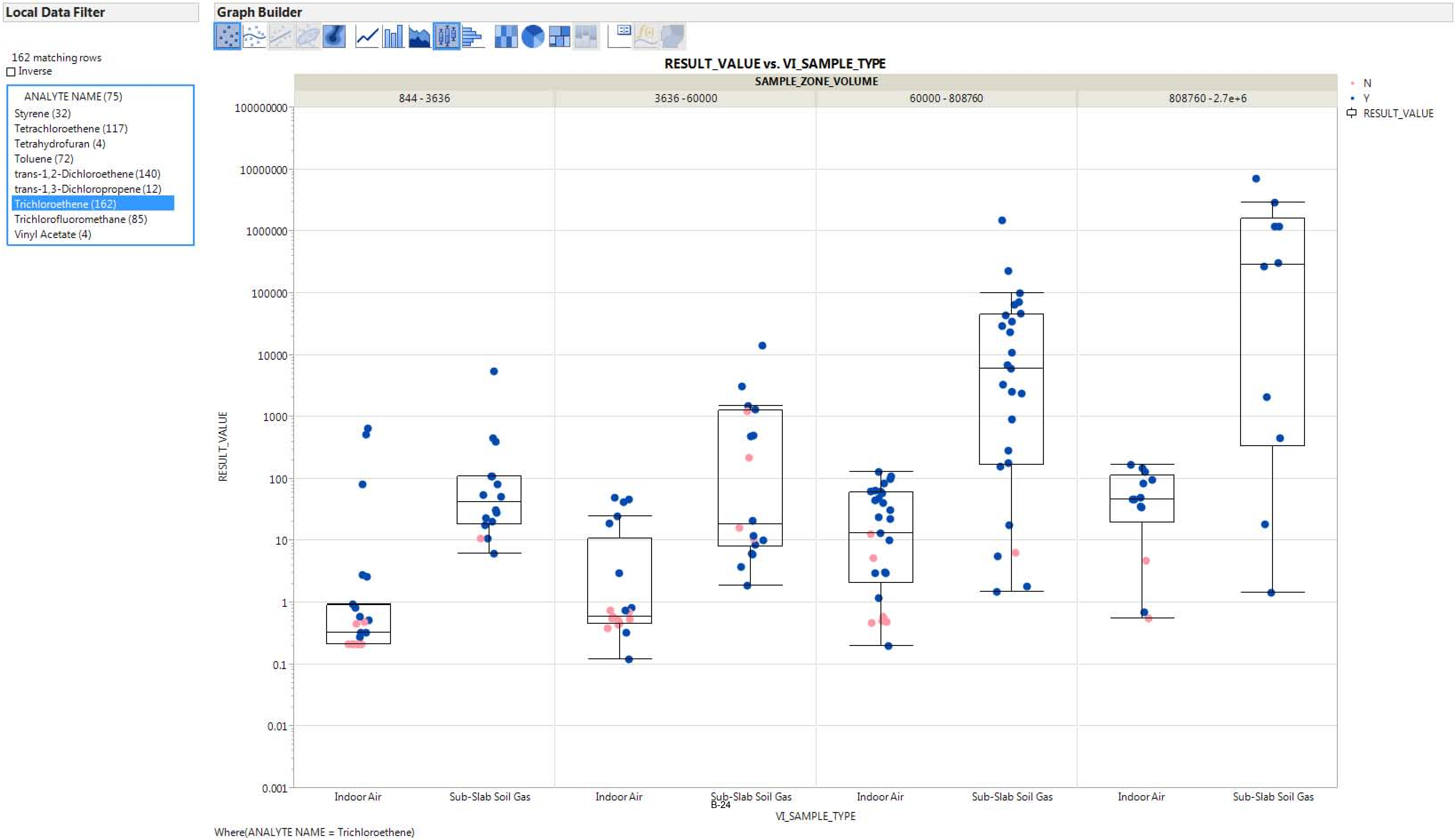
Local Data Filter

162 matching rows
☐ Inverse

ANALYTE_PREFERRED (75)
- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)
- Vinyl Acetate (4)

Graph Builder

Where(ANALYTE_PREFERRED = Trichloroethene)



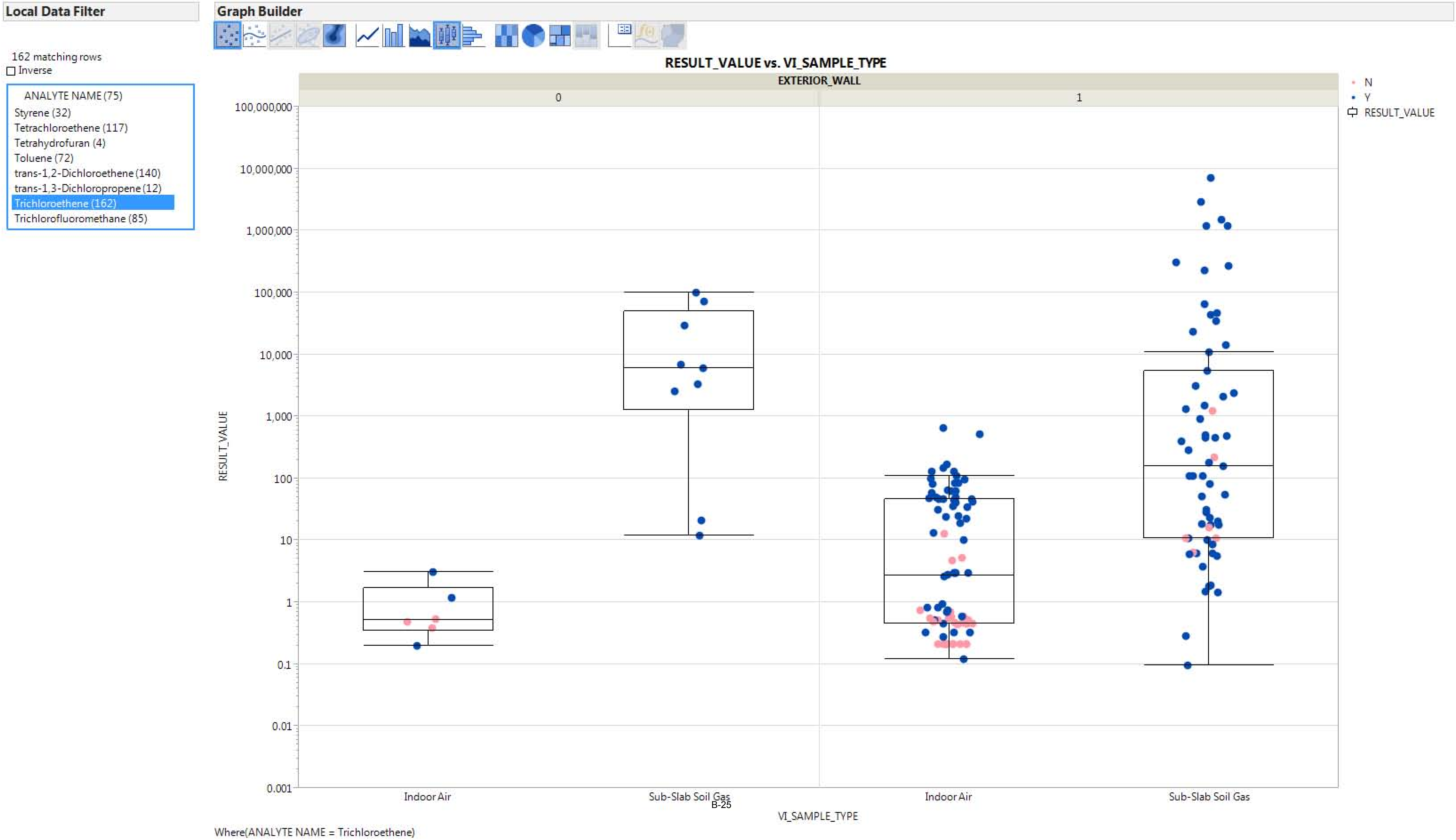
Local Data Filter

162 matching rows
☐ Inverse

ANALYTE NAME (75)
- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)
- Vinyl Acetate (4)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



Local Data Filter

162 matching rows

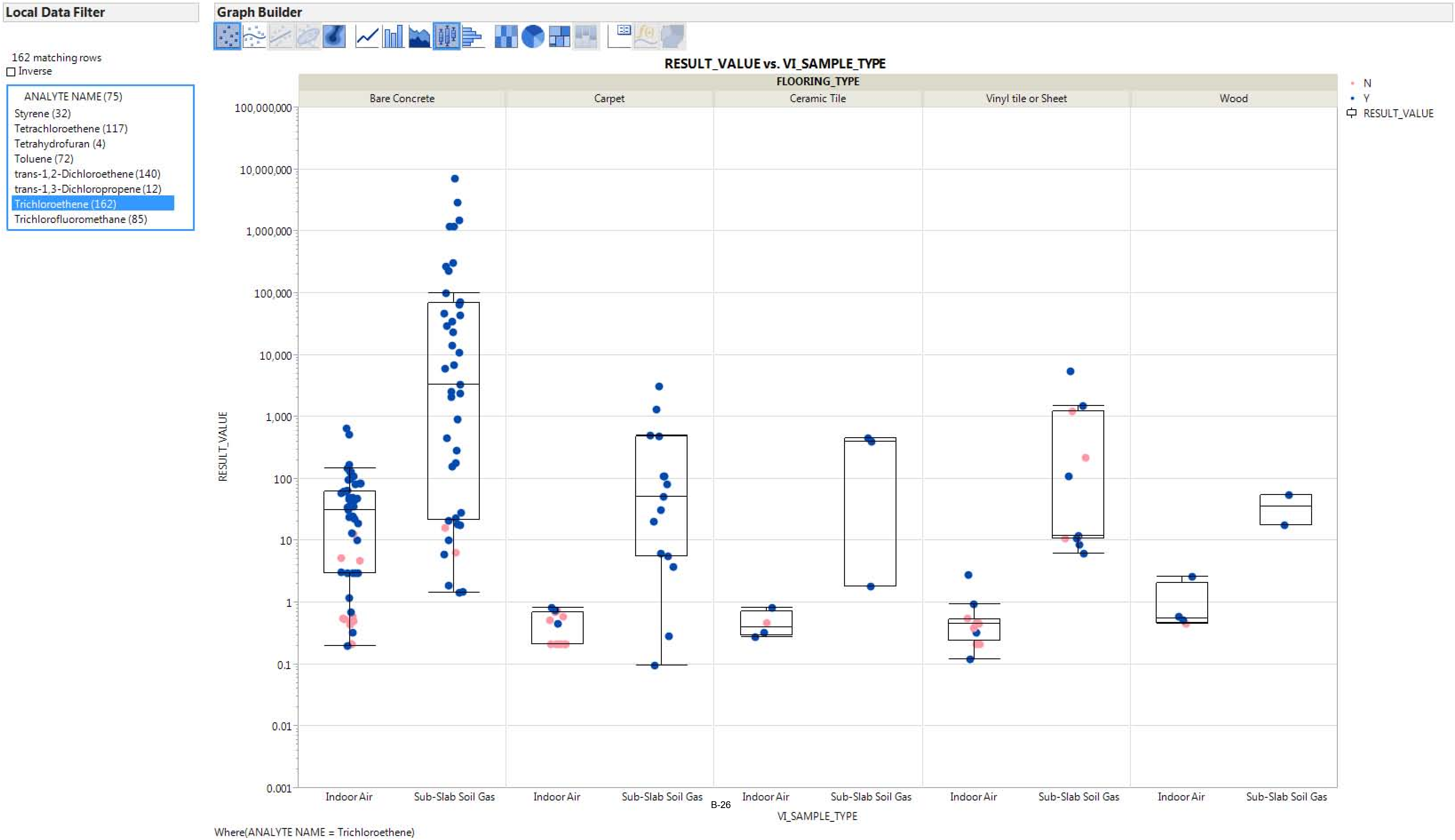
☐ Inverse

ANALYTE NAME (75)

- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



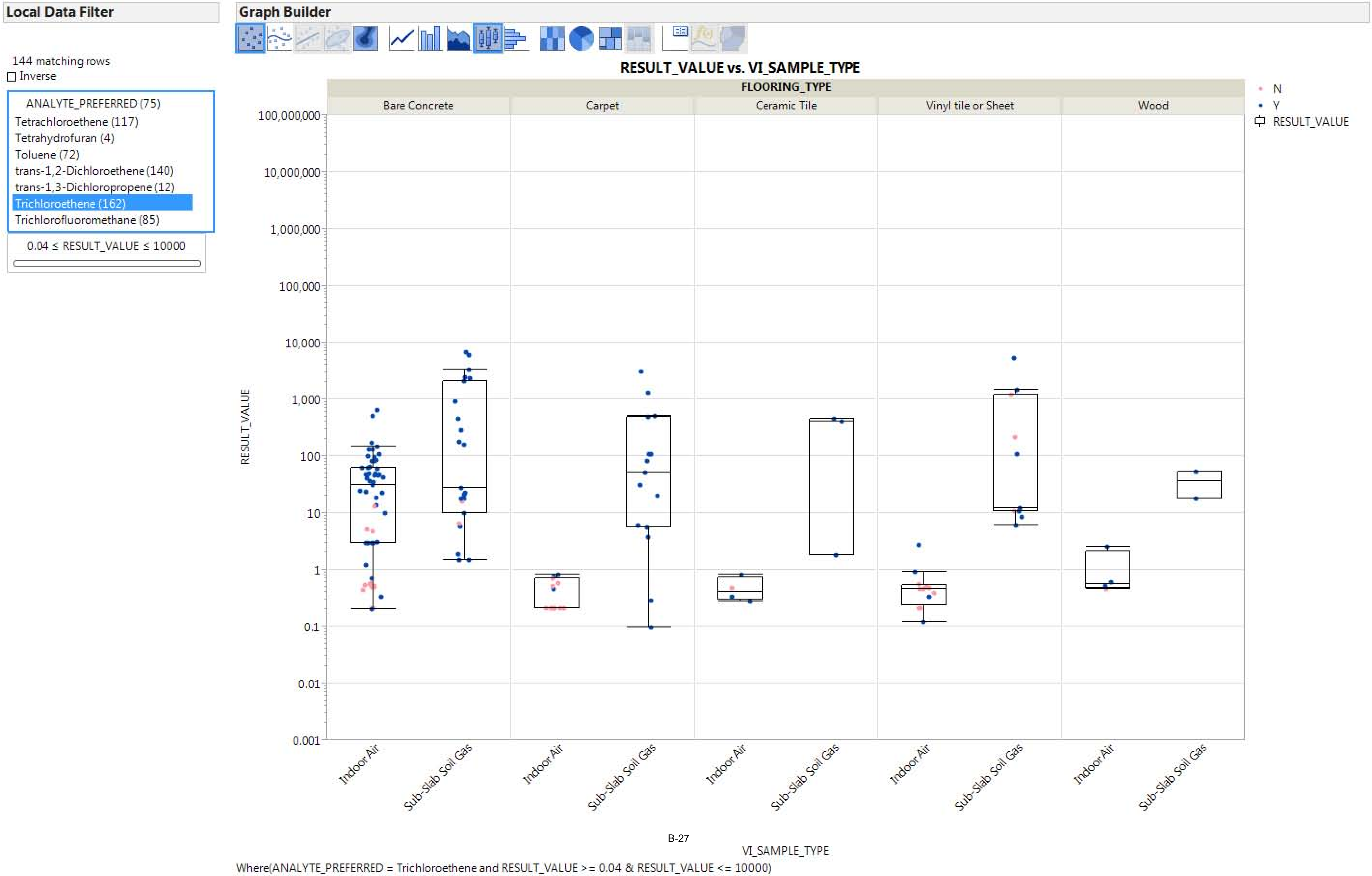
Local Data Filter

162 matching rows
☐ Inverse

ANALYTE NAME (75)
- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



Local Data Filter

144 matching rows

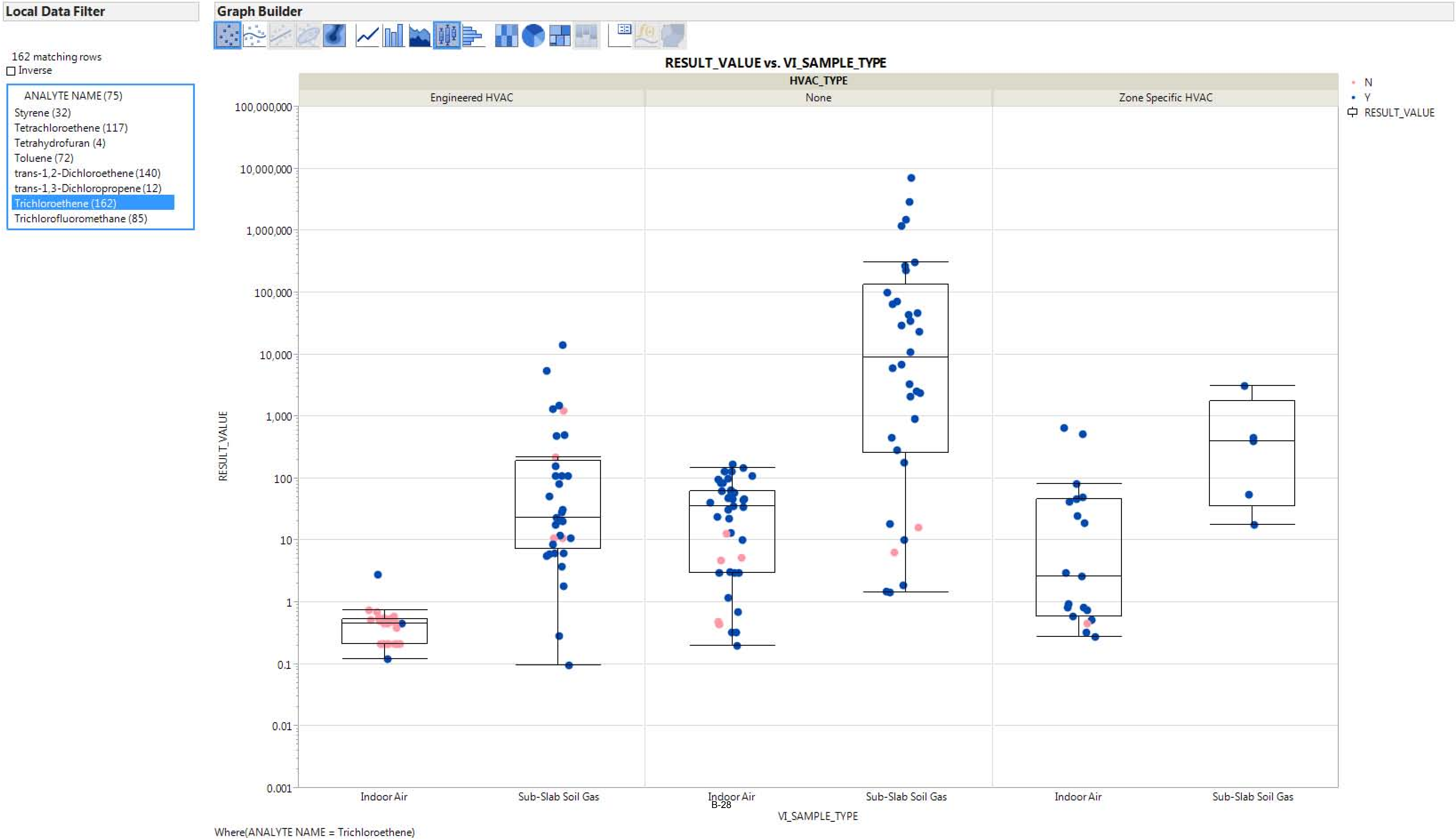
☐ Inverse

ANALYTE_PREFERRED (75)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)

0.04 ≤ RESULT_VALUE ≤ 10000

Graph Builder

Where(ANALYTE_PREFERRED = Trichloroethene and RESULT_VALUE >= 0.04 & RESULT_VALUE <= 10000)



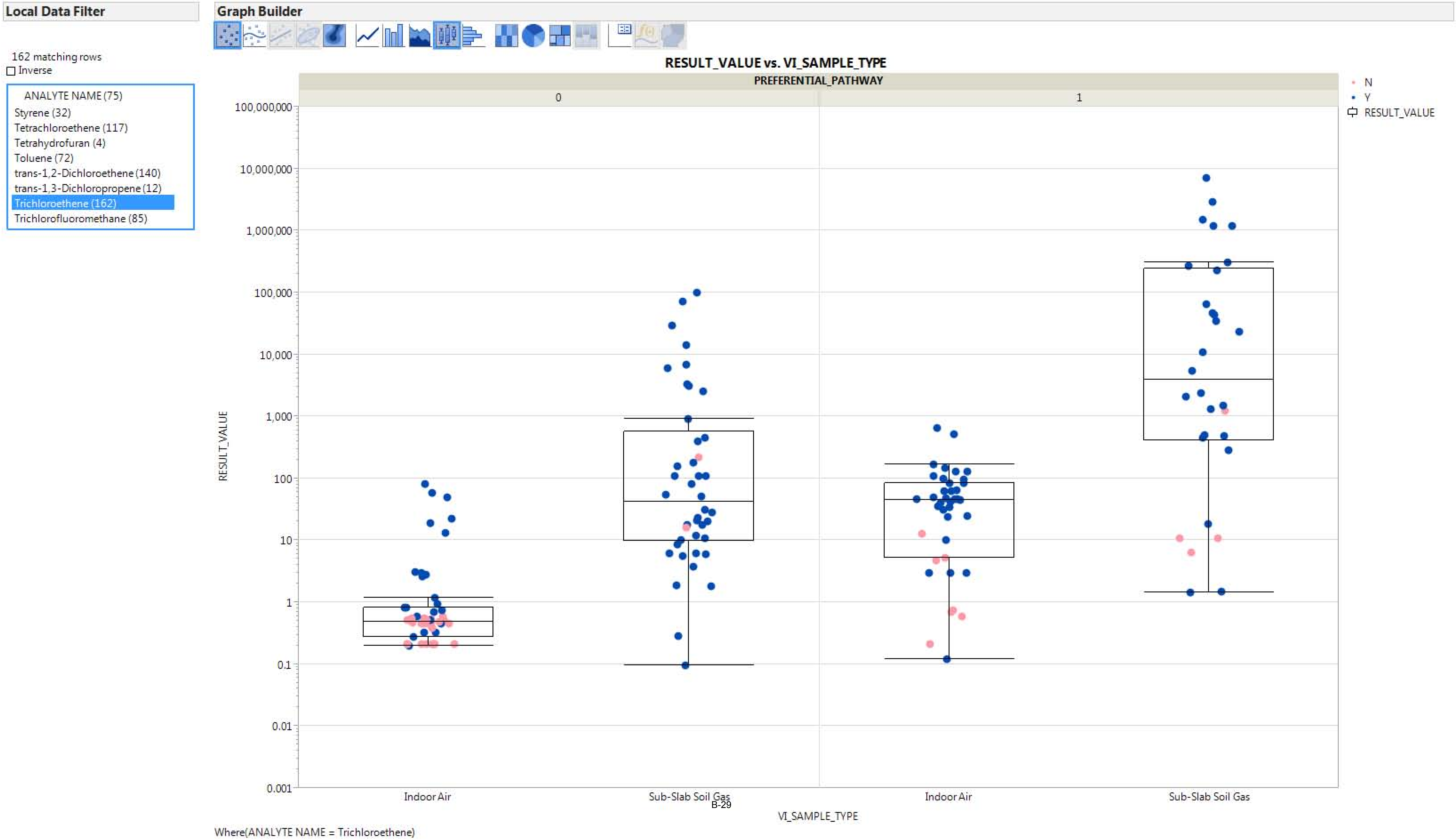
Local Data Filter

162 matching rows
☐ Inverse

ANALYTE NAME (75)
- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



Local Data Filter

162 matching rows

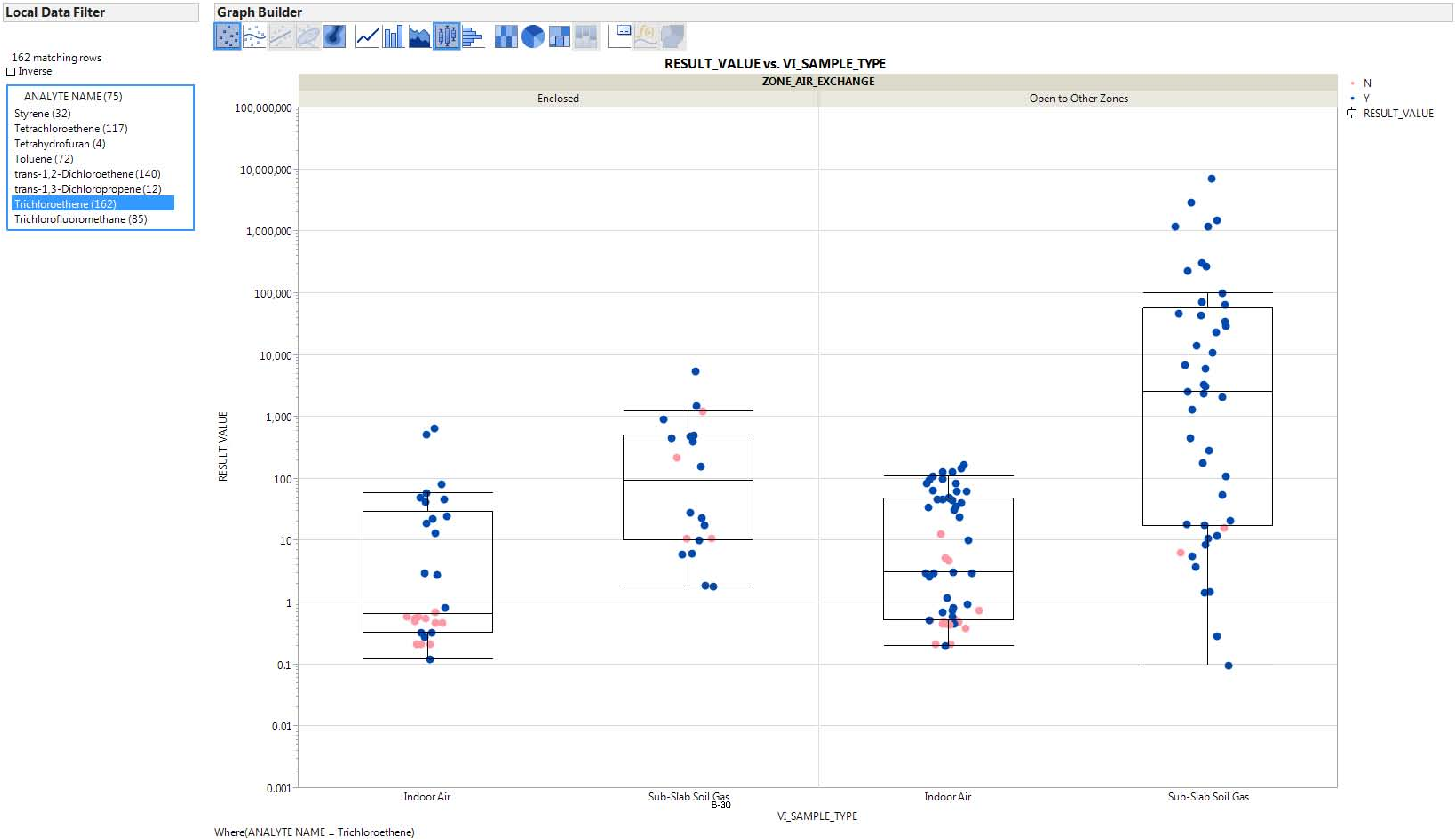
☐ Inverse

ANALYTE NAME (75)

- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



Local Data Filter

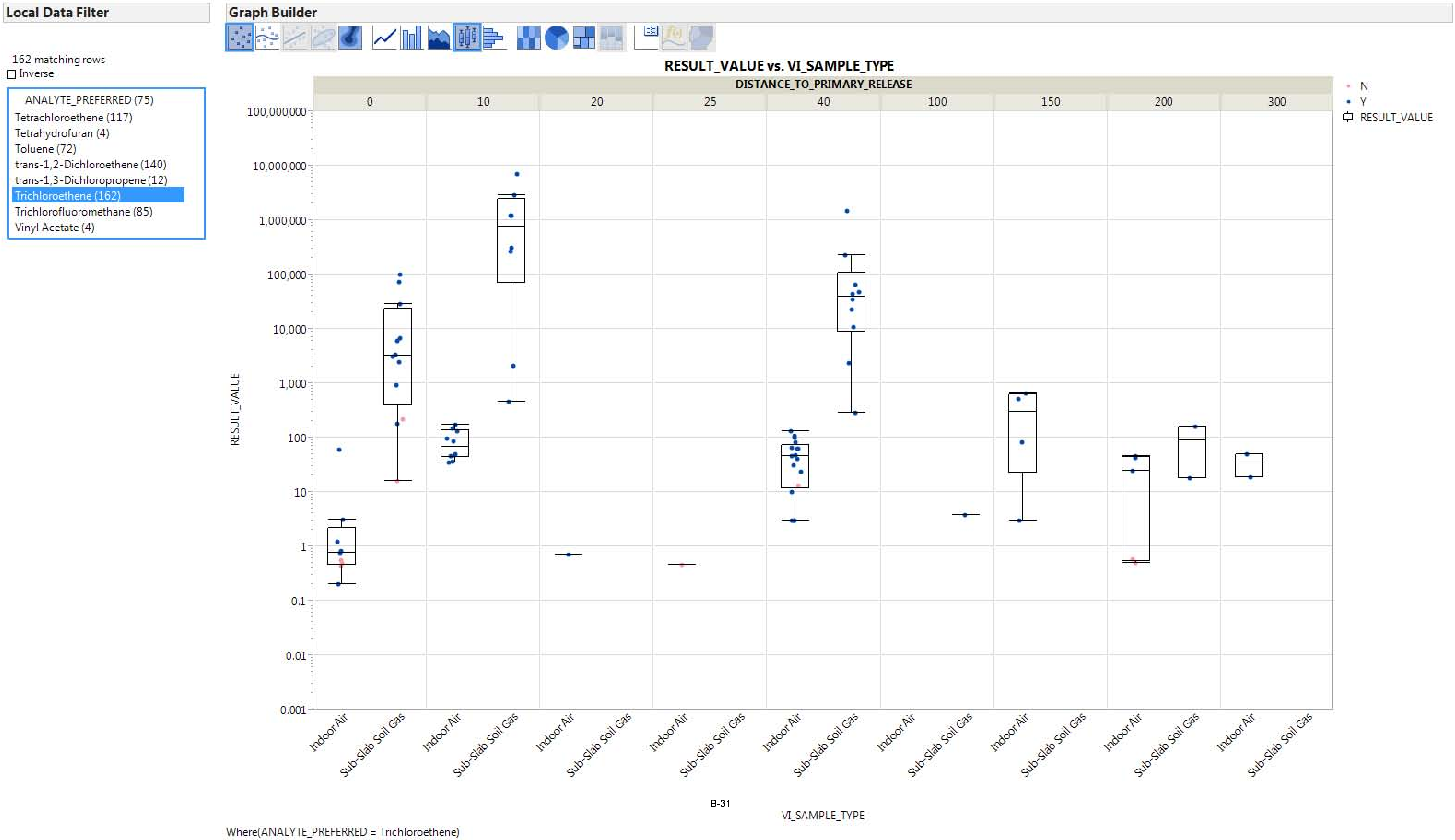
162 matching rows

☐ Inverse

ANALYTE NAME (75)
- Styrene (32)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)

Graph Builder

Where(ANALYTE NAME = Trichloroethene)



Local Data Filter

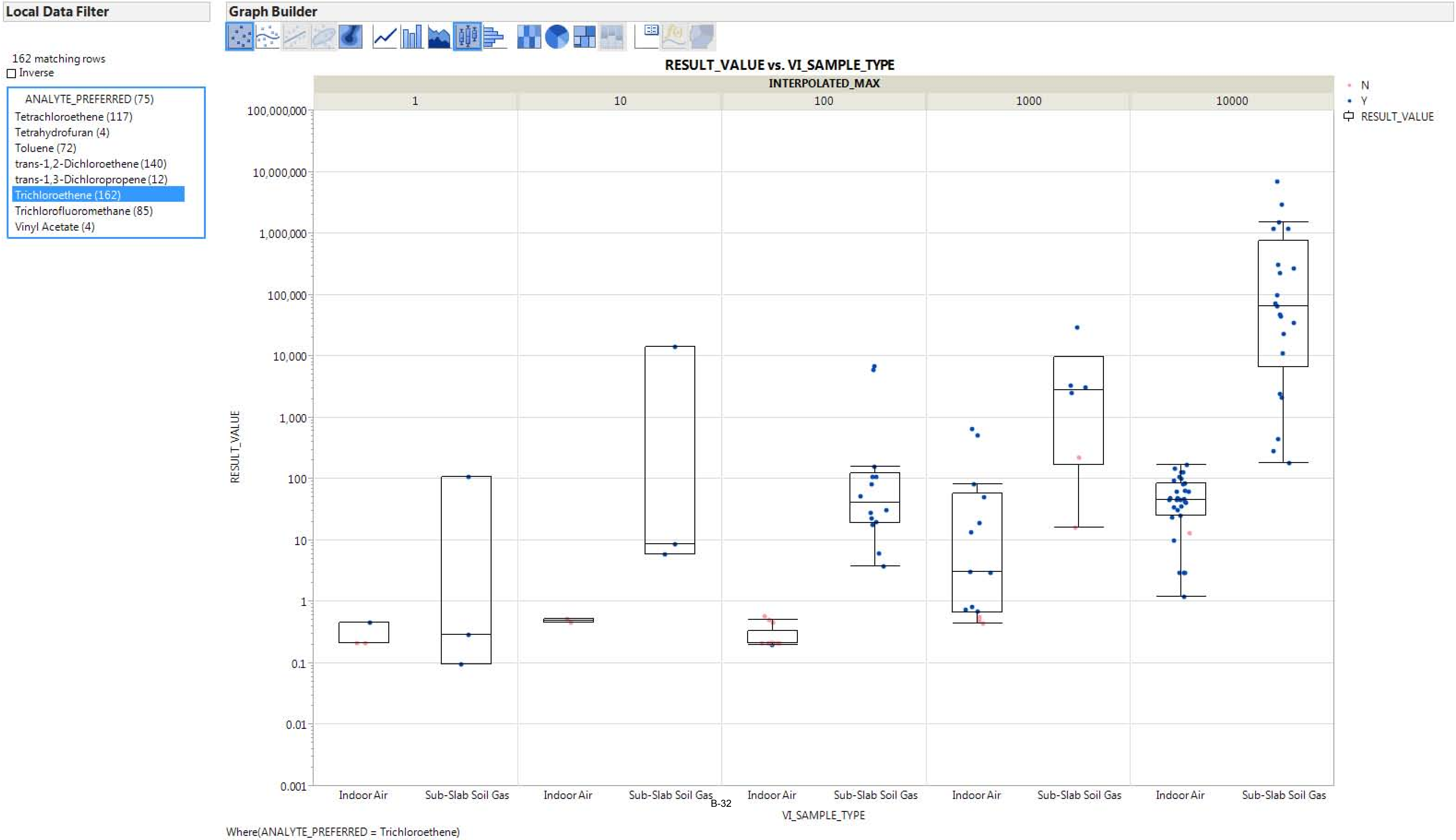
162 matching rows

☐ Inverse

ANALYTE_PREFERRED (75)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)
- Vinyl Acetate (4)

Graph Builder

Where(ANALYTE_PREFERRED = Trichloroethene)



162 matching rows
☐ Inverse

ANALYTE_PREFERRED (75)
- Tetrachloroethene (117)
- Tetrahydrofuran (4)
- Toluene (72)
- trans-1,2-Dichloroethene (140)
- trans-1,3-Dichloropropene (12)
- Trichloroethene (162)
- Trichlorofluoromethane (85)
- Vinyl Acetate (4)

Where(ANALYTE_PREFERRED = Trichloroethene)

Appendix C – Data Dictionary/Vapor Intrusion Database Guidance

VAPOR INTRUSION DATABASE GUIDANCE

POPULATION, QUALITY ASSURANCE, AND QUALITY CONTROL

Table of Contents

Purpose

The purpose of this document is to provide guidance to parties involved in the population and quality assurance/quality control (QA/QC) processes for the Vapor Intrusion (VI) Database.

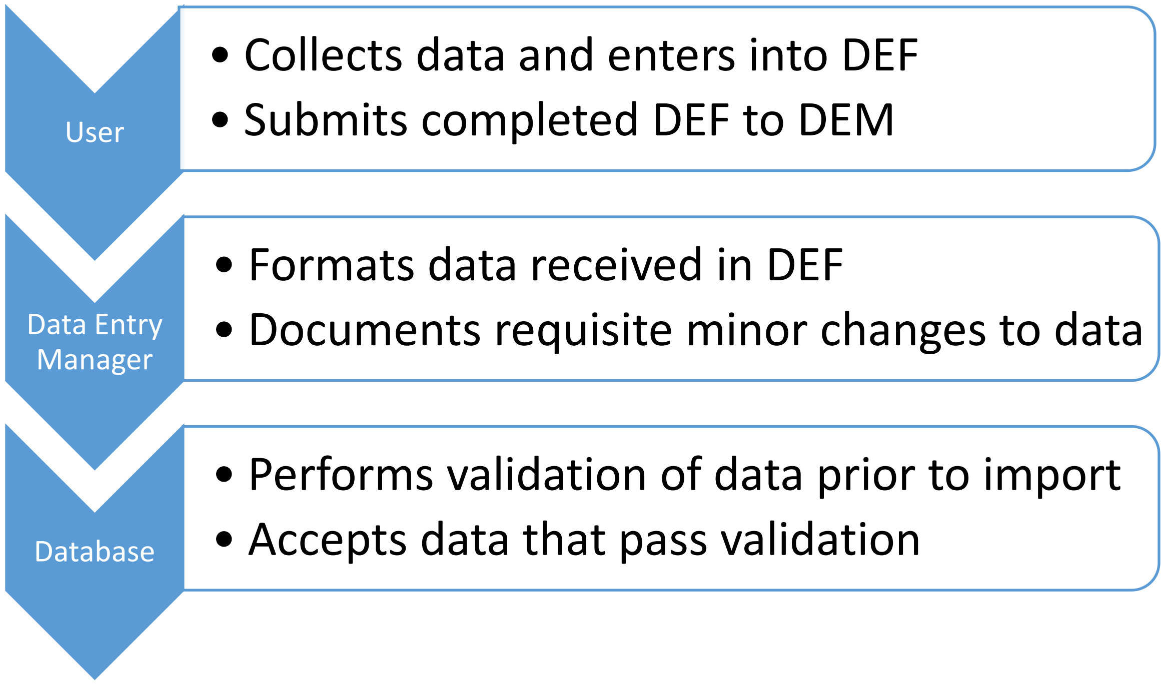
Organization

This document is organized into three sections. The first section discusses database population processes and procedures. The second section discusses QA/QC processes and procedures. The third section serves as a repository for information regarding parameter definitions, units, and default sources for each of the conceptual database objects.

Overview of Database Population

Database Population consists of all of the procedures and processes required to input data from a report, figure, or database into the VI Database. The first phase of the process requires a team or individual, hereafter referred to as a User, to manually collect the data required and enter them into the Data Entry Form (DEF). The DEF used for the initial population of the VI Database, VIDI (Vapor Intrusion Data Entry Interface), is in the form of a Microsoft Excel workbook. Once the data are compiled in VIDI by the User, the data are submitted to the Data Entry Manager (DEM). The DEM then formats the data for import into the VI Database. Occasionally minor changes to the data are needed to meet database requirements for import. These changes are documented by the DEM electronically in the form of a OneNote notebook specific to the Installation for which the change must occur. Prior to import, a validation of the data is performed by the database and if the data do not meet all the requirements, the data are rejected and the DEM is alerted regarding the data quality issues. This validation authenticates that numerical fields contain numbers, boolean fields contain true of false statements, and required fields (such as building number) are present. After correction of any data quality issues, the DEM imports the data into the database. Figure 1 provides an overview of the Data Entry Process.

Figure 1- Data Entry Process



User

- Collects data and enters into DEF
- Submits completed DEF to DEM

Data Entry Manager

- Formats data received in DEF
- Documents requisite minor changes to data

Database

- Performs validation of data prior to import
- Accepts data that pass validation

QA/QC of Data

A QA/QC procedure is implemented to reduce the number of potential data entry errors in data that reside in the database. The QA/QC process for the VI Database is described below.

Validation

The first part of the QA/QC process occurs as part of the database entry process. The acceptability of data entered by the User is validated against predefined parameter data types by a query. For example, the validation performed by the database will not allow text to be submitted where numbers are required.

Verification

The next part of the QA/QC process involves independent review of the data by an individual designated as the Reviewer. The Reviewer receives an export from the database in the form of a Microsoft Excel workbook which contains the data to be verified for a specific Installation (Installation-specific Verification Workbook, IVW) as well as notes, verbal or written,that guide the Reviewer to the data needed. These notes are provided by the User and contain the items listed below.

Location of the sources used to populate Building Characteristics Information field.

Figure(s) showing the building floor plans and sampling locations.

Note: Reviewer will use this figure (or figures) to determine approximate locations of Sample Zones (see Parameter-specific Guidance section for a description of Sample Zones).

Location of information needed to determine zone areas, ceiling heights, floor coverings, heating, ventilation, and air conditioning (HVAC) information, zone air exchange info, and any preferential pathways or sub-slab structures.

Location of maps showing depth to groundwater, groundwater well locations, and maximum measured contaminant concentrations in groundwater monitoring wells.

Location of maps showing groundwater contaminant contours relative to building locations.

Location of the sources used to identify primary release information.

Location of information on background sources.

The IVWs require that the Reviewer verify approximately 25% of the data in the IVWs. Each IVW utilizes a color coding system to indicate to the Reviewer which data require verification. Text that is red is used to designate fields that do not need to be reviewed and should not be modified. These fields are used by the DEM to upload corrected data to the proper location once the QC process is complete. The rows in an IVW that need to be verified by the Reviewer are highlighted in yellow. Fields that are highlighted yellow but have red text do not need to be verified, as they fall under the category of red text. Each parameter that needs to be verified will have two fields associated with it. The first field (left side) will contain the information for the parameter that is contained in the database. The second field (right side) will be blank. The verification process workflow is as follows.

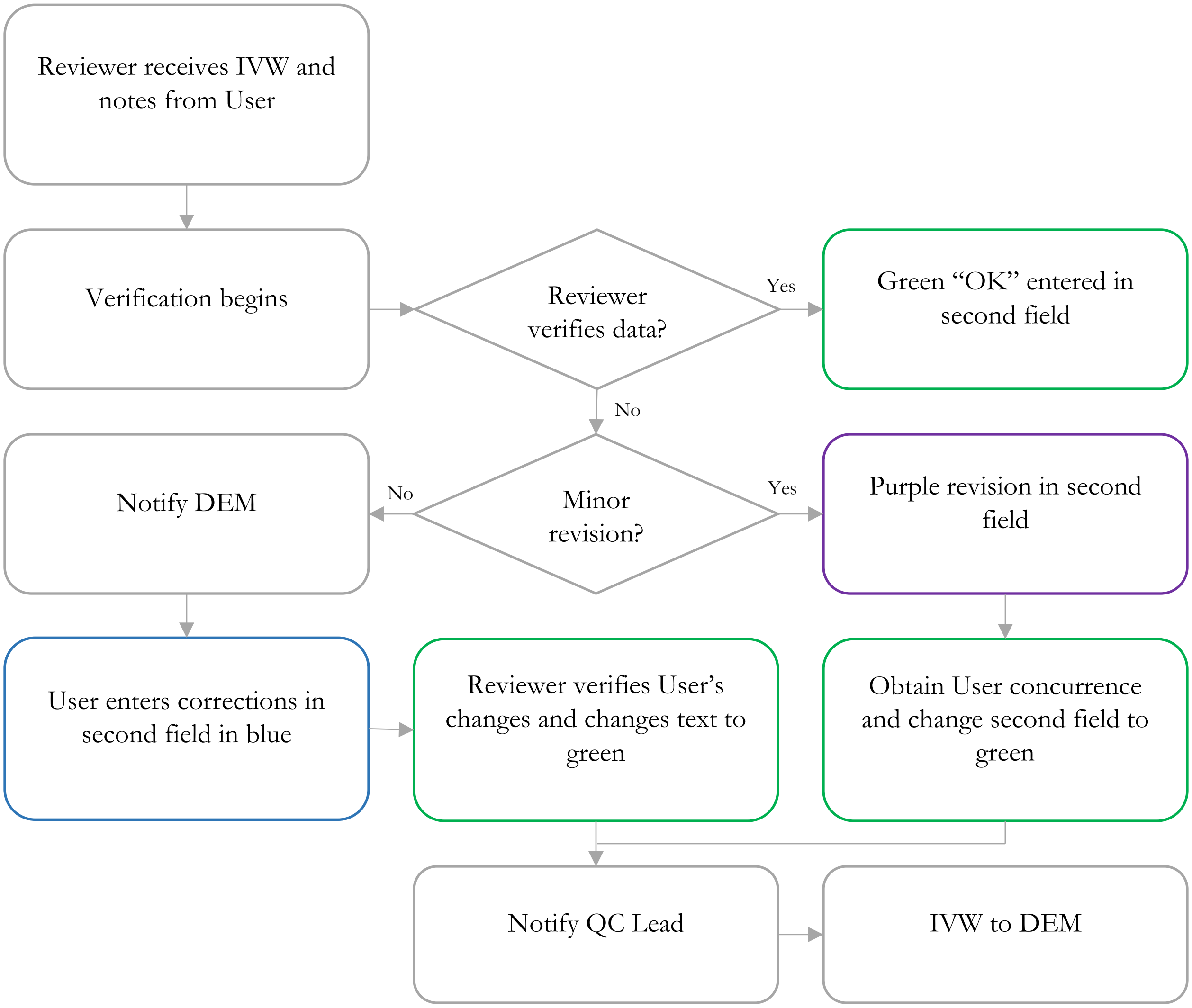
- The Reviewer reads the first field. The Reviewer then goes to the User's designated data source and attempts to confirm the information provided in the first field.
- If the information can be confirmed, the Reviewer then enters "OK" in green text in the second field. The green text is the signal to the DEM that both the User and Reviewer concur.

- If the Reviewer finds what appears to be contradictory information, a need for more information, or any other discrepancy, the Reviewer enters the data into the second column as it should appear in the database and changes the color of the text to purple. Purple indicates that there is at least one non-concurrence between the User and the Reviewer.
    - The Reviewer then contacts the User to discuss any non-concurrences. The User and Reviewer then work together to resolve the non-concurrences.
        - If the User demonstrates to the Reviewer's satisfaction that the information in the first field is correct, the Reviewer changes the text in the second field to "OK" using green text.
        - If the User and Reviewer agree that the data in the database need to change, the Reviewer revises the data in the second field until both the Reviewer and User are satisfied and then the Reviewer changes the text color to green.
    - If the IVW requires substantial revisions due to a misunderstanding on the User's part, the Reviewer may request, given the DEM's concurrence, that the User take the IVW and enter the corrected data into the second field and change this text to blue.
        - The User then makes appropriate revisions and turns the IVW over to the Reviewer for verification. The Reviewer then verifies the blue fields and changes the fields to green.
    - Once non-concurrences are resolved, the second fields in the IVW should contain only green text. This indicates to the DEM that any issues with the data in the IVW have now been resolved to the satisfaction of both the Reviewer and the User.
    - The Reviewer notifies his or her QC Lead that the review is complete and submits the IVW to the Lead.
    - The QC Lead then submits the IVW to the DEM.
    - The DEM updates the database to incorporate the changes in the IVW.

    It must be emphasized that data contained in the IVW will be uploaded to the database as contained in the IVW as is. No further review of the data will occur except a 10% back-check of the data to ensure the import was performed appropriately. As such, Reviewers must ensure that the data appear in the second field as they should appear in the database. Figure 2 provides a flowchart for the QA/QC process.

- If the Reviewer and User determine that Sites, Buildings, Sample Zones, or Sample Zone-related records have been omitted and must be added, the Reviewer notifies the DEM and the DEM provides a template to be populated by the User. When the User completes the population, the User returns the file to the DEM and the DEM provides the Reviewer with an additional IVW specific to the added data.
- If the Reviewer determines that Sites, Buildings, Sample Zones, or Sample Zone-related records were included when they should have been omitted, the Reviewer will notify the DEM. The DEM will, upon receiving concurrence from both the Reviewer and the User, remove the records from the database.

Figure 2 - Flowchart of QC/QA Process



Parameter-specific Guidance

Population methodologies are used to indicate to the User and Reviewer the hierarchy of sources to be used for the database. The primary data source has the highest priority, secondary the second highest, and so on. Users and Reviewers should use a lesser data source than the primary only if the data are unavailable in the primary source or the data are questionable.

Installation

Installation is the highest level object in the VI Database. It represents a single military installation.

Example: Naval Air Station Jacksonville

Installation Name

Definition

The official name of an installation documented in the ENV_INSTALLATION table in NIRIS (Naval Installation Restoration Information Solution) or military branch environmental database.

Units

Not Applicable

Population Methodology

Primary – Verify name with the DEM. If an unofficial name was used in the DEF, the DEM changed the name to the official Installation name before import.

Site

Site is the second highest level object in the VI Database. It represents a site at a given installation.

Example: SITE 000012

Site Name

Definition

The official name of a site documented in the ENV_SITE table in NIRIS or military branch environmental database.

Units

Not Applicable

Population Methodology

Primary –Verify the name with the DEM. If an unofficial name was used in the DEF, the DEM changed the name to the official Site name before import.

Building

The Building object represents a building at a Site. Each site may have one or more buildings entered into the database. Buildings are generally defined as structures with a roof and walls. With regard to whether abutting structures or additions constructed separately were considered separate buildings the project team followed the nomenclature in use at the facility.

Example: Building 103

Building Name

Definition

Accepted name of a building.

Units

Not Applicable

Population Methodology

Primary – Use the building name provided in a report.

Secondary – Use the name provided in INFADS (Internet Naval Facilities Assets Data Store) in the FACILITY NAME field for Navy sites.

Building Number

Definition

Accepted number for the building by the Installation.

Units

Not Applicable

Population Methodology

Primary – Use the building number provided in a report.

Secondary – Use the number provided in INFADS in the FACILITY NUMBER field for Navy sites.

Building Height Maximum

Definition

The maximum height of the building exterior. Excludes any unusual features such as steeples or antennae.

Units

Feet

Population Methodology

Primary – Use the value provided in the HEIGHT field under the MEASUREMENTS heading in INFADS. This measurement appears to represent actual exterior building height for buildings with flat roofs and an average exterior building height for buildings with pitched roofs. If documented field observations contradict the data in INFADS, then defer to the field observations and add the source of the data to the notes.

Secondary – Use the maximum reported exterior height for buildings with flat roofs. If the roof is pitched, use best professional judgment to estimate the average of the high and low points of the pitched roof.

Tertiary – Leave blank.

Building Height Minimum

Definition

The minimum height of the building exterior. This parameter will only differ from the Building Height Maximum for buildings with multiple elevations. An example would include buildings where one portion is one story and another portion is two story.

Units

Feet

Population Methodology

Primary – Use the value provided in the HEIGHT field under the MEASUREMENTS heading in INFADS. This measurement appears to represent actual exterior building height for buildings with flat roofs and an average exterior building height for buildings with pitched roofs. INFADS provides only one value for height, so this will be identical to the building height maximum.

Secondary – Use the minimum reported exterior height for buildings with flat roofs. If the roof is pitched, use best professional judgment to estimate the average of the high and low points of the pitched roof.

Tertiary – Leave blank.

Building Construction Date

Definition

Initial construction date of the building. Dates of remodeling can be noted, but are not necessary.

Units

Years

Population Methodology

Primary – Use the FACILITY BUILT DATE under CONSTRUCTION in INFADS.

Secondary – Use construction date provided in a report, if available.

Tertiary – Leave blank.

Building Footprint Area

Definition

The footprint area of the ground floor enclosed by the building. This parameter does not include the surface area of other floors (e.g., second floor/basement) or area under awnings.

Units

Square Feet

Population Methodology

Primary – Use the area for the entire building provided in a report.

Secondary – Use the AREA under MEASUREMENTS in INFADS. INFADS tends to list total square footage as opposed to areal square footage. If the value for FLOOR ABOVE GROUND QUANTITY and the value for FLOOR BELOW GROUND QUANTITY under MEASUREMENTS in INFADS are 1 and 0, respectively, it should be assumed that the INFADS AREA applies to a single floor and the AREA can be used. If the values for the previous fields are different than stated, using Google Maps to provide a best professional estimate is recommended.

Tertiary – Leave blank.

Building Use

Definition

Primary use for the building. Examples include warehouse, office, church etc.

Units

Not Applicable

Population Methodology

Primary – Use a use provided in a report.

Secondary – Leave blank.

Number of floors

Definition

The number of floors present in a building. Includes basements, but excludes underground utility corridors.

Units

Not Applicable

Population Methodology

Primary – Use the number of floors provided in a report. The value may be checked against the sum of the values for FLOOR ABOVE GROUND QUANTITY and FLOOR BELOW GROUND QUANTITY under MEASUREMENTS in INFADS. The maximum number of floors should be used in cases where one portion of the building contains more floors than another.

Secondary – Leave blank

Building Volume

Definition

Database Calculated Field, unless the building has multiple elevations.

Units

Cubic Feet

Population Methodology

Primary – Leave blank unless the building has multiple elevations. If a building has multiple elevations, the User must calculate the building volume.

Sample Zone

The Sample Zone object represents an enclosed location within a building where at least one indoor air sample has been collected. The conceptual idea that best represents Sample Zone is a box. A Sample Zone should have limited air mixing with other Sample Zones. Air mixing between Sample Zones is hard to qualify at times. In such cases, the User is encouraged to seek help from the QC Lead.

Example: Office

Sample Zone Name

Definition

A User-defined name which represents the Sample Zone.

Units

Not Applicable

Population Methodology

Primary – User-defined. Suggested names include a use (e.g., office), a room number (e.g., 107B), or an indoor air sample collection location ID (e.g., YS38-IA07). The latter should be used only if a more suitable name cannot be determined. Sample Zone Names should be unique within a building.

Sample Zone Number

Definition

A User-defined number which represents the Sample Zone.

Units

Not Applicable

Population Methodology

Primary – User-defined. Numbers can be based off a room number, be sequential, or follow some other convention. Sample Zone Numbers should be unique within a building.

Sample Zone Footprint Area

Definition

The enclosed footprint area of the Sample Zone.

Units

Square Feet

Population Methodology

Primary – Use a plan view, scaled figure in a report to measure the footprint area. Large areas need not subtract out small areas such as closets or offices from the area if inconvenient. The Reviewer should contact the User if questions arise to agree on the definition of the Sample Zone.

Secondary – Leave blank.

Sample Zone Interior Ceiling Height Maximum

Definition

Maximum ceiling height in a Sample Zone. Drop ceilings will be considered as ceilings.

Units

Feet

Population Methodology

Primary – Use the maximum ceiling height found in the Sample Zone regardless of the geometric configuration inside the Sample Zone. Pictures (if available) may be used for comparison to reported values.

Secondary – Leave blank.

Sample Zone Interior Ceiling Height Minimum

Definition

Minimum ceiling height in a Sample Zone. Drop ceilings will be considered as ceilings.

Units

Feet

Population Methodology

Primary – Use the maximum ceiling height found in the Sample Zone regardless of the geometric configuration inside the Sample Zone. Pictures (if available) may be used for comparison to reported values.

Secondary – Leave blank.

Sample Zone Depth to Groundwater

Definition

Depth to groundwater under the Sample Zone.

Units

Feet below Ground Surface

Population Methodology

Primary – Use depth to groundwater isocontours or values cited in a report to estimate the depth to groundwater under the Sample Zone. The shallowest depth that underlies the Sample Zone should be used. If seasonal variations are reported, use the shallowest value.

Secondary - If there is a nearby (ideally, within 100 feet) groundwater monitoring well, use the depth to groundwater for that well. If there are multiple wells nearby, use the depth from the well with the shallowest depth to groundwater.

Tertiary – Leave blank.

Sample Zone Exterior Wall

Definition

Exterior wall is used to designate whether the Sample Zone has at least one wall which is an external wall. An external wall separates the inside of the building from the outdoor environment.

Units

Yes or No

Population Methodology

Primary – Use plan view figures of the building to determine if a Sample Zone has external walls.

Secondary – Leave blank.

Sample Zone Flooring Type

Definition

Classification of the visible flooring material present within the footprint of the Sample Zone. Some variability in flooring type may be encountered; for example, a building survey form may indicate bare concrete in closets, whereas most of the Sample Zone is carpeted. In such cases, carpet should be indicated as the flooring type with the exception for closets recorded in the Notes field. In cases with multiple flooring types, with any one type comprising more than 10% of the space, the “Multiple” flooring types should be entered with a description added to the Notes field.

Units

Defined List

Population Methodology

Primary – Use photos that clearly show the flooring material in the Sample Zone. However, photos may represent only a small area. In such cases, best professional judgment is required to estimate other flooring types in the zone. Users should include an estimate of the level of uncertainty they have in the Flooring Type and make a recommendation regarding the use of the data they provide.

Secondary – Use a description in a Report/Building Survey. Some uncertainty may be associated with such data, however, as reports and surveys tend to focus little attention on flooring materials. Users should include an estimate of the level of uncertainty they have in the Flooring Type and make a recommendation regarding the use of the data they provide.

Tertiary – Leave blank.

Sample Zone HVAC Type

Definition

Classification of the HVAC systems that service the Sample Zone. It is likely that this parameter will have a moderate level of uncertainty associated with it.

Units

Defined List

Population Methodology

Primary – Use the description of the HVAC system as found in the Energy Audits, along with professional judgment, to determine which HVAC type from the list best describes the HVAC system in a Sample Zone. Users should include an estimate of the level of uncertainty they have in the HVAC Type and make a recommendation regarding the use of the data they provide.

Secondary - Use the description of the HVAC system as found in a report/building survey, along with professional judgment, to determine which HVAC type from the list best describes the HVAC system in a Sample Zone. Users should include an estimate of the level of uncertainty they have in the HVAC Type and make a recommendation regarding the use of the data they provide.

Tertiary – Leave blank.

Sample Zone Preferential Pathway

Definition

A pathway by which vapor may move into the Sample Zone in a less inhibited manner than the traditional pathway. Examples include utility vaults and conduits and elevator shafts. Note any floor drains within the Sample Zone. Recognize that there may be a significant uncertainty in identifying preferential pathways that may be significantly contributing to indoor air concentrations.

The Navy VI Tool provides the following guidance concerning what types of features to consider as preferential pathways and should be used to determine whether potential significant preferential pathways exist.

Preferential pathways are natural or anthropogenic subsurface features of higher permeability or air filled porosity than the surrounding matrix. Preferential pathways may transport vapors farther or faster than what would be predicted by vapor transport models or assumptions (i.e., the Johnson and Ettinger model or attenuation factors). Because of this, preferential pathways may create an atypical connection/pathway between a vapor source and a building. Identifying significant preferential pathways is a critical component of the CSM. In order for a pathway to be "preferential" it must contribute to significantly different vapor transport compared to the expected transport through the surrounding matrix. Per ITRC (2007) VI Guidance:

"Most buildings have subsurface utility penetrations, so their presence alone is not considered preferential ... some increased component of soil gas flow into the building is usually required to consider the pathway to be preferential."

Since the pathways are in the subsurface, they may not be obvious, and a careful inspection is often required to identify their presence or absence. Detailed building surveys/inspections, blueprints/as-

built drawings, and geological investigations are some resources to help identify potential significant preferential pathways.

Examples of Anthropogenic Preferential Pathways

- *Subsurface utility conduits (e.g., a sewer line intersecting contaminated groundwater)*
- *Floor drains (e.g., around the gravel pack of the drain pipe where it enters the building or inside the pipe if contaminated groundwater has entered a sewer line and the trap is not maintained)*
- *Building sumps or dry wells*
- *Drainage pits*
- *Large, unsealed penetrations through otherwise solid concrete floors*
- *Unsealed saw-cut expansion joints in concrete floors, or floors where seals have desiccated or deteriorated over time*
- *Utility conduits and surrounding granular fill, but only where there is a pressure gradient driving flow or the surrounding soil is too moist to allow appreciable vapor diffusion*
- *Unlined crawlspaces, especially where the vadose zone is enough to make pumping important*
- *Elevator pits and shafts*

Examples of Natural Preferential Pathways

- *High permeability soils (e.g., gravel)*
- *Heterogeneous sediments*
- *Fractured bedrock*
- *Animal burrows*

Units

Yes or No

Population Methodology

Primary – If preferential pathways are cited in reports/building surveys that match the guidance provided by the Navy VI Tool in the Definition above, then enter “YES” and document the available data in the Notes section. If not, enter “No.”

Sample Zone Use

Definition

Primary use for the Sample Zone. Examples include bathroom, office, machine shop, paint booth, etc.

Units

Not Applicable

Population Methodology

Primary – Use the use provided in a report for the area comprising the Sample Zone. If no information is available, contact the assigned expert to obtain information.

Secondary – Leave blank.

Sample Zone Volume

Definition

Database Calculated Field unless the Sample Zone ceiling height varies significantly (>5 ft).

Units

Cubic Feet

Population Methodology

Primary – Leave blank unless the ceiling height varies >5 ft. In that case, the User must calculate the Sample Zone volume.

Sample Zone Soil Type

Definition

Soil type underlying the Sample Zone.

Units

Defined List

Population Methodology

Primary – Use the soil type provided in a report, including boring logs and cross sections. If silts or clays are indicated in boring logs or cross sections for the vadose (unsaturated) zone near or beneath the building, the User should enter "Fine" as the soil type. This includes strata containing coarser-grained components such as silty sand, gravelly clay, etc. The "Coarse" soil type should be entered in cases where no fines are indicated or only traces of fines are indicated. The interbedded soil type should be entered in cases where there are two or more layers with different (i.e., coarse and fine) soil types.

Secondary – Leave blank

Sample Zone Subgrade Structures

Definition

Structures that underlie a Sample Zone that are not designed for continuous occupancy. Examples include hydraulic lift pits, utility vaults, etc.

Units

Yes or No

Population Methodology

Primary – If Subgrade Structures are cited in reports/building surveys, then enter "YES" and document the available data in the Notes section. If not, enter "No."

Sample Zone Background Source

The Sample Zone Background Source object represents local sources of an analyte which may cause indoor air or sub-slab concentrations to be elevated. If not identified, background sources can lead to a false conclusion that VI is occurring and/or significant when in reality, it is not. Sample Zone Background Sources will typically be due to outdoor air volatile organic compound (VOC) sources or chemicals used or stored in the building and apply to each Sample Zone in the building if present.

Example: Spray can of degreaser known to contain trichloroethene found in flammables cabinet.

Analyte

Definition

The analyte identified as potentially having a background source (e.g., trichloroethene). Only analytes detected in indoor air within the building need to be recorded.

Units

Not Applicable

Default

Primary – If there are background sources documented in a report, add the analyte data here.

Background Source Name

Definition

Name that describes the background source (e.g., spray can of degreaser.)

Units

Not Applicable

Default

Primary – Use the name of the background source presented in the report unless it is confusing. If it is confusing, enter a User-defined name.

Sample Zone Groundwater

The Sample Zone Groundwater object represents the groundwater under a Sample Zone. Only analytical data that represent concentrations at or near (10 feet below[1]) the water table should be considered. Contact the QC Lead if unsure about whether groundwater data meet database requirements due to depth below water.

Analyte

Definition

The analyte detected in the groundwater.

Units

Not Applicable

Default

Primary – Report. Analytes detected at least an order of magnitude above the reporting limits should be included. Only chlorinated VOCs (CVOCs) will be populated.

Secondary - Blank

Interpolated Maximum under Sample Zone

Definition

Maximum groundwater concentration of the analyte under the Sample Zone as determined by interpolation (isoconcentration maps).

Units

Micrograms per Liter

Default

Primary – Report - Isoconcentration maps, if available, should be used to populate this field if:

1. They show contours extending under the building and specific Sample Zone.
2. They represent conditions within a year of indoor air and subslab sampling events or information is available to suggest the VOC plume is stable.

Cases where isoconcentration maps are not available should be referred to a hydrogeologist for assistance.

Secondary - Blank

Interpolated Minimum under Sample Zone

Definition

Minimum groundwater concentration of the analyte under the Sample Zone as determined by interpolation (isoconcentration maps).

Units

Micrograms per Liter

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[1] OSWER Final Draft Guidance for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Sources to Indoor Air (External Review Draft). U. S. Environmental Protection Agency. April 2013.

Default

Primary – Report - Isoconcentration maps, if available, should be used to populate this field if:

1. They show contours extending under the building and specific Sample Zone; and
2. They represent conditions within a year of indoor air and subslab sampling events or information is available to suggest the VOC plume is stable.

Cases where isoconcentration maps are not available should be referred to a hydrogeologist for assistance.

Secondary - Blank

Measured Maximum

Definition

Maximum measured (validated analytical result) groundwater concentration of the analyte in groundwater wells within 100 feet of the Sample Zone perimeter in any direction.

Unit

Micrograms per Liter

Default

Primary – Report – Monitoring Well Location Maps - If no well is located within 100 feet of the Sample Zone perimeter, the field should be left blank. If there is only one groundwater well within 100 feet of the Sample Zone perimeter, use the concentration in that well for both the minimum and maximum.

Secondary - Blank

Measured Minimum

Definition

Minimum measured (validated analytical result) groundwater concentration of the analyte in groundwater wells within 100 feet of the Sample Zone perimeter in any direction.

Units

Micrograms per Liter

Default

Primary - Report – Monitoring Well Location Maps. If no well is located within 100 feet of the Sample Zone perimeter, the field should be left blank. If there is only one groundwater well within 100 feet of the Sample Zone perimeter, use the concentration in that well for both the minimum and maximum.

Secondary - Blank

Measured Max Location ID

Definition

NIRIS location ID associated with the location where the Measured Maximum was observed.

Units

Not Applicable

Default

Primary - Report– Monitoring Well Location Maps. If no well is located within 100 feet of the Sample Zone perimeter, the field should be left blank. If there is only one groundwater well within 100 feet of the Sample Zone perimeter, use the concentration in that well for both the minimum and maximum.

Secondary - Blank

Measured Minimum Distance

Definition

Shortest distance from the Sample Zone perimeter to the location where the Measured Maximum was observed.

Units

Linear Feet

Default

Primary – Monitoring Well Location Maps. If no well is located within 100 feet of the Sample Zone perimeter, the field should be left blank. If there is only one groundwater well within 100 feet of the Sample Zone perimeter, use the concentration in that well for both the minimum and maximum.

Secondary - Blank

Sample Zone Primary Release

The Sample Zone Primary Release object represents the vadose zone release point/area of contaminants in the vicinity (e.g., within 100 feet) of the Sample Zone. It does not represent the resulting plume from the migration of the contaminants to groundwater. Many Sample Zone Primary Releases will be synonymous with surface disposal sites, leaking underground storage tanks, solvent spills, disposal pits, and stormwater or sewer conveyance lines. The objective of the Sample Zone Primary Release field is to provide as much relevant information as possible about how close a vadose zone source may be to a Sample Zone.

Example: Historical chlorinated solvent surface disposal site.

Analyte

Definition

The contaminants of potential concern identified in the Remedial Investigation (RI)/Pre-RI as part of the Primary Release.

Units

Not Applicable

Default

Primary – Use the contaminants of potential concern for a Primary Release discussed in the RI/Pre-RI Report or consult with the assigned expert.

Document in the Notes section if the primary release has been or is undergoing active remediation.

Distance to Primary Release

Definition

Minimum distance from a Sample Zone perimeter to the point of release.

Units

Feet

Default

Primary – Best professional judgment, order-of-magnitude estimate of the lateral distance between the point of release and the Sample Zone perimeter using a scaled figure. If the Primary Release occurred within the Sample Zone (e.g. solvent disposed of in sump in corner of building) the Distance to Primary Release should be entered as zero.

Secondary – Best professional judgment, order-of-magnitude estimate of the lateral distance between the point of release and the Sample Zone perimeter using the opinion of the assigned expert. If the Primary Release occurred within the Sample Zone (e.g., solvent disposed of in sump in corner of building) the Distance to Primary Release should be entered as zero.

Primary Release Source Name

Definition

Accepted name for the primary release. Should be unique to distinguish it from other primary releases in the building.

Units

Not Applicable

Default

Primary – Use the name provided in a report.

Secondary – Use the name provided by the assigned expert.

Sample Zone Locations

The Sample Zone Location object represents a physical location where one or multiple samples have been collected. Sample matrices may be collocated but should be designated with separate Sample Zone Location entries due to the VI Database construction. Acceptable sample types are sub-slab soil gas or indoor air.

Is NIRIS or Military Branch Environmental Database ID?

Definition

Field is to indicate the answer to the question "Is the Location ID you are providing found in NIRIS or military branch environmental database?" If unsure, put No. Most Location IDs should be in NIRIS or other environmental database.

Units

Yes or No

Population Methodology

Primary – If it is believed that the Location ID is in NIRIS or the other military branch environmental database, enter "Yes." Otherwise enter "No." Uniform alphanumeric formats for Location IDs suggest that they are present in the environmental databases.

Location ID

Definition

Accepted, designated name for a sample collection location. Location IDs and Sample IDs are not synonymous. For example, at sample location X with location ID P32X-7, samples IA01-1, IA01-2, and SG01 were collected. For this field, the User would enter P32X-7, not IA01-1, -2 or -3.

Units

Not Applicable

Population Methodology

Primary – Use Location IDs for sub-slab soil gas or indoor air sampling locations found in report figures, text, or tables.

VI Sample Type

Definition

Matrix type associated with the Location ID. A Location ID may have more than one VI Sample Type but each should be recorded on a separate line in the DEF.

Units

Defined List

Population Methodology

Primary – Use the sample matrix found in a report figure, table, or text to determine the VI Sample Type. Location IDs may have a VI sample type of Indoor Air or

Sub-slab Soil Gas. Location IDs with both VI Sample Types should be listed twice, with each one having a different VI Sample Type.

Note: NIRIS sample types are not necessarily reflective of the actual sample type because not all VI sample types were available in NIRIS historically.

Appendix D – Exploratory Data Analysis and Statistical Protocols

NESDI Project #476, A Quantitative Decision Framework for Assessing Navy VI Sites – Interim Tech Memo Steps 11 and 12: Exploratory Data Analysis and Statistical Protocols

PREPARED FOR:	NAVFAC EXWC
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DATE:	August 15, 2014
PROJECT NUMBER:	436747

The United States Naval Facilities Engineering Command (NAVFAC) Expeditionary Warfare Center (EXWC), NAVFAC Atlantic, and CH2M HILL are conducting the 3-year research project titled, "*A Quantitative Decision Framework for Assessing Navy VI Sites-NESDI Project #476*." The work is being funded through the Navy's Environmental Sustainability Development to Integration (NESDI) program. This project involves developing and analyzing a database of empirical data from Navy sites where the potential for subsurface vapors related to historical releases of volatile organic compounds (VOCs) to migrate into nonresidential buildings (i.e., vapor intrusion or "VI") has been investigated. The ultimate goal of the project is to develop a VI decision framework (relationships, decision rules, and other guidelines) and recommendations to incorporate into Navy VI guidance documents, training, or other evaluation tools.

Previous technical memorandums (TMs) for this project summarized efforts and information pertaining to the following: the scope and design of the database, data usability criteria, site and building selection, initial database population, initial exploratory data analysis (EDA), data gaps identification, and quality control. The primary purposes of this TM are as follows:

- Summarize the results of EDA based on the populated database.
- Summarize tables and fields that were added to the database as information needs were refined while conducting EDAs.
- Identify potential patterns and/or correlated variables that may significantly impact the occurrence and magnitude of VI and, therefore, warrant more formal statistical evaluations.
- Provide an overview of the planned protocols for conducting further statistical analyses.
- Begin to suggest which variables and data analyses may be most likely to yield useful information to incorporate into the Navy's quantitative decision framework.

There are more types of analyses possible with this database than can be fully completed under this project, so one of the objectives of this TM is to present information that will help the project team determine which analyses are most important or most likely to provide the greatest value in further refining the Navy's Quantitative Decision Framework.

The following three-track data analysis process was applied based on feedback from recent conference calls:

1. An EDA was performed using the full data set, before removing suspected cases of background influence and before calculating attenuation factors (AFs). The EDA was performed at this time in this way because calculating an AF inherently reduces the amount of data/information (converts two values into one). The authors chose to perform the EDA before removing suspected background samples because conclusions made after removing background are always subject to the criticism that they result from how background was removed, and were not inherently a property of the data set.
2. A stepwise, structured approach to filtering out potential background contributions was applied and modeled after the approach used by the U.S. Environmental Protection Agency (USEPA) (2012) in their analysis of a primarily residential VI database. These background screening/filtering steps will be applied at the stage of the analysis where AFs are calculated. This will include analyses of different populations of AFs using screening or filtering steps of various levels of rigorousness. Accounting for the potential bias introduced via background indoor or outdoor sources and evaluating the distribution of AFs that remains after implementing various screens for background will allow the identification of reasonable default AFs for industrial buildings.
3. The consistency and usefulness of variables potentially related to preferential vapor flow pathways were reviewed in the database. Specifically, the entries in the database about a preferential flow pathway (yes/no), preferential pathway notes, subgrade structures (yes/no), and subgrade structure notes were reviewed. In a number of cases, possible inconsistencies were identified and additional information was gathered from site documents or persons experienced with the site. This led to populating several additional fields for each sample zone to refine the characterization of the most common pathways in the database (vaults/pits or floor drains).

As discussed in the last TM (CH2M HILL, 2013), developing defensible conclusions and recommendations from the data and data analysis depends on an understanding of the quality of information included in the database, along with an understanding of the level of consistency in the interpretation of the parameters that have been entered in the database. Updates to the database since the last TM are summarized below, followed by a discussion of the EDA results.

Update of Database Since Last TM

The previous TM (CH2M HILL, 2013) summarized the structure of the database as it existed at that time. This overall structure of the database remains largely unchanged. Some additional tables and fields have been added to capture additional site characteristics, provide more detailed breakdown of previously existing characteristics, or support data analysis. The changes include:

- A table was added to capture the unitless Henry's Law coefficients for the VOCs of interest. These data are used to calculate groundwater vapor source concentrations for use in data analysis. The USEPA (2014) Vapor Intrusion Screening Level (VISL) tables were the source of the values. Temperature-specific coefficients were calculated based on a default water temperature of 20 degrees Celsius.
- The method for pairing data to calculate subslab-to-indoor-air AFs was modified. Since the subslab and indoor air data are sometimes collected on different days within a given sampling event, some method was need to pair data for a given event. Previously, data collected within a sample zone during the same calendar month were paired. There were cases, however, when subslab samples were collected at the end of the month and indoor air samples were collected at the beginning of the following month, resulting in missed pairs. In the new scheme, indoor and subslab samples collected within 14 days of each other were paired.

- A table was created to capture the various reasons that analytical results might be flagged relative to the potential presence of background sources. The fields in this table capture whether the following conditions exist:
  - Groundwater concentrations (measured or interpolated) were ND under or near a building.
  - Indoor air concentrations were greater than 2-times the measured outdoor concentration for a given sampling event.[1]
  - Subslab concentrations were greater than 50-times [2] the literature background value for indoor air.
  - The calculated groundwater vapor source concentrations were greater than 1000-times[3] the literature background value for indoor air.
  - Indoor results were greater than the literature background value for indoor air.
  - Analysis of site-specific data, specifically the indoor-to-subslab concentration ratio for multiple analytes, suggested the presence of a background source.

The background value was selected for quantitative analysis in data screening was the 90th percentile of the Building Assessment Survey and Evaluation (BASE) study indoor air distribution (NYSDOH, 2006 Appendix C-2). The BASE study database was derived from intensive sampling of 100 randomly selected public and commercial office buildings in the U.S. with sampling from 1994-1996. The use of the 90th percentile value is consistent with how background was defined in the USEPA database study (2012). If the BASE study 90th percentile was a less than value, indicating detectable indoor air concentrations were rarely found in office buildings at the elevated detection limits that were common in the 1990s, then the Median of 90th Percentile Concentration from multiple residential studies (USEPA, 2011) was used instead, as done in the USEPA residential database report (USEPA, 2012). If both studies had a less than value for the 90th percentile, then the authors considered that background was unlikely and did not screen out any data for background for that compound. At the time of writing of this TM, no other North American commercial building background studies were readily available to the authors in a suitable format.

The comparison of commercial buildings to residential background is not ideal, but can provide some useful information because:

1. Persons frequently purchase many products for cleaning, pest control, etc., from the same sources for both residential and commercial uses. Cosmetics, cooking, building materials, furniture, and human exhalation are all examples of VOC sources that are present to varying extents in many residential and commercial environments. However, air exchange rates and building volumes are often different for residential and commercial structures.
2. Other than office buildings, it is difficult to find commercial buildings with no possibility of previous industrial use of VOCs, that are geographically separated from other industrial users of VOCs, and thus are certain to be representative of “background” conditions.
3. From a public health perspective, if an exposure occurs in the workplace at levels typical of those in the residential environment, the added risk from the workplace exposure can be presumed to be moderate. This is the case because most persons are in their home for more hours per year than in the workplace.

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[1] 2x factor was selected on the basis of professional judgment that values less than 2x above ambient concentrations were almost certainly heavily influenced by ambient concentrations. While some ambient influence is undoubtedly present in concentration values where indoor air is for example 4x ambient concentration, as the multiple increases the likely contribution of ambient concentrations decreases.

[2] After considering multiple values for this factor, USEPA in their residential database report (EPA-530-R-10-002), the agency selected 50x. This value was considered reasonable based on the authors’ professional judgment and was used to allow consistent comparison to the USEPA report.

[3] After considering multiple values for this factor, USEPA in their residential database report (EPA-530-R-10-002), the agency selected 1000x. This value was considered reasonable based on the authors’ professional judgment and was used to allow consistent comparison to the USEPA report.

In addition, a field was added to capture whether a background source was suspected for other reasons, along with a text field to allow users to document the reason.

- A table was added with the background indoor air literature values used in the comparisons.
- Fields were added to the sample zone characteristics table to add details about the type of subsurface features (vaults/pits or floor drains) that were present.

Exploratory Data Analysis Methods

According to USEPA (www.epa.gov/caddis/da_exploratory_0.html), an EDA is "an analysis approach that focuses on identifying general patterns in the data, and identifying outliers and features of the data that might not have been anticipated. EDA is an important first step in any data analysis. Understanding where outliers occur and how different environmental variables are related can help one design statistical analyses that yield meaningful results." According to Seltman, 2009, EDAs are mainly used to detect mistakes, check assumptions, help preliminarily select appropriate models, determine relationships among explanatory variables, and assess the relationships between exploratory and outcome variables.

Although the database includes all available VOC data collected at the buildings/sites, the focus of this EDA was on the following eight chlorinated aliphatic hydrocarbons because they were detected most frequently:

- 1,1,1-Trichloroethane (1,1,1-TCA)
- cis-1,2-Dichloroethene (cis-1,2-DCE)
- Tetrachloroethene (PCE)
- Trichloroethene (TCE)
- Vinyl Chloride
- 1,1-Dichloroethane (1,1-DCA)
- 1,1-Dichloroethene (1,1-DCE)
- 1,2- Dichloroethane (1,2-DCA)

The final report will describe the data set as a whole and then subsets of the data set sorted according to potential predictor variables using descriptive statistics such as:

- Minimum, maximum, mean, median, standard deviation
- Frequency of detection by analyte
- 5th, 25th, 50th, 75th, 95th percentiles

The 95th percentile descriptive statistic is relevant because USEPA frequently uses it as an upper bound in risk assessment and VI data analysis. For example, the 95th percentile is commonly used as an upper confidence limit for point of exposure concentrations at hazardous waste sites (USEPA, 2002). The 95th percentile values of AF distributions taken from USEPA's VI residential database report are commonly used as the default AFs.

The primary graphical tool used in this EDA was a box and whisker plot, which is a way of graphically describing the distribution of the data. Data were plotted and analyzed using JMP Software. Quantile box and whisker plots are used to show quantiles of continuous distributions; the top and bottom portions of the boxes are the 25th and 75th quantiles, and the line across the middle of the box identifies the median sample value of the data set. The hollow circles represent the outliers of the data set. Outliers are defined for this purpose as data points beyond either the lower inner fence (1st quartile – 1.5*[3rd quartile –1st quartile]) or the upper inner fence (3rd quartile + 1.5*[3rd quartile – 1st quartile]) of box and whisker plots. The term "outlier" in this context conveys no judgment about the quality of the data point; it is only an observation about where it lies on the distribution. The whiskers above and below the boxes identify the maximum and minimum concentrations in the data set. The Quantile Box and Whisker Plots automatically generated by JMP can sometimes show additional quantiles (90th, 95th, or 99th percentiles) on the response axis (shown as horizontal lines between the box and max/min whiskers). If a distribution is normal, the quantiles shown in a box plot are approximately equidistant from each other. For example, if the quantile marks are grouped closely at one end, but have greater spacing at the other end, the distribution is skewed toward the end with more spacing. At the top of the box and whisker plots, the number of nondetectable samples in each category is given as "N(N)" as well as the number of detectable samples, "N(Y)".

The detected concentrations (in red) are graphed separately from ND concentrations (shown in blue at the reporting limit). In order to create the box and whisker plots, ranges of values for individual independent variables were selected. Ranges were selected to provide a tractable number of groups, to include a significant number of data points in most groups, and (when possible) to use familiar round values. In some cases where this presentation as box and whiskers for particular data ranges left unanswered questions, the data were also presented as XY graphs.

Probability and frequency plots were also used to assist in understanding the shape of the distribution (normal, log-normal, etc.). The plots were reviewed to determine if there were potential inflection points indicating a shift in the distribution of the data that suggested there may be two different populations, with different characteristics (e.g., one where VI was occurring and one without VI[4]).

Descriptive statistics for filtered data groupings of soil gas and indoor air will be presented and discussed in the final report for the following groupings. Subsets of these data groupings were selected based on professional judgment for discussion in this TM:

- By facility
- By facility and building
- By building use (shop/industrial, office, warehouse, mixed, etc.)
- By sample zone use
- By building size
- Be sample zone volume
- Be HVAC type
- By sample zone interior ceiling height maximum
- By sample zone interior ceiling height minimum
- By flooring type
- By presence/absence of exterior wall
- By sample zone exterior wall
- By sample zone preferential pathway
- By sample zone subgrade structures (type such as vault, utility trench)
- By groundwater concentration
- By distance to primary release
- By sample zone soil type
- By building footprint area and groundwater concentration

Frequency of Detection, Data Distributions, and the Effect of Nondetect Results

The usability of sampling and analytical data for performing EDAs and developing AFs is greatly influenced by the proportion of results that are not detected ("ND" or "U"-qualified) or below analytical reporting limits provided by the laboratories. All of the analytes considered for the EDA and development of AFs have various proportions of results below reporting limits (or "frequency of detections"). This section discusses how ND results affect the overall distributions of the data, and provides a recommendation for the proxy values that can be used in place of ND or U-qualified values for purposes of EDA and developing pairs of indoor and subslab samples for calculating AFs.

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[4] This approach has been used previously, see for example Hoddinott, K.B. Ed. "Superfund Risk Assessment in Soil Contamination Studies" 3rd Volume, ASTM, West Conshohocken PA 1998

The frequencies of detection for indoor air and subslab samples for the compounds of interest are shown in Tables 1 and 2.

PCE and TCE have the highest frequency of detection in both the indoor air and subslab samples, with 85 percent or higher detection frequencies in the subslab samples and approximately 50 percent detection frequencies in the indoor air samples. Detection frequencies for the other VOCs ranged from 3 to 50 percent in the indoor or subslab samples. Data sets containing increasing amounts of ND values are said to be "censored," and this needs to be considered and accounted for in the analysis (Gilbert, 1987). USEPA guidance provides various options for consideration when analyzing these censored data sets, depending upon the degree of censoring (USEPA, 2013; USEPA, 2009). Note also that there is overlap between the reporting limits for ND results and detected concentrations for some analytes (Tables 1 and 2). The potential for bias in the EDA and AF calculations introduced by ND results was explored through graphical analysis and evaluation of two of the three approaches for assessing ND data: (1) substitution (assigning a proxy value such as the reporting limit or one-half the reporting limit); (2) maximum likelihood estimation; and (3) non-parametric methods (Helsel, 2005). Maximum likelihood estimation is not included in this analysis, because it assumes that the data fit a theoretical statistical distributions. Goodness of fit tests were not performed on these data sets at this time.

This analysis focused on indoor air results for the select analytes and included the following steps:

- Prepare graphical plots (box and whisker plots and standard normal probability plots) of: (1) all indoor air results, which include detected results and reporting limit values for ND results; (2) detected concentrations only in indoor air; and (3) ND results only using reporting limits.
- Prepare order statistics for all indoor air results (detect and ND) using the Kaplan-Meier method. The Kaplan-Meier method is a non-parametric method derived from right-censored survival analyses in medical research, which is "flipped" to develop statistics for left-censored environmental data sets with multiple results below reporting limits (USEPA, 2013). The Kaplan-Meier method was used to calculate order statistics in USEPA's (2012) VI AFs database (USEPA, 2012) and used here as the "gold standard" for order statistics with ND values addressed using a state of the practice method. The Kaplan-Meier order statistics were compared with the order statistics based on all indoor air results and detected indoor air results to determine if including ND values created a bias in overall indoor air statistics.

The analyses of the effects of data censoring were conducted for four selected analytes: TCE, PCE, cis-1,2-DCE, and 1,1,1-TCA. These were selected to reflect a range of frequency of detection: TCE and PCE were detected at approximately 50 percent of indoor air samples, cis-1,2-DCE was detected in 27 percent of indoor air samples, while 1,1,1-TCA was detected in 11 percent of indoor air samples. These selected analytes were evaluated to provide examples of how censoring potentially affects usability of the data. These analyses are presented in Figures 1 through 4.

A comparison of the box and whisker plots (in Figures 1 through 4) indicated that, as expected, including ND values at the reporting limits shifts the distributions to the left, decreases the median, and lowers variability of the "all results" data set as seen by the smaller interquartile range (the "box") between the "all results" and "detects" populations. The probability plots (Figures 1 through 4) for the "all results" and "detects" populations generally look similar, both with inflection points at approximately the same points in the distributions. This suggests that the ND results have limited influence on the overall shape or distribution of the data. Comparison of the order statistics calculated with the Kaplan-Meier method and order statistics for all results shows a small (approximately 2-fold) increase in values at the lower percentiles, but that the statistics between the two methods for the upper percentiles (90th and 95th) generally are indistinguishable. The notable exception is cis-1,2-DCE, where a large proportion of ND results had a reporting limit of 10 micrograms per cubic meter (ug/m^3), which would be reflected prominently in order statistics of the "all results" data set.

The results from this analysis suggest that ND reporting limits can be used as the “result” value in the exploratory data analyses and AF calculations. Including ND results with reporting limits substituted as values for ND results provides a larger data set for EDA and allows calculation of more pairs of AFs. While including ND at detection limit values slightly decreases the overall distribution of indoor air concentrations, the individual reporting limit values provide more conservative AFs. This is conservative because the true indoor air concentrations with ND results are certainly lower than the reporting limit values. In addition, a comparison of “all results” with a method that formally estimates statistics accounting for censored values shows that censoring does not affect the upper percentile values in indoor air, and therefore does not affect the reliability of AFs based on upper percentile values. There will be some analytes, such as cis-1,2-DCE, where this approach will produce a high bias to indoor air concentrations, though a high bias to indoor air concentrations generally results in more conservative AFs.

Exploratory Data Analysis Results

More than 350 graphs were produced during this EDA, and a very rough draft of text was produced for use in the final report. It was not feasible, however, to provide that much material in a TM format at this time, so a summary of only select variables, graphs, and results is provided in this TM, with a focus on select information that: (1) highlights some of the more significant findings; and (2) can be used to select parameters and potential correlations that likely warrant further, more robust statistical evaluations. A more thorough discussion of all the EDA results will be included in the final report.

As such, it should be emphasized that where the authors have ventured ***preliminary*** interpretations in this TM they are indeed ***preliminary*** and will need more careful review and checking through independent lines of evidence before being used for Department of Defense (DoD) decision making. However, the authors offer those interpretations at this time to stimulate thinking among the team. Where the authors have noted that a certain trend holds for one contaminant (for example PCE) but does not hold for a closely related contaminant (for example TCE) with similar physical properties, that should be seen as clear evidence that more data analysis is required. Such results could occur because of indoor sources, or because one data set is dominated by a single nontypical base or building.

EDA was conducted at both the building and sample zone level. In some cases, two structures with minor points of attachment were considered separate buildings. The sample zone is defined as an enclosed location within a building where at least one indoor air sample has been collected. The conceptual idea that best represents the sample zone is a box. Ideally, a sample zone would have limited air mixing with other sample zones; however, further research is necessary to evaluate this assumption and this is outside the scope of this NESDI Project 476.

Overall Characteristics of Indoor Air Data Set--Comparing Frequency of Detections at Industrial and Residential Buildings

TCE and PCE were the most commonly detected chlorinated constituents in the indoor air data set, at 50 and 49 percent, respectively (Table 1). These percentages are similar to those reported in the USEPA (2011) background indoor air data set for residences (43 and 63 percent, respectively). The distribution of TCE at the DoD buildings contains a skewed upper tail, with a maximum value of 650 μg/m^3 (Figure 5). The distribution of PCE also shows a skewed upper tail, with a maximum value of 312 μg/m^3 (Figure 6). Exceedances of the risk-based industrial screening level[5] for PCE of 47 μg/m^3 were infrequent in the data set, while exceedances for TCE were more frequent.

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[5] Unless otherwise specified, all references in this document to risk-based industrial screening levels refer to the USEPA Regional Screening Level Table May 2014, TR=1E-6, HQ=1, and to the industrial air values. These screening levels may change in future years. Stable compounds that are below screening levels can still provide useful scientific data for the purposes of this project; however, the authors do discuss screening levels here

Cis-1,2-DCE a common biodegradation product of TCE and PCE and was detected in indoor air 27 percent of the time, which is 5-times higher than the 5 percent frequency of detection in the USEPA (2011) residential background data compilation (Figure 7). There is no current USEPA risk-based screening level for this compound.

Trans-1,2-DCE was detected in 28 percent of the indoor air samples, twice as frequently as the 14 percent detection frequency in the USEPA (2011) indoor residential background data set (Figure 8). Trans-1,2-DCE is more often used industrially than either cis-1,2-DCE or the commercial mixture of the two isomers (ATSDR, 1996). There is no current USEPA risk-based screening level for this compound.

1,1-Dichloroethene (1,1-DCE) was detected in 14 percent of the indoor air samples, which is similar to the 13 percent frequency of detection in the USEPA (2011) indoor residential background data compilation. All samples in the database were well below the current risk-based industrial screening level of 880 µg/m^3. The distribution appears to be bimodal (Figure 9).

Vinyl chloride was only detected in 6 percent of the indoor air samples, compared with 9 percent of the samples in the USEPA (2011) residential background data set. Vinyl chloride is aerobically degradable (AFCEE 2004). One hypothesis discussed later in this TM is that the aerobic degradation of vinyl chloride limits the migration into indoor air at significant concentrations.

1,1,1-TCA was detected in 11 percent of the indoor air samples, which was much lower than the 53 percent detection frequency in the USEPA (2011) background residential indoor air compilation (Figure 10). All of the detections in the samples for this project were orders of magnitude below the current risk-based screening level for industrial indoor air of 22,000 µg/m^3.

The most common biodegradation product of 1,1,1-TCA is 1,1,-DCA, which is also found in plastic products (NJDEP, 2103). 1-1-DCA was detected in 21 percent of the indoor samples, but only 1 percent of the time in the USEPA (2011) background residential data set (Figure 11). None of the samples in the authors' database exceeded the industrial indoor risk-based screening level of 7.7 µg/m^3, although a few approached that value.

1,2-Dichloroethane (1,2-DCA) was detected in 13 percent of the indoor air samples, similar to the 14 percent detection frequency in the USEPA (2011) indoor residential background data set. 1,2-DCA has a much lower current industrial risk-based screening level of 0.47 µg/m^3, which was exceeded in a few samples. The distribution appears to be bimodal (Figure 12).

Indoor Air Data Subdivided by Sample Zone Use

The database included information about the use of both the building and the sample zone. Sample zones are more likely to have a single type of use than buildings as a whole. However, even at the sample zone level, these distributions showed substantial overlap in concentration between use categories. For PCE some of the highest outlying values were found in both the industrial/shop and office categories, perhaps because office zones are frequently found in the same buildings where PCE was used/released. Warehouse uses show the highest outlying concentrations for cis-1,2-DCE and 1,2-DCA. 1,2-DCA is often associated with plastic products. 1,2-DCA can also be found as a solvent or a dilutent for pesticides, paints, coatings, and adhesives (Howard, 1990). Therefore, neither sample zone use nor building use as single variables are strongly predictive of indoor concentrations.

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for three purposes. First, a comparison of concentration distributions to screening levels provides a national perspective on the frequency with which concentrations that may be considered problematic, if attributable to subsurface soils in DoD buildings. Second, compounds for which concentrations above screening levels were observed have likely received the greatest attention in the underlying reports. Sampling and analysis strategies are often optimized in an attempt to provide information needed to compare results to compound-specific screening levels. The quality of available information about potential indoor sources and contaminant distributions in environmental media is likely to be best for those compounds approaching or exceeding screening levels. Third, to the extent that the factors controlling transport through the vadose zone and into structures differ by compound because of their differing physical properties, those compounds that commonly exceed screening levels merit prioritized scientific attention.

Indoor Air Subdivided by Flooring Type

The database contains information about the floor covering type, compiled at the sample zone level. For two of the constituents which frequently receive elevated scrutiny at VI sites (PCE and TCE, Figures 13 and 14), the highest indoor concentrations are usually associated with bare concrete or vinyl sheet flooring. It is unclear if this could be a causative mechanism (for example, sorption by the carpet, carpet backing, or wood) or whether this is a confounded observation. Confounding could occur because bare concrete and vinyl tile are flooring types associated with more industrial and utilitarian spaces, which are more likely to be proximate to the point of release of a significant volume of solvent than are office spaces. While new building materials can be a source of VOCs, those sources generally decline in strength markedly within a year after building construction or renovation. Therefore, the authors do not believe that building material emissions are likely to be the dominant influence in most of these buildings, given their ages. For most nonpolar VOCs, carpet provides higher sorption than either vinyl or wood flooring. In one test reported in the literature, wood flooring sorption for PCE was not observed, although some sorption to vinyl flooring was observed (Won et al., 2001). It appears that there is enough correlation between PCE and TCE and floor covering that this variable deserves additional data analysis and consideration of the literature to see if there is a causative mechanism here or merely correlation.

Indoor Air Grouped by Building Footprint Area

The median and 75th percentile detectable PCE indoor concentrations decrease significantly (by up to orders of magnitude) with increasing building size (Figure 15). This provides relatively strong evidence that larger buildings provide more volume for dilution in cases where either the VI occurs in only a portion of the building or where the strength of indoor sources is not proportional to the size of the building. For example, the same mass of volatiles would result in higher concentrations in a small building compared with a large building because of dilution and mixing. However the same pattern was not observed for TCE, 1,2-DCE, or 1,2-DCA. The trend is reversed for 1,1-DCA, where the detected concentrations appeared to increase with increasing building area. Thus further data analysis is required because a true physically based trend for PCE should at least be visible for TCE, given their similar chemical and biological behavior. One possible explanation is that concentrations influenced by one or more indoor sources are dominating one or more of the building footprint area classes or for one or more compounds.

Indoor Air Grouped by Maximum Building Ceiling Height

Ceiling height could have two potentially opposite effects: the strength of the stack effect[6] is proportional to the square root of the building height (Hui, 1993, ITRC 2007); therefore, taller buildings would be projected to have more soil gas entry; and all other factors being equal, increased ceiling height on the ground floor should decrease indoor concentrations, when those concentrations are attributable to VI though the floor because a greater volume of indoor air is available for dilution (ITRC, 2007). This ceiling height concept is covered in the Johnson and Ettinger model with a term for the mixing zone height (Environmental Quality Management, 2004).

The potential for VI to occur through building walls would be an additional complicating factor in this analysis since greater ceiling heights would correspond to more wall area for infiltration. Building walls can be a source of VI in buildings with hollow block construction for example.

The PCE and TCE data sets (Figures 16 and 17) suggest that maximum indoor air concentrations may be associated with intermediate (11- to 30-foot) ceiling heights. Note also that the percentage of indoor air

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[6] Stack effect is the movement of air into and out of buildings, chimneys, flue gas stacks, or other containers, resulting from air buoyancy. Buoyancy occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences.

samples with a detectable concentration is greater with intermediate ceiling heights. That is a theoretically possible outcome when two separate effects are moving in opposite directions. This trend was not observed for 1,2-DCA.This analysis should therefore be continued to make sure that indoor sources are not influencing the conclusions for this variable.

Indoor Air Grouped by Sample Zone Volume

A working assumption about the definition of sample zone used in this project is that air is expected to be reasonably well and rapidly mixed throughout the zone (and perhaps over a larger volume, up to and including the full building in some cases). Conceptually, indoor air concentrations should decrease as sample zone volume increases if all other variables are constant and if the source is due to a discrete activity or a preferential pathway, or if vapors are intruding through only a portion of the floor. As shown in Figure 18, the maximum, 75th percentile, and median PCE concentrations among detected samples generally appear to decrease with sample zone volume, above 12,000 cubic feet (ft^3), a typical volume of a modest single family home. Frequency of PCE detection was also highest in the smallest sample zones; 77 percent of the samples from zones under 3,600 ft^3 were detectable, but only 17 percent of the samples collected in the largest zones (over 136,800 ft^3) were detectable. Thus the trends in percentage detectable samples and in the maximum, 75th percentile, and median agree for this parameter.

The trend for TCE, however, was substantially different (Figure 19). The group of sample zones with the largest volumes (>600,000 ft^3) had the highest median and 75th percentile concentrations. The group of sample zones with the largest volumes also had the highest frequency of TCE detection (75 percent of 54 total samples). For perspective, this largest group of sample zones in the database can be visualized as being larger than a floor the size of an American football field[7] with a 10-foot ceiling. This conflict between the PCE and TCE trends points to a need to further analyze the data set. It is possible, for example, that the trends are being driven by indoor sources or by a small number of buildings in some cases. A strong TCE flux source would be needed to sustain high concentrations of TCE in these large spaces, especially considering that the air exchange rate of large open buildings such as factories, garages, and warehouses tends to be medium to high[8]. Ventilation rates for new DoD buildings are generally required to comply with ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62.1[9].

The trends for cis-1,2-DCE and 1,2-DCA are much less pronounced, suggesting that indoor concentrations for these compounds are largely independent of sample zone volume. The authors will need to review this conclusion to see if this could be an artifact of a lower detection frequency in the data set.

Indoor Air and Subslab Grouped by Presence or Absence of an Exterior Wall

Figures 20 and 21 present the results of an analysis of indoor concentrations as a function of the presence or absence of an exterior wall in the sample zone. For PCE there appears to be little difference in the medians, but the 75th percentile and 90/95th percentiles appear to be five times or more higher in sample zones with exterior walls. The trend for higher concentrations in sample zones with exterior walls is more pronounced for TCE – exterior walls are 10 times or more higher. At first glance, these observations seem contrary to physical expectations, which would be for exterior zones to be associated with more dilution by exterior air and less significant building capping effects. One possible confounded explanation is that exterior wall

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[7] Dimensions of football fields can be found at http://turf.missouri.edu/stat/reports/fielddems.htm

[8] Recommended design air exchange rates for these spaces are typically greater than 2 air exchanges per hour see: http://www.engineeringtoolbox.com/air-change-rate-room-d_867.html. Testing of a series of DoD zones with volumes between 9,900 ft^3 and 27,600 ft^3 using a variety of methods generally showed air exchange rates between 0.5 and 2 per hour. See Tetra Tech "Final Report on Air Exchange Rate Analysis and Protocol Development" submitted to AFCEE, February 2012. http://rd.tetratech.com/vaporintrusion/projects/doc/AER_Study_Report_Final.pdf

[9] Unified Facilities Criteria "Heating, Ventilating and Air Conditioning Systems" UFC 3-410-01, July 1, 2013 http://www.wbdg.org/ccb/DOD/UFC/ufc_3_410_01.pdf

sample zones are more common in smaller buildings. It is possible that sample zones with exterior walls are subjected to greater wind-related driving forces for VI. The presence of exterior walls appears to have little influence on concentrations of cis-1,2-DCE and 1,2-DCA. As discussed previously, this may indicate a potential confounding effect from indoor sources. The behavior of cis-1,2-DCE could also differ from that of TCE and PCE due to aerobic biodegradation (AFCEE, 2004).

The presence of an exterior wall also appears to increase the risk of very high subslab concentrations for TCE and PCE (Figure 22). The mechanistic explanation for this observation is not immediately apparent and thus this finding requires further consideration.

Indoor Concentrations Grouped by Preferential Pathway

The observation of preferential pathways by field staff is not standardized. The coding of preferential pathway data into the database is thus subject to a misclassification bias. Figure 23 presents the data segregated by the presence or absence of atypical preferential pathways for VI. TCE is the only constituent for which a notable effect of preferential pathways was observed in the expected direction (that higher concentrations would be associated with preferential pathways). Further work is ongoing to perform a more refined analysis of preferential pathways that attempts to overcome these data collection and coding problems.

Indoor Air and Subslab Soil Gas by Presence of Subgrade Structures

Normally subgrade structures would be expected to increase the risk of VI where groundwater or deep vadose zone sources are involved because they reduce the vertical separation between source and the indoor environment. In none of the cases examined did the presence of a subgrade structure appear to increase indoor concentrations; therefore, in the interest of brevity, these graphs are not presented. However, the presence of subgrade structures actually appears to reduce subslab concentrations for TCE and PCE (Figure 24) (as well as indoor concentrations to a lesser extent). Further examination of this phenomenon may be useful.

Indoor Air by Groundwater Concentration Ranges

Groundwater concentrations were recorded in the database in four groups:

- Measured maximum concentration within 100 feet of the sample zone
- Measured minimum concentration within 100 feet of the sample zone
- Interpolated maximum concentration under sample zone
- Interpolated minimum concentration under sample zone

Interpolation of groundwater concentrations under the sample zone was almost always based on monitoring wells located exterior to the building. Therefore, any such interpolation would not generally take into account any increase of groundwater concentration beneath the building that would be attributable to the capping effect of the building (Schumacher, 2010).

According to the data dictionary, groundwater concentrations were only to be recorded in the database if they exceeded the reporting limit by ten-fold. Groundwater concentrations were in most cases only included in the database for the one or two most important compounds at any given site. Groundwater concentrations were not entered into the database in many cases where evidence of a vadose zone source for the subslab soil gas concentrations was clear.

In order to determine if there was a systematic relationship between the groundwater concentration in the shallowest layer and indoor air concentration, groundwater data were grouped by multiples of USEPA's

(2014) VISL for groundwater[10]. In addition to providing convenient bins, this also allowed an opportunity to examine the usefulness of the VISL approach. The groundwater VISL takes into account toxicity considerations, a generally conservative AF assumption (0.001), and physical partitioning relationships between groundwater and soil gas (Henry's Law)[11]. Recall that these conservative AFs are based on residential data sets and the authors' objective is to show that a less conservative AF can be appropriately used at DoD commercial buildings. USEPA anticipates that there are a specific set of circumstances under which their groundwater VISLs would not be conservative:

- *"Very shallow groundwater sources (for example, depths to water less than 5 ft below foundation level):*
- *Shallow soil contamination vapor sources (for example, sampled at levels within a few feet of the base of the foundation)*
- *Buildings with significant openings to the subsurface (for example, sumps, unlined crawlspaces, earthen floors) or significant preferential pathways, either naturally-occurring or anthropogenic (not including typical utility perforations present in most buildings).[12]"*

An indoor source would also produce a result in which it would appear that the groundwater VISL might not be conservative because in that case there would be no logical or mechanistic relationship between the groundwater concentration and indoor concentration. In the following sections, these analyses are discussed by compound.

Note that this preliminary data analysis lumps together sites/zones where only a groundwater source is present, along with areas where a vadose zone source is also present or even predominates. Recall that most of the sites included in this database have relatively shallow groundwater. In most cases at older chlorinated hydrocarbon sites, some equilibration will have occurred so some concentrations will be present in both the vadose zone and groundwater. Further data analysis is planned in an attempt to isolate cases where the primary release did not occur in or at the sampled building. However, the number of such cases in the database may be limited.

PCE in Indoor Air and Subslab as a Function of Groundwater Concentrations

As shown in Figure 25, the maximum interpolated groundwater concentration appears to predict indoor air concentrations of PCE that exceed the industrial indoor air screening level of 47 µg/m^3. Interpolated maximum groundwater concentration was entered into the database to one significant figure. On that basis, no groundwater concentrations below 1000 micrograms per liter (µg/l) are associated with indoor air concentrations above this screening level (80 data points). Indeed, even among sites with interpolated groundwater concentrations above 1000 µg/l, about 75 percent of the indoor air samples are below the screening level.

As shown in Figure 26, the results using maximum measured groundwater concentration are quite similar – none of the 68 samples with maximum measured groundwater concentrations below 326 µg/l have indoor air concentrations near the current industrial indoor air screening level. An XY graph view of the maximum measured groundwater concentrations provides more insight into this observation (Figure 26). Among all sites, no PCE concentrations above the indoor air screening levels are found at sites with groundwater concentrations below 700 µg/l PCE. Only MCIEAST-MCB CAMLEJ has any indoor concentrations above the industrial screening level regardless of the groundwater concentrations (blue circle on figure). In general, the XY plot shows a general trend of higher indoor concentrations being associated with higher maximum

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[10] In the case of cis-DCE, which does not currently have a USEPA regional screening level, and thus does not appear in the VISL calculator, the authors substituted a set of equivalent values derived from California DTSC Office of Human and Ecological Risk, HHRA Note 3; May 21, 2013; cis-1,2-DCE 31 µg/m^3 from Table 3 "Industrial Air Screening Level Calculated using RSL Calculator". VISLs were calculated using USEPA OSWER Vapor Intrusion Assessment Vapor Intrusion Screening Level (VISL) Calculator Version 3.3.2, May 2014 RSLs.

[11] USEPA, Vapor Intrusion Screening Level (VISL) Calculator User's Guide, May 2014

[12] USEPA, Vapor Intrusion Screening Level (VISL) Calculator User's Guide, May 2014.

measured groundwater concentrations. However, it also shows that as the groundwater concentration increases the width of the range of corresponding indoor air concentrations also appears to increase. Although the highest indoor PCE concentrations occur at MCIEAST-MCB CAMLEJ, some data points at Little Creek and Hill have relatively high indoor concentrations corresponding to modest groundwater concentrations. These ratios will be explored in more depth in the AF section of the final report.

Subslab PCE concentrations also increase with increasing groundwater concentrations; in the interest of brevity, figures are not provided. Whether the observed subslab concentrations are attributable to vadose zone sources, groundwater sources, or both has not yet determined in this analysis.

TCE Indoor Air and Subslab Concentrations as a Function of Groundwater Concentrations

The VISL for TCE in indoor air is only 3 µg/m^3, which makes site screening on the basis of groundwater concentrations more challenging for the practitioner than it is for PCE. When the indoor concentration data are analyzed in terms of the maximum measured concentration (Figure 27), higher indoor air concentrations are associated with higher groundwater concentrations, as expected. It can be seen that:

- At concentrations below approximately 100 µg/l, there appears to be little relationship between groundwater concentration and indoor air concentration, except for a few outlying points, circled in green. The authors intend to further analyze those points to determine if they may be associated with indoor sources or atypical preferential pathways.
- Increased measured maximum groundwater concentrations are generally associated with increased indoor air concentrations once TCE concentrations exceed approximately 100 µg/l (orange hand-interpreted line on graph). However, there is considerable scatter in the data correlation, so that any given elevated groundwater concentration range corresponds to a wide range of indoor air concentrations.
- The highest detectable indoor air concentrations relative to the groundwater concentrations are primarily seen at MCIEAST-MCB CAMLEJ and NAS Jacksonville.
- Outliers above the general trend are observed at four different sites (green and blue ovals) and will be further reviewed.

The database contains at least 15 samples; where based on groundwater results, screened using USEPA's conservative VI screening levels, the practitioner would have considered that there might be a VI concern and nondetectable indoor air results with reporting limits above the screening level were obtained. Thus the data obtained in those cases were not sensitive enough to answer the question definitively under current regulatory criteria (at least based on current conservative screening levels). The authors can further analyze this subset in an attempt to determine why such inconclusive indoor air results are so common.

Subslab TCE concentrations also increase as expected with increasing groundwater concentrations; in the interest of brevity, figures are not provided at this time. At this level of analysis, it is not clear if these subslab concentrations are attributable to indoor air or groundwater or both.

Indoor Air Concentrations as a Function of Soil Type

For the highly chlorinated ethane compounds PCE and TCE, higher indoor air concentrations appear to be associated with fine-grained soils (Figures 28 and 29). In cases where the point of release is in or near the building sampled, fine-grained soils have a greater tendency to trap contaminants in the vadose zone near the building and would tend to diminish the effectiveness of natural attenuation processes such as volatilization attributable to barometric pumping[13]. In contrast to the USEPA (2011) residential database where residences are located distant to the primary release, it is reasonable to assume that a number of the

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[13] Barometric pumping in this context means that as the barometric pressure varies, air flows from the atmosphere into shallow soil or vice versa.

buildings in this database are located near or over the primary vadose zone release, which would need to be confirmed with further evaluation. This trend appears to hold, but to a lesser extent for the degradation product cis-1,2-DCE, the highly chlorinated chlorinated ethane TCA, and the degradation product 1,1-DCA.

Similar relationships in which higher concentrations are associated with fine soils are observed in the subslab data for PCE, TCE, 1,1,1-TCA (figures omitted from this interim TM for brevity, but will be presented in the final report).

Relationships between Source Strength or Distance to Primary Release and Indoor or Subslab Concentrations

Distance to the primary release appears to strongly influence the maximum, 75th percentile, and frequency of detection for PCE in indoor air, as would be expected for VI processes (Figure 30). This relationship is not observed for TCE indoor air in the current analysis. This suggests that further analysis of the TCE indoor air data set is needed, for example to determine if indoor air sources are biasing this trend. The amount of available data for cis-1,2-DCE is insufficient for a fruitful analysis of this variable. In subslab soil gas, the median concentration markedly declines at distances to the primary release over 100 feet for both PCE and TCE.

Analysis suggests that the relationship between indoor air and subslab source strength for TCE is nonlinear (Figure 31). There is only one detectable value above the regional screening level (orange circle in figure) associated with a subslab concentration below 100 $\mu g/m^3$. The general trend (green manually drawn line) shows that an apparent inflection point is reached near 1,000 $\mu g/m^3$. As shown in Figure 32, the points where the indoor air concentration is above the screening level and the subslab concentration is between 100 and 10,000 $\mu g/m^3$ are drawn from only two facilities (yellow circle, Figure 32). Those data points require further examination. It is possible that they result from large area sample zones, where a single indoor air sample was plotted vs. multiple subslab concentrations within the zone.

The relationship with source strength was even more dramatic for PCE (Figure 33). The PCE concentration in indoor air appears to increase only as subslab soil gas concentrations exceed 100,000 $\mu g/m^3$. Only one sample in the whole database was above the indoor screening value for PCE and did not have at least 100x attenuation across the building envelope. That orange circled data point in Figure 10 came from an office in a garage at Camp Lejeune: a small space (400 square feet) with bare concrete floor and no HVAC. That data point is also the only indoor value exceeding the screening level with a subslab concentration of PCE below 100,000 $\mu g/m^3$

Future analyses will combine both source strength and distance to release point in a multivariate analysis. For example, Figure 34 shows how TCE concentrations in indoor air relate to the maximum groundwater vapor concentration (the deep soil gas concentration calculated based on Henry's Law from the maximum groundwater concentration). It shows that screening level exceedances in indoor air occur only with high source strength combined with short distances to the point of release.

Procedures for Assessing Attenuation Factors and Evaluating Background Sources

The terminology used in this section was selected to be as consistent with USEPA terminology as possible to enhance comparability between the databases.

Pairing of Data for Attenuation Factor Calculations

1. The database is structured in sample zones, with associated groundwater, subslab, and indoor sample types.
2. AF calculations are based on data pairs where both samples were collected within 14 days. Where multiple data pairs are found for a given time window, the analysis includes only the most contemporaneous subslab or groundwater point for a given indoor air observation.
3. Where more than one subslab or indoor air sample is present within a sample zone, AFs are calculated as follows:
    a. Use the mean indoor and subslab concentrations within the zone, which results in a single AF per sample zone.
    b. Pair each indoor sample with every other subslab sample in a zone. For example, six AFs would be calculated if a zone has two indoor and three subslab sample locations.

Background Screening Procedures

1. The number of data pairs before and after background screening will be provided in the final report for each step in the screening process.
2. Data pairs with subslab or groundwater concentration below detection limits were excluded (termed the "subsurface concentration screen" by USEPA). Note, however, that ND reporting limits were used when calculating mean subslab concentrations, whereas one-to-one pairs with ND subslab concentrations were excluded.
3. Information about a background source(s) provided in site reports was reviewed. The "Background" table in the database was a repository for this type of information. There are few entries, with most of these pertaining to outdoor/indoor results comparisons. This likely reflects the content of the referenced reports, as few of these explicitly address background. The reports often contain survey information, but the information in the database is there only if a specific source was identified as important in the report narrative.
4. Indoor-to-subslab ratios were calculated for different analytes. Analytes with ratios one order of magnitude[14] or more different than the other analytes indicate the potential influence of a background source. Graphs summarizing the indoor and subslab results by sample zones and dates help expedite the review of this information. This step is the equivalent of the USEPA (2012) data consistency screen. Data are compared with site-specific ambient concentrations where available to assess the potential for outdoor air background sources. Data pairs where the indoor concentrations were less than two-times the ambient concentration are excluded from the AF calculations given the likelihood that ambient air is the primary source of the measured indoor concentrations. Steps 1 through 4 define what USEPA (2012) calls the "**Baseline screen.**"
5. Consistent with USEPA (2012), a subslab source strength screen will be implemented to determine if there is a subsurface source concentration below which the influence of VI cannot be reliably assessed. The USEPA (2012) source strengths of 50x for subslab and 1000x for groundwater vapor will be used. This involves calculating values 50-times the indoor air background concentrations as described below. Subslab locations with concentrations < 50x background levels are excluded. Groundwater concentrations are converted to a deep soil gas equilibrium concentration using Henry's Law at an assumed temperature of 20 degrees Celsius and then "groundwater vapor" locations with concentrations <1000x the indoor air background are excluded. The source strength screen is

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[14] USEPA database report page 25 (USEPA, 2012)

implemented at a building level, not at sample zone level because VI that occurred in a room adjacent to the sample zone could influence the sample zone indoor air concentration.

6. The background screening step will be implemented by excluding all indoor air data less than the 90th percentile of the BASE study indoor air distribution (NYSDOH Appendix C-2, NYSDOH, 2006). This is consistent with how background was defined in USEPA (2012). If the BASE study 90th percentile is a less than value, indicating detectable indoor air concentrations were rarely found in that study at its elevated detection limits, then the median of 90th percentile concentrations from multiple residential studies was used instead, as done by USEPA (2012). If both studies have a 90th percentile less than value, no data will be screened out for background for that compound.

Summary of Exploratory Data Analysis

As noted earlier, the ultimate goal of the project is to develop a VI decision framework (relationships, decision rules, and other guidelines) and recommendations to incorporate into Navy VI guidance documents, training, or other evaluation tools. The objectives of this TM were to summarize the results of the EDA, identify potential patterns that may affect VI and warrant further or more detailed evaluations for the final report, and provide an overview of the methods for further analyses. A summary of findings from the EDA conducted herein is provided in this section, with a focus on the variables, analyses, and findings warranting further analyses and are most likely to provide the greatest value in further refining the Navy's Quantitative Decision Framework and useable insights to Navy project managers or regulators. Ideally, these insights will be mathematically simple enough to be reduced to rules of thumb that can be conveyed through guidance and training, as well as being incorporated into the Navy's Quantitative Decision Framework. The most significant findings and insights from the EDA summarized in this TM and that warrant further consideration include:

- Relationship Between Sampling Zone (or Building) Size to Indoor Air Concentrations: PCE indoor concentrations decrease significantly (by up to orders of magnitude) with increasing building size (Figure 15). This is consistent with the hypothesis that larger buildings provide more volume for dilution in cases where VI occurs in only a portion of the building. For example, the same mass of volatiles would result in higher concentrations in a small versus large building because of dilution and mixing. A similar pattern was seen for PCE with sample zone footprint. However, the same pattern was not immediately apparent with the other VOCs. Further data analysis is warranted based on the strength of the mechanistic arguments and the observed trend with PCE.

- Relationship of Subslab to Indoor Air Concentrations: As shown (Figures 31 through 33), plots of subslab versus indoor air concentrations generally display a "hockey stick" shape with an inflection point. These plots indicated that subslab concentrations in the lower range (below the inflection point) have no apparent effect on indoor air concentrations, suggesting that in this range the measured indoor air concentrations are background-related. Subslab and indoor air concentrations at or above the inflection points appear to be correlated. The inflection point for industrial buildings is generally considerably higher than would be implied by current regulatory approaches, such as the USEPA VISLs (2014) or in various state guidance or screening levels. The authors expect to be able to express the outcome of the analysis, both as industrial building subslab screening levels for PCE, TCE, and other compounds, and AFs that will be less conservative than those derived from residential datasets.

- Relationship of Groundwater to Indoor Air Concentrations: Plots of groundwater versus indoor air concentrations show indoor concentrations as usually relatively constant until an inflection point is reached (Figures 25 through 27). This pattern appears to be present even before completing the background screening steps or fully considering the proximity of vadose zone sources. Similar to the pattern observed with subslab versus indoor air concentrations: (1) groundwater concentrations below the inflection points appear to have no apparent effect on indoor air concentrations; (2) it is conceivable that concentrations at or above the inflection points may be correlated; and (3) the inflection point for industrial buildings is generally considerably higher than would be implied by current regulatory screening approaches. The authors expect to express the outcome of the analysis, both as industrial groundwater screening levels for PCE, TCE and other compounds and AFs that will be less conservative than those derived from residential datasets.

- Soil Type: Plots of soil type versus indoor air concentrations suggest that indoor air concentrations may be higher for buildings with fine soils than coarse soils (Figures 28 and 29). One possible explanation for this may be related to the differences in adsorption, natural attenuation, and/or volatilization of VOCs in fine versus coarse grained soils, particularly for those buildings located above or near a primary vadose zone release. This outcome may be useful when prioritizing Navy buildings for investigation.
- Exterior Wall: A review of the EDA results potentially suggested that higher indoor concentrations may be more frequent in sample zones with an exterior wall (Figures 20 and21). This trend was also potentially the case with subslab concentrations. The potential causative mechanism (e.g., an effect of wind pressure on exterior walls or an effect of the thickened foundation elements that are generally present beneath exterior walls) is uncertain. While this was an unexpected finding, it warrants further investigation to determine if it can or should be factored into the building or sample zone prioritization procedures.
- Source Strength and Distance vs. Indoor Concentration: As shown in Figure 34, source strength and distance appear to correlate with the potential for significant indoor air impacts and warrant further analysis. Source strength and distance are likely to be useful parameters for consideration when prioritizing buildings and investigating VI impacts.

Predicting VI due to a distant soil gas or groundwater source is a complex multi-step process. Therefore, it was not surprising that some of the single variables explored did not in and of themselves appear to be good predictors of indoor air concentrations from VI. There are inherent uncertainties for some variables in the individual site reports that were used to populate the NESDI database. In many cases there is such a multiplicity of types and conditions present in the field that simple classification into a small number of bins was challenging and further evaluation may not be warranted for this project. Examples could include variables such as the HVAC type and flooring material.

The EDA conducted and summarized in this TM suggested the possibility of focusing VI evaluations on a number of key compounds. For example, the EDA suggested that subsurface sources of vinyl chloride do not generally result in significant VI impacts, which may be related to its aerobic biodegradation potential. 1,1,1-TCA concentrations, while somewhat more frequently detected, were well below risk-based screening levels, so discriminating VI from background sources may not be needed.

Next Steps in the Analysis

Building on the exploratory data analysis presented in this TM and any feedback received from the Navy staff and project advisors, the authors plan to undertake the more rigorous portion of the data analysis. The findings summarized above will be further supported by four types of evidence/analyses:

- Graphical: Multiple graphical presentations of the data will be used to further support the findings by looking for consistent evidence across compounds. This may also include presentations before and after various screens intended to remove potential background sources or other potential influences/confounding factors.

- Statistical Hypothesis Testing: Appropriate statistical tests will be conducted to further support/validate the key findings summarized in this TM. No one statistical test will be appropriate because some of the variables are continuous and others are categorical. Among the tests that may be applied are t-tests, ANOVA (analysis of variance), tests of regression coefficient significance, and nonparametric hypothesis tests.
- Physical Mechanism: Key conclusions should have a plausible underlying physical mechanism that may be supported by first principles or the VI literature.
- Case Study: Each key conclusion will be reviewed to determine which bases/buildings provide the key data that drive the observed relationships. Conclusions that hold even if a single base/building is removed from the data set will be considered to be more robust. As necessary, persons with experience at the key facilities will be consulted to determine if the observed relationships and mechanisms are plausible at the individual facility level.

These further analyses will include an evaluation of whether background sources, preferential pathways, or other potential variables influence the findings summarized in this TM. The database is set up to allow it to be screened sequentially to remove data points judged most likely to be influenced by background sources. Similarly, the data set can be re-examined after a screen to remove those sample zones where the influence of atypical preferential pathways may be affecting the interpretation of the results.

As described earlier, the additional analyses will include an assessment of inflections points, as well as calculating AFs specific to industrial buildings.

The final report will incorporate the findings into the Navy's Quantitative Decision Framework in order to advance the management of Navy VI sites, as well as inform the broader national conversation about the appropriate management of VI potential in commercial and industrial structures. The database developed in this project was developed with the expectation that it can be expanded and used to address additional technical and program management questions.

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Tables

TABLE 1

Frequency of Detection of VOCs in Indoor Air Samples

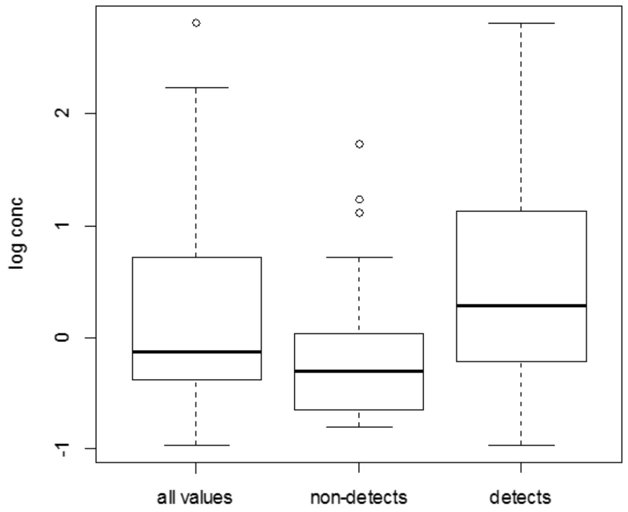
Analyte	Total Number	Number Detects	Frequency of Detection	Indoor Air Concentrations (ug/m^3)			
				Minimum Detected	Maximum Detected	Minimum Reporting Limit	Maximum Reporting Limit
1,1,1-Trichloroethane	101	11	11%	0.14	7.7	0.27	5.2
1,1-Dichloroethane	126	27	21%	0.014	5.2	0.015	3.9
1,1-Dichloroethene	245	34	14%	0.017	13	0.016	160
1,2-Dichloroethane	218	29	13%	0.0405	2	0.20	160
cis-1,2-Dichloroethene	216	58	27%	0.083	180	0.2	40
Tetrachloroethene	202	99	49%	0.041	312	0.22	6.5
trans-1,2-Dichloroethene	231	65	28%	0.0075	350	0.015	160
Trichloroethene	270	134	50%	0.11	650	0.16	54
Vinyl Chloride	261	15	6%	0.0044	0.072	0.0072	100

TABLE 2

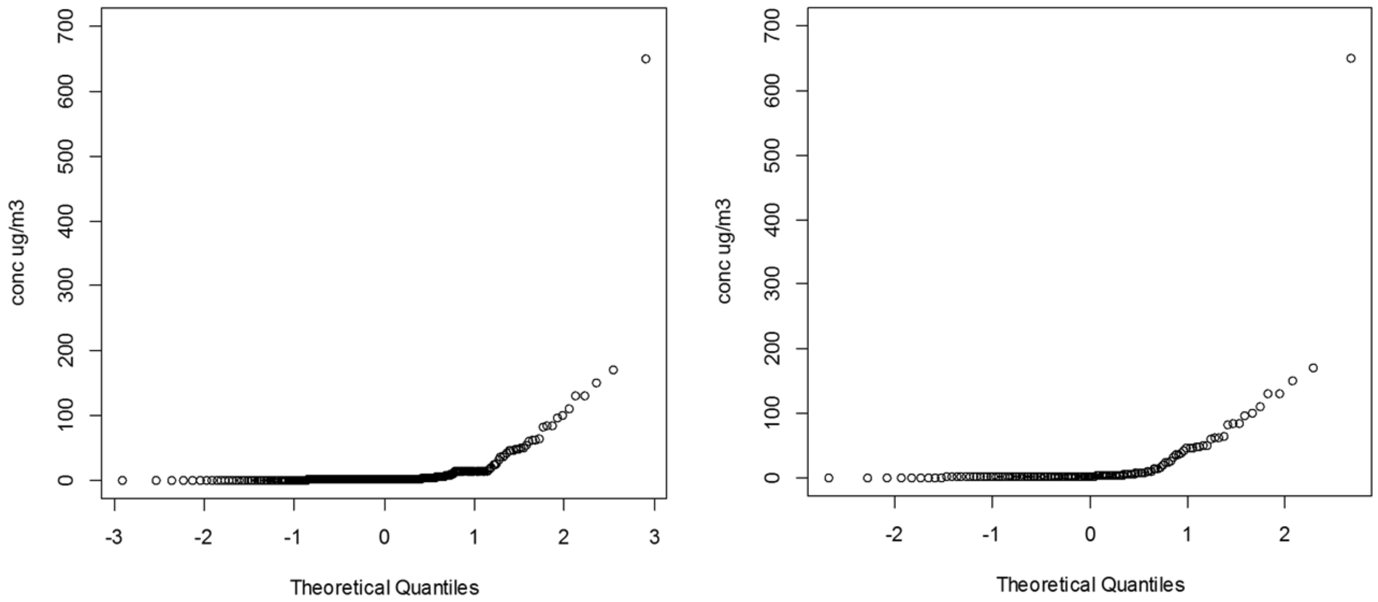
Frequency of Detection of VOCs in Subslab Soil Vapor Samples

Analyte	Total Number	Number Detects	Frequency of Detection	Subslab Soil Vapor Concentrations (ug/m^3)			
				Minimum Detected	Maximum Detected	Minimum Reporting Limit	Maximum Reporting Limit
1,1,1-Trichloroethane	150	96	64%	0.2728	530,000	1.1	60,021
1,1-Dichloroethane	142	59	42%	0.6	96,000	0.81	44,522
1,1-Dichloroethene	263	46	17%	0.74	114,980	0.19	280,000
1,2-Dichloroethane	269	6	2%	0.4047	2.1	0.18	280,000
cis-1,2-Dichloroethene	213	95	45%	0.13	475,779	0.19	280,000
Tetrachloroethene	219	202	92%	0.5494	16,956,033	1.15	10,852
trans-1,2-Dichloroethene	244	87	36%	0.1	110,000	0.18	280,000
Trichloroethene	260	222	85%	0.095	7,000,000	0.18	1,666
Vinyl Chloride	272	7	3%	0.088	40,000	0.18	180,000

Figures

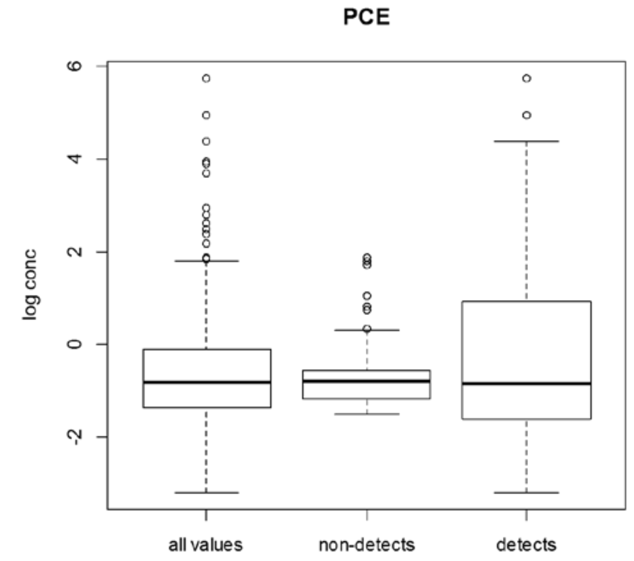


TCE			
	KM	All Results	Detects
25th	0.13	0.42	0.62
50th	0.42	0.75	1.9
75th	2.6	5	13
90th	31	31	61
95th	62	61	97


TCE all results

TCE detects

Figure 1. Graphical Analysis and Order Statistics of TCE Indoor Air Data



PCE

	KM	All Results	Detects
25th	0.13	0.26	0.2
50th	0.20	0.44	0.43
75th	0.47	0.9	3
90th	3.2	4	11
95th	11	11	41

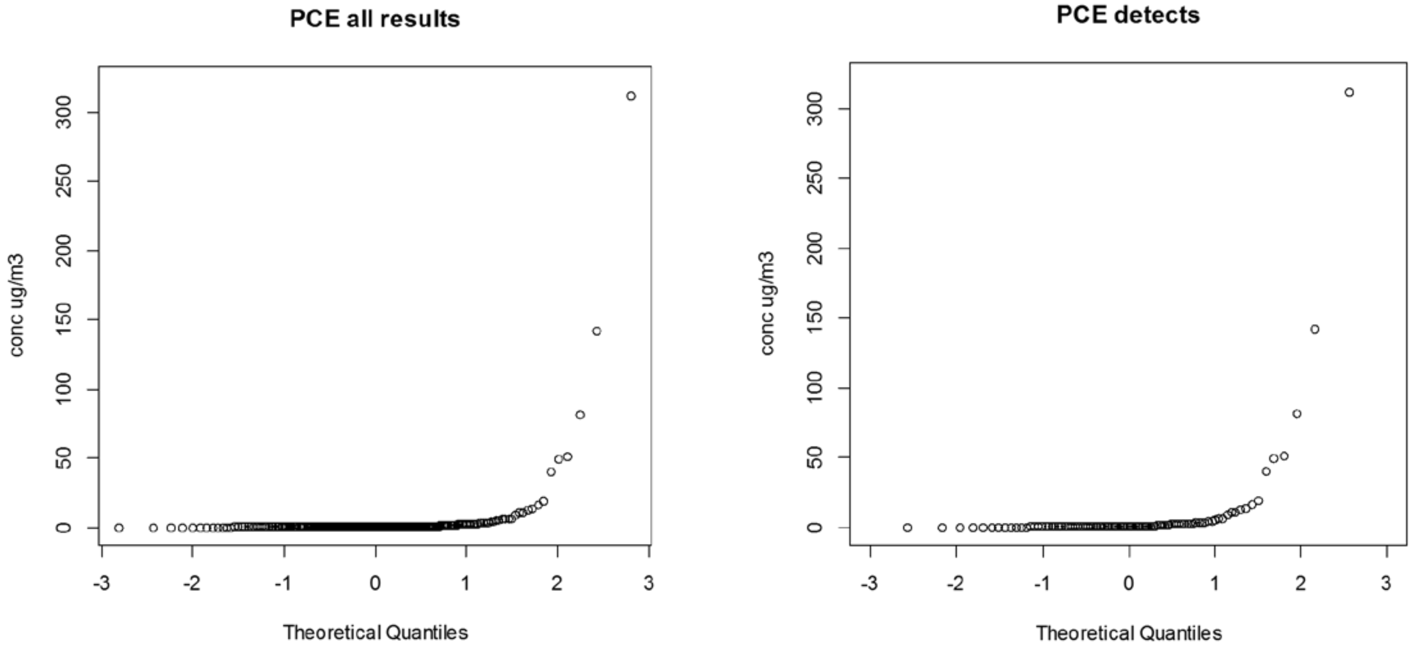
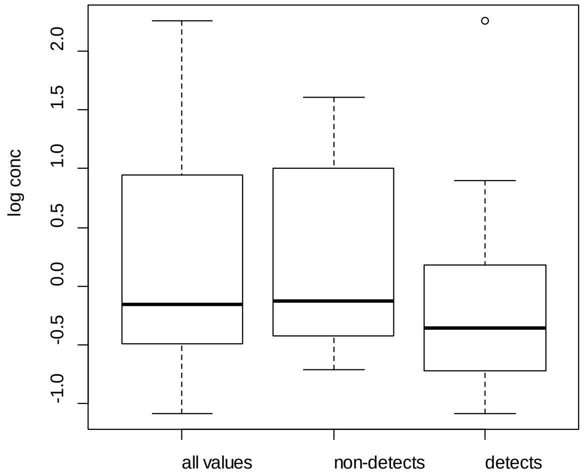
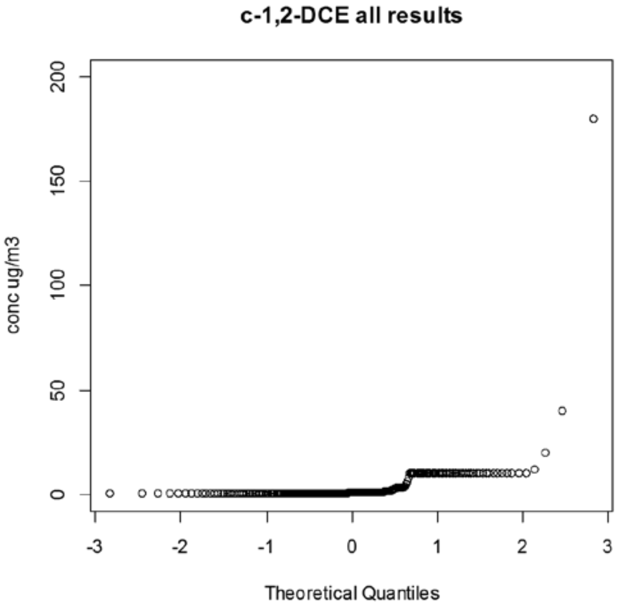


Figure 2. Graphical Analysis and Order Statistics of PCE Indoor Air Data



C-12-DCE

	KM	All Results	Detects
25th	0.11	0.32	0.19
50th	0.20	0.70	0.44
75th	0.26	8.4	1.5
90th	1.4	10	3
95th	3	10	5



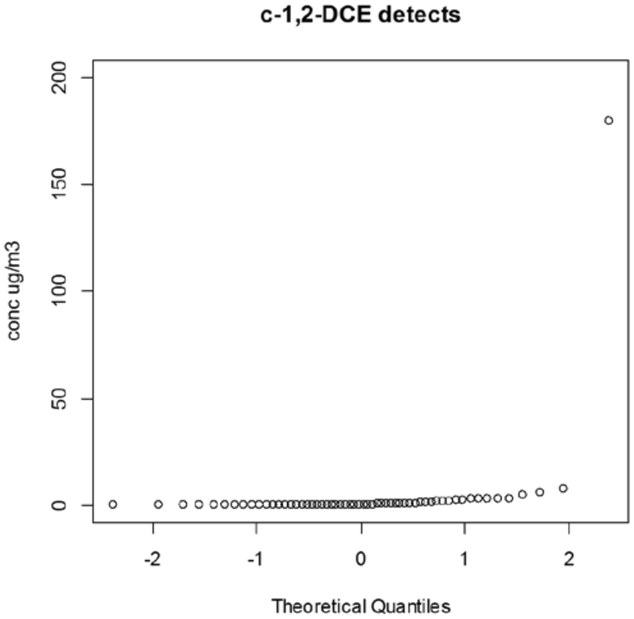
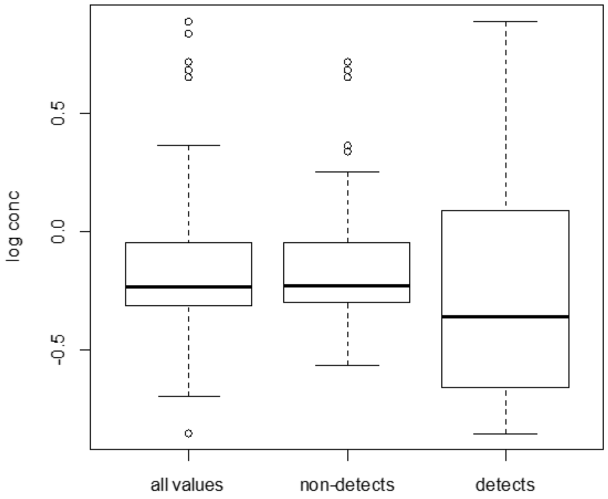


Figure 3. Graphical Analysis and Order Statistics of cis-1,2-DCE Indoor Air Data



1,1,1-TCA			
	KM	All Results	Detects
25th	0.20	0.48	0.22
50th	0.22	0.58	0.44
75th	0.23	0.90	1.34
90th	0.44	1.36	6.9
95th	0.51	2.3	7.3

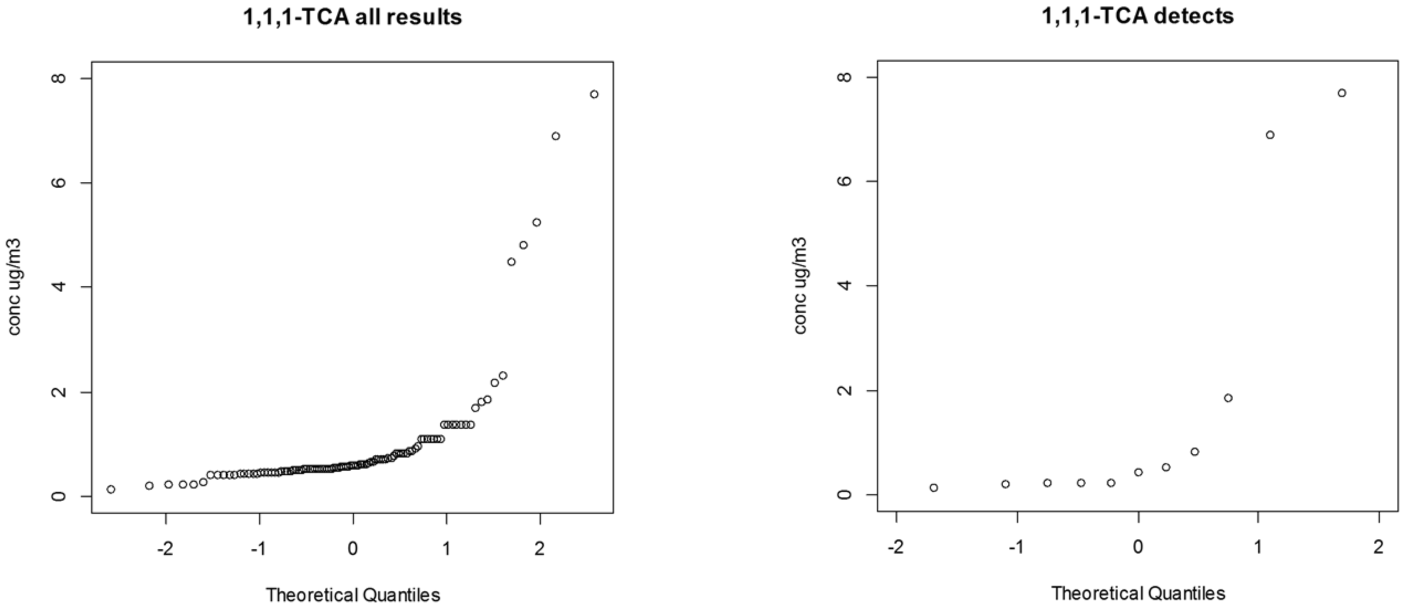


Figure 4. Graphical Analysis and Order Statistics of 1,1,1-TCA Indoor Air Data

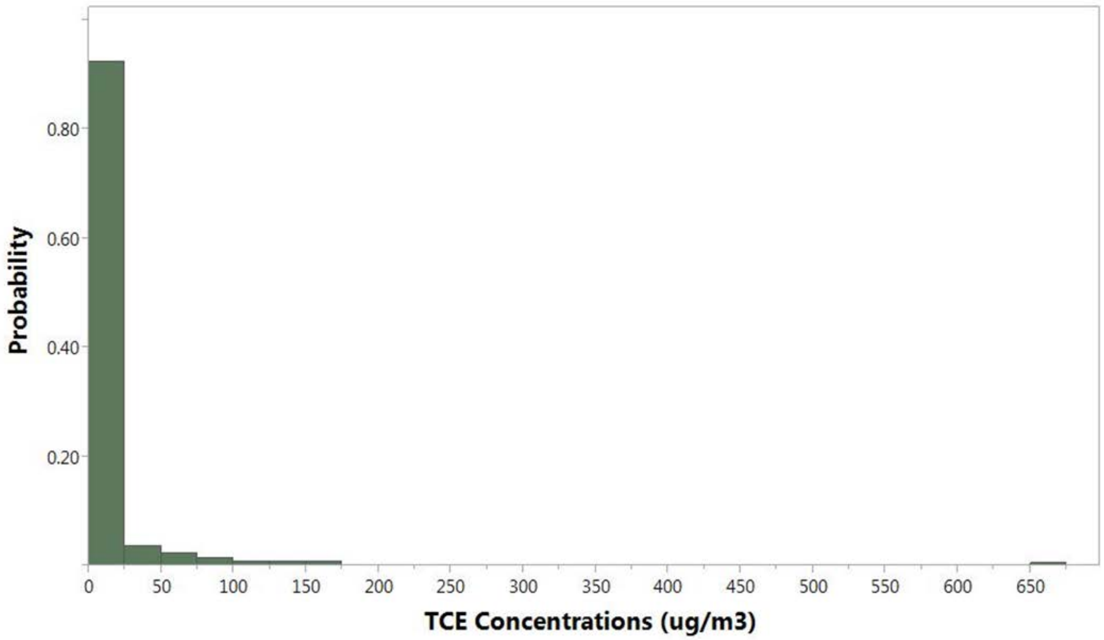


Figure 5
Histogram of All Trichloroethene Indoor Air Results
NESDI Vapor Intrusion Project

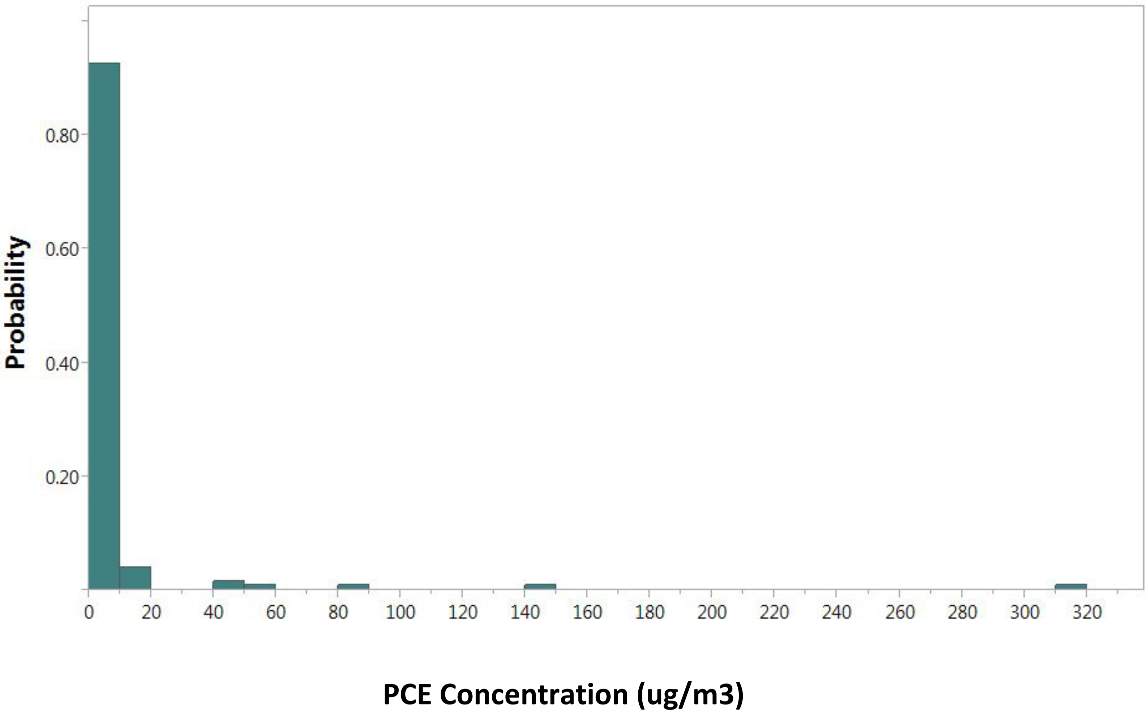


Figure 6
Histogram of All Tetrachloroethene Indoor Air Results
NESDI Vapor Intrusion Project

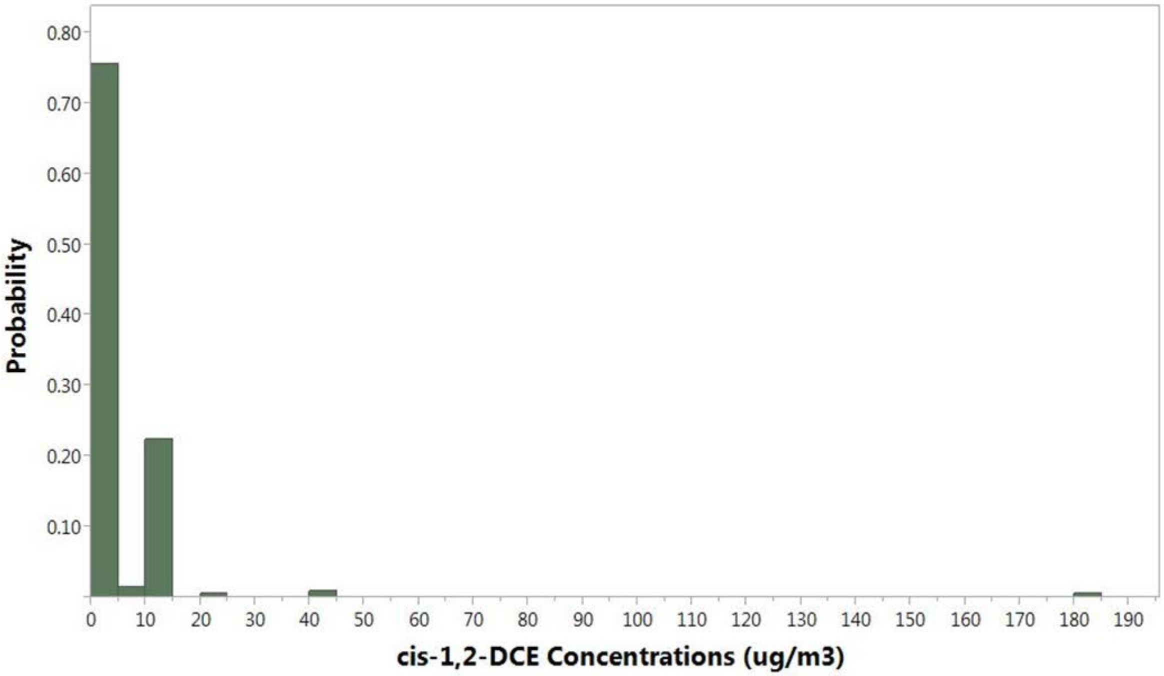


Figure 7
Histogram of All cis-1,2-Dichloroethene Indoor Air Results
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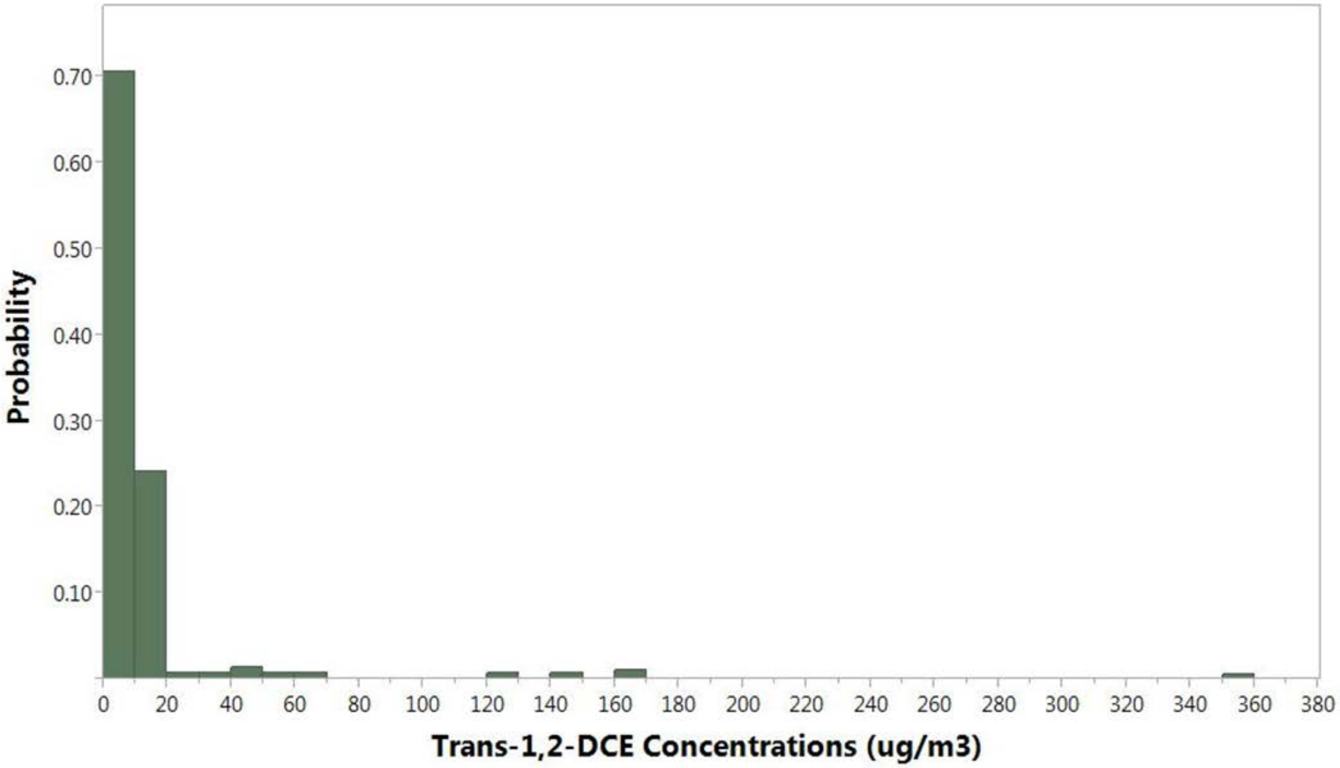

Figure 8
Histogram of All trans-1,2-Dichloroethene Indoor Air Results
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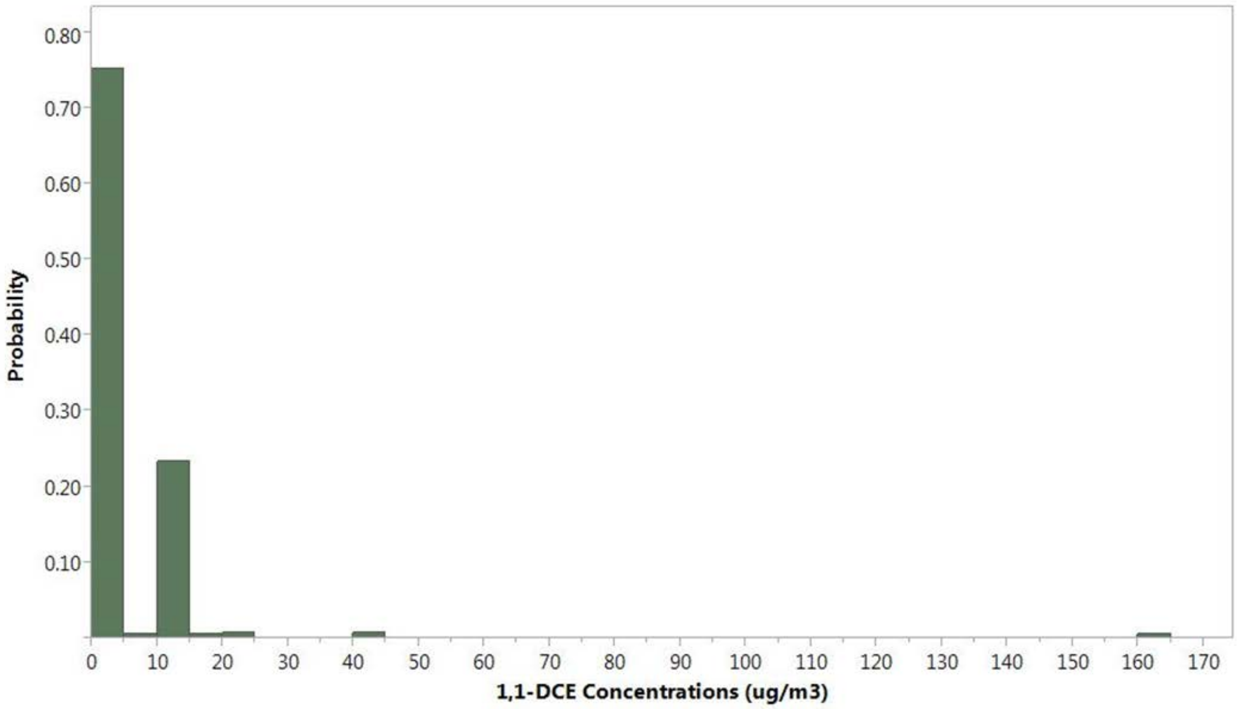

Figure 9
Histogram of All 1,1-Dichloroethene Indoor Air Results
NESDI Vapor Intrusion Project

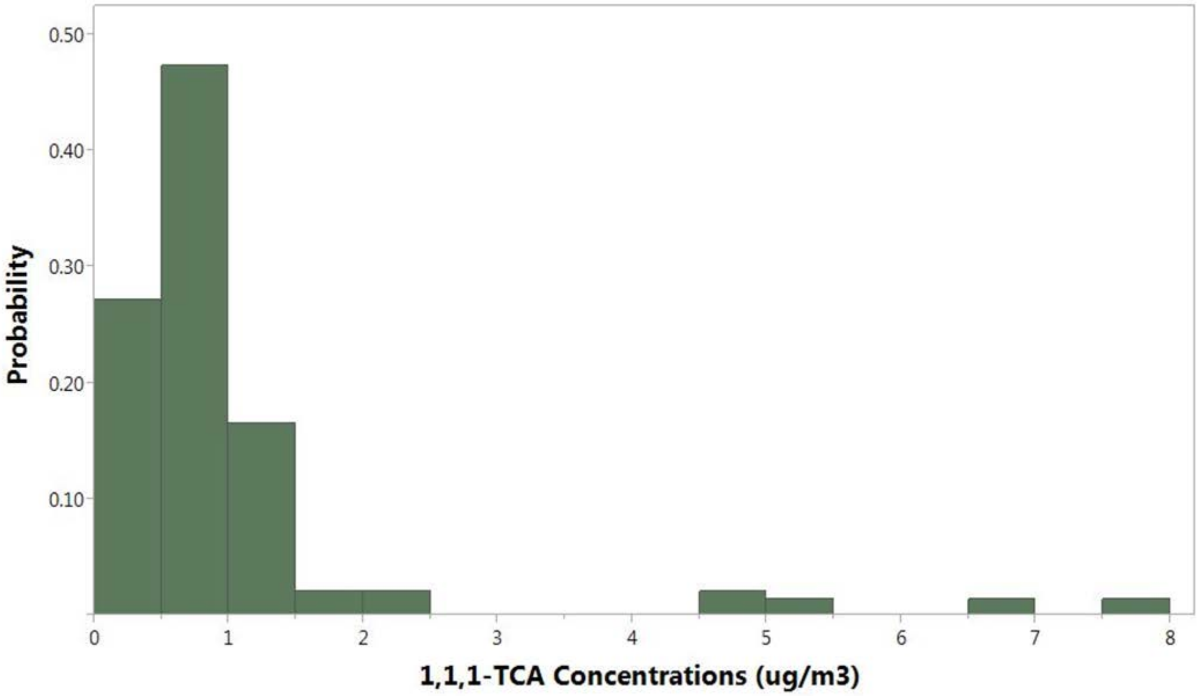

Figure 10
Histogram of All 1,1,1-Trichloroethane Indoor Air Results
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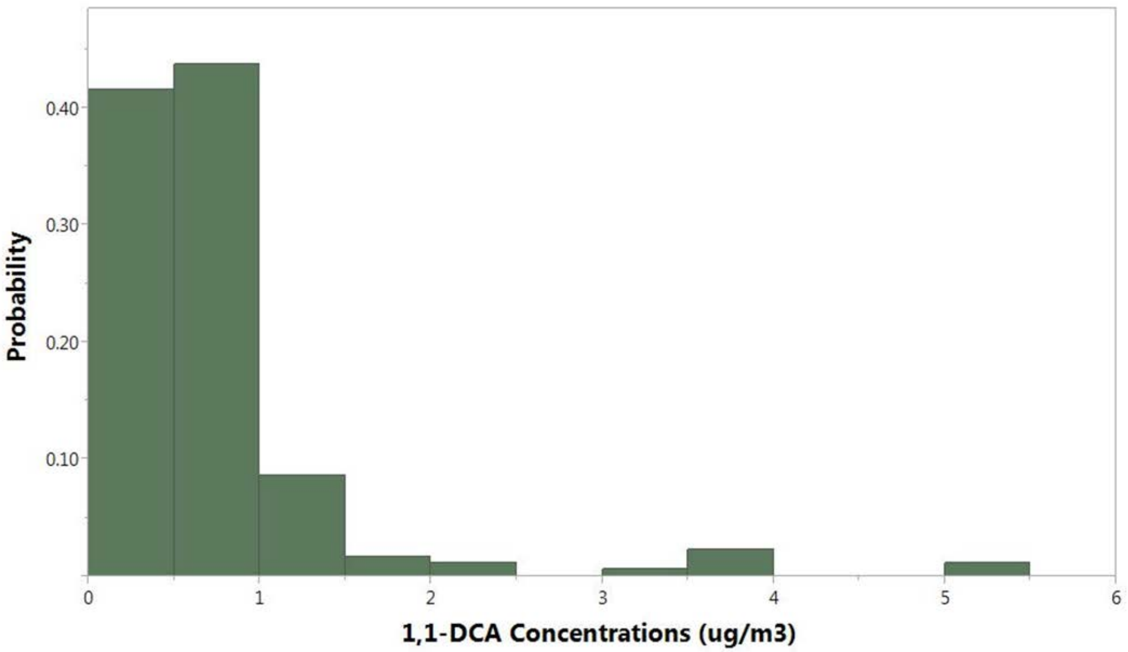

Figure 11
Histogram of All 1,1-Dichloroethane Indoor Air Results
NESDI Vapor Intrusion Project

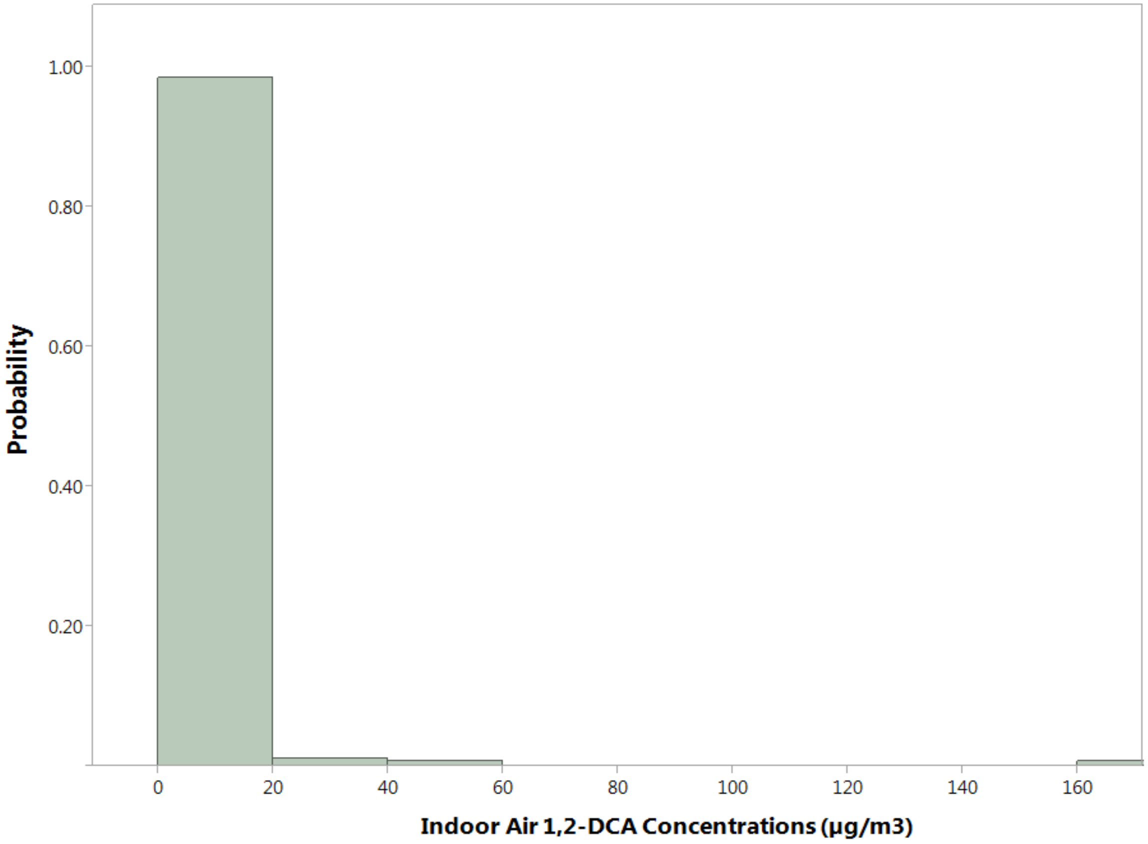

Figure 12
Histogram of All 1,2-Dichloroethane Indoor Air Results
NESDI Vapor Intrusion Project

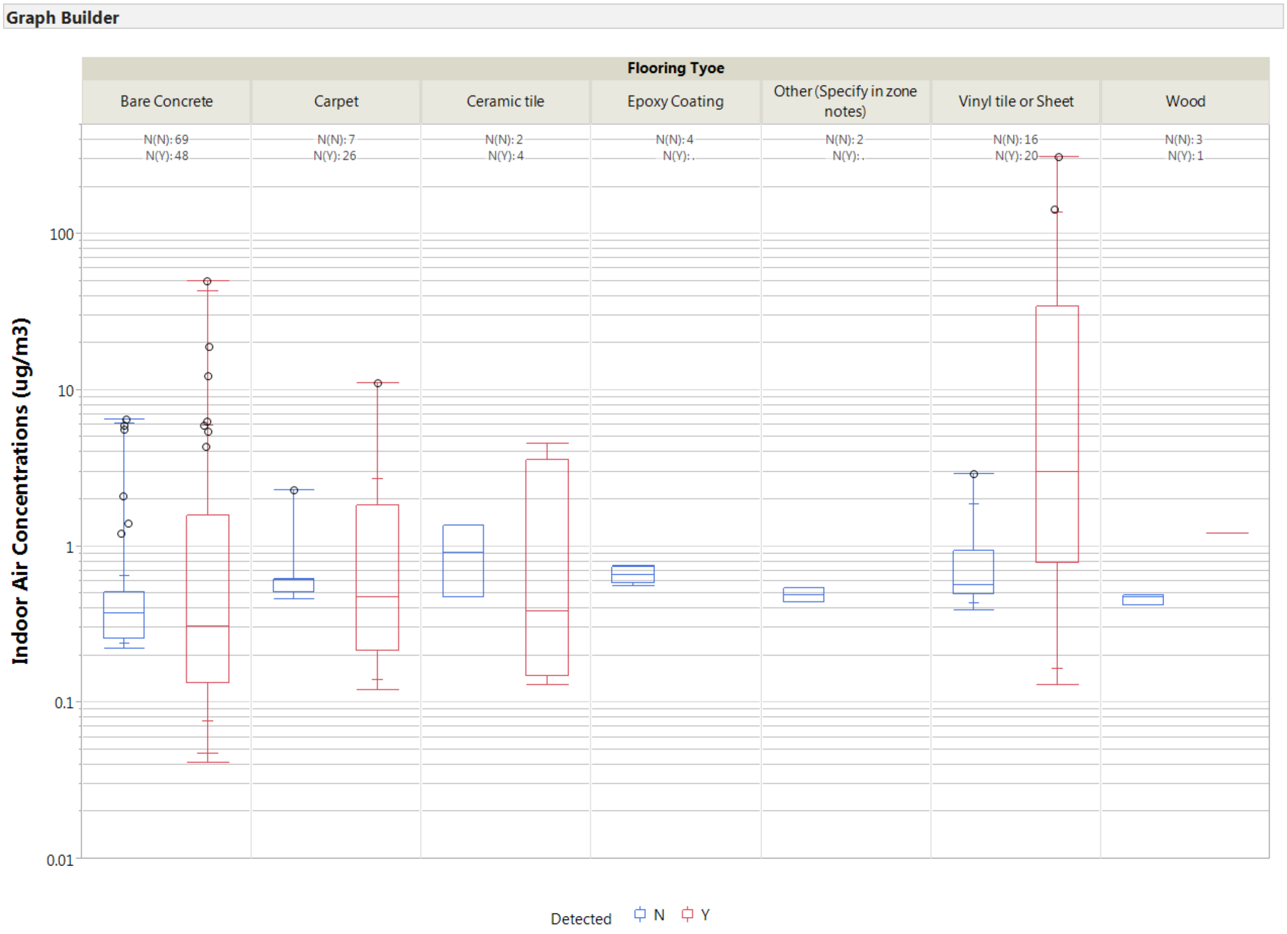

Figure 13
Variability in Tetrachloroethene Indoor Air Concentrations across Floor Types
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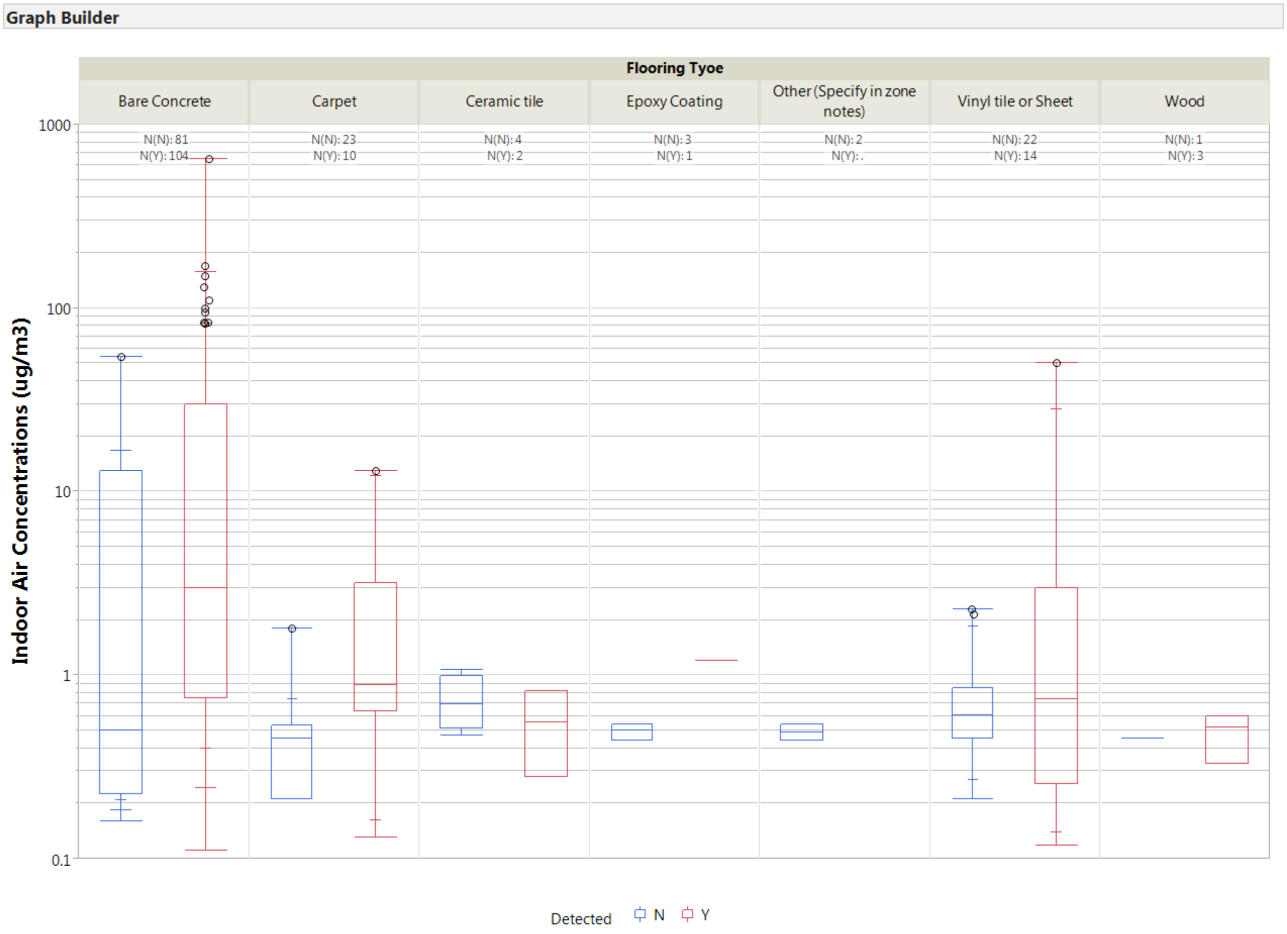

Figure 14
Variability in Trichloroethene Indoor Air Concentrations Across Floor Types
NESDI Vapor Intrusion Project

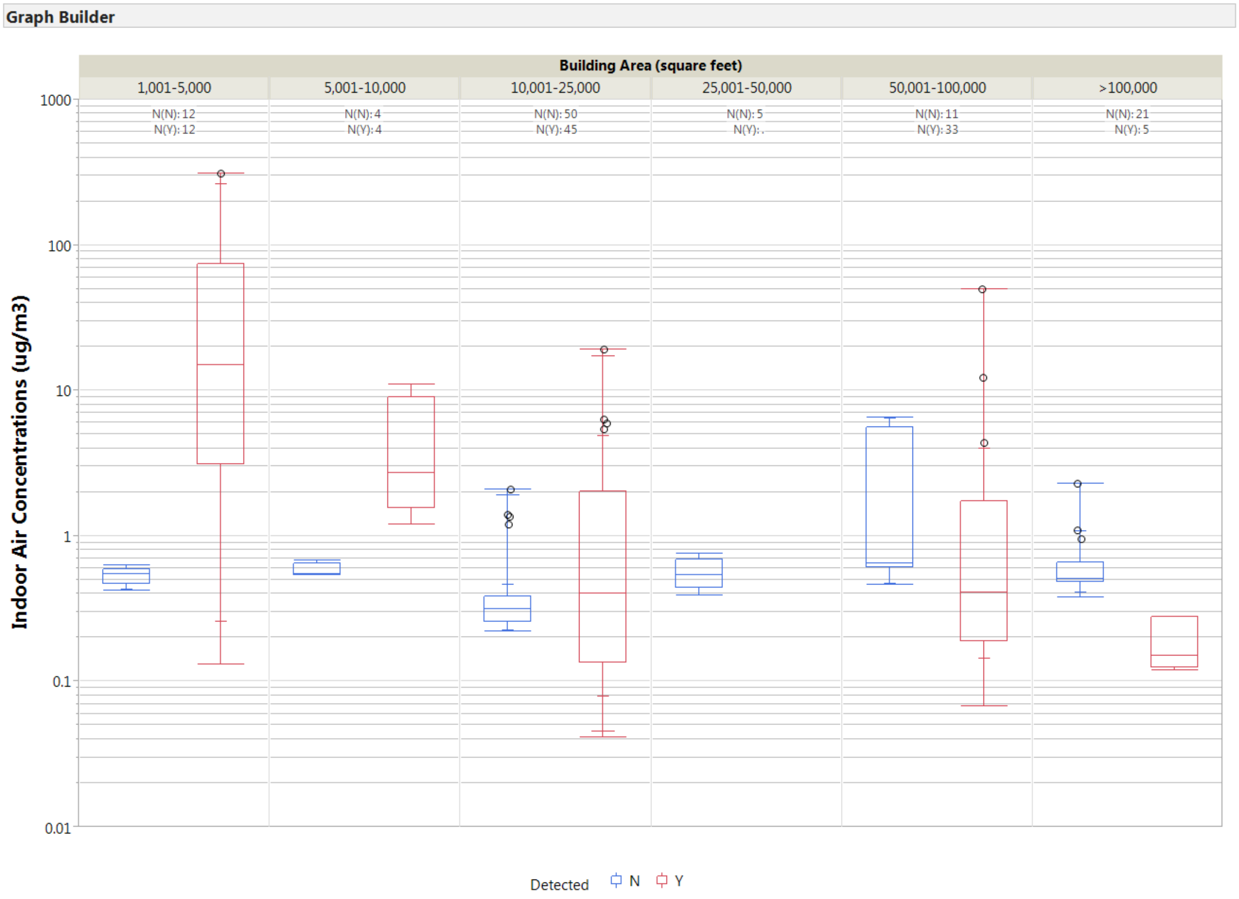

Figure 15

Tetrachloroethene Indoor Air Results Across Building Areas

NESDI Vapor Intrusion Project

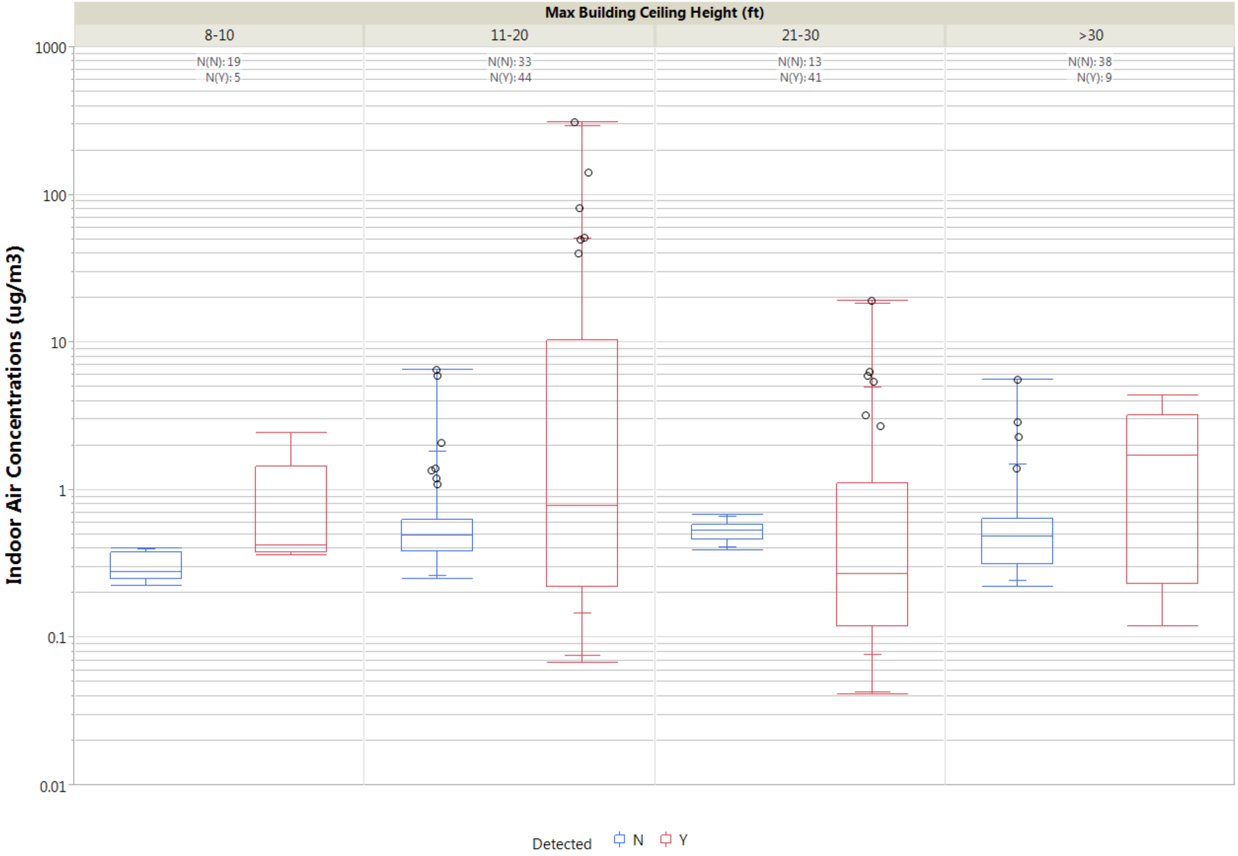

Figure 16
Tetrachloroethene Indoor Air Results as Related to Maximum Ceiling Height
NESDI Vapor Intrusion Project

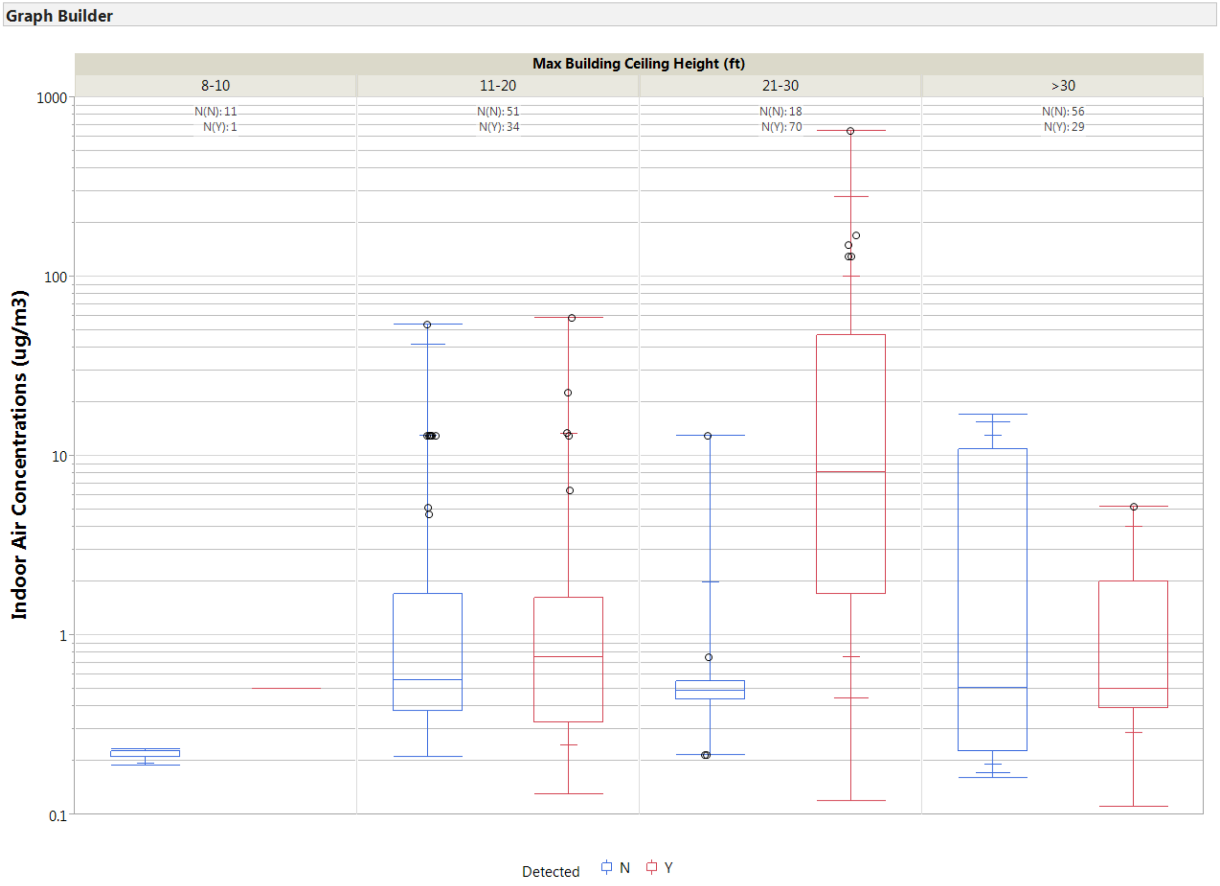

Figure 17
Trichloroethene Indoor Air Results as Related to Maximum Ceiling Height
NESDI Vapor Intrusion Project

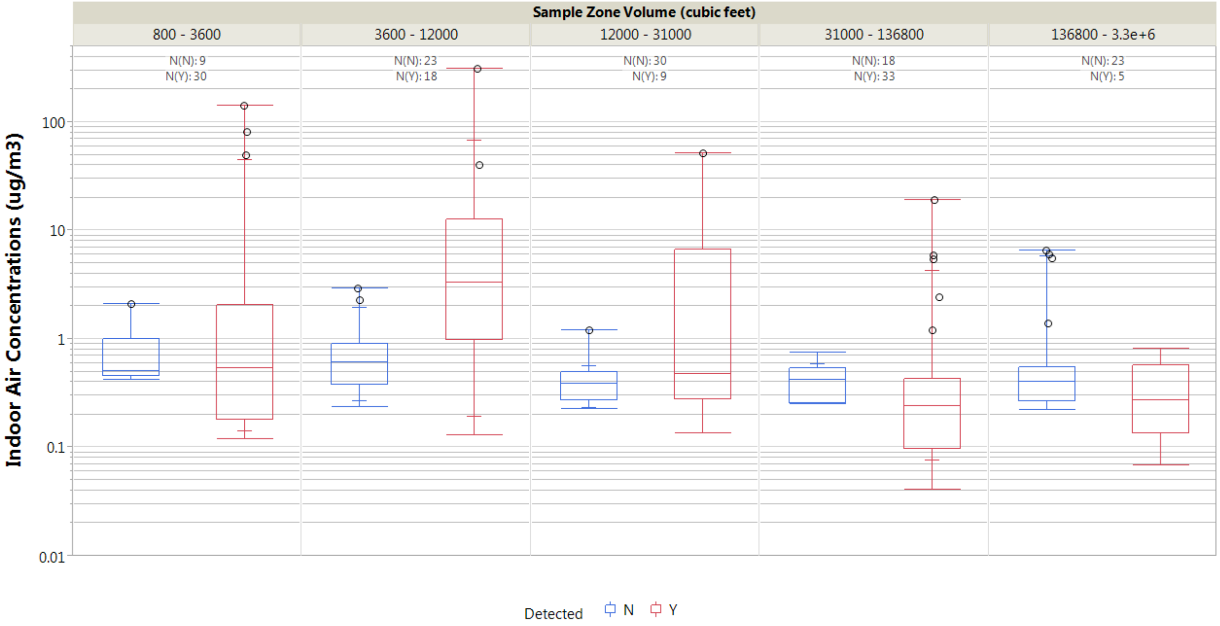

Figure 18
Tetrachloroethene Indoor Air Results as Related to Sample Zone Volume
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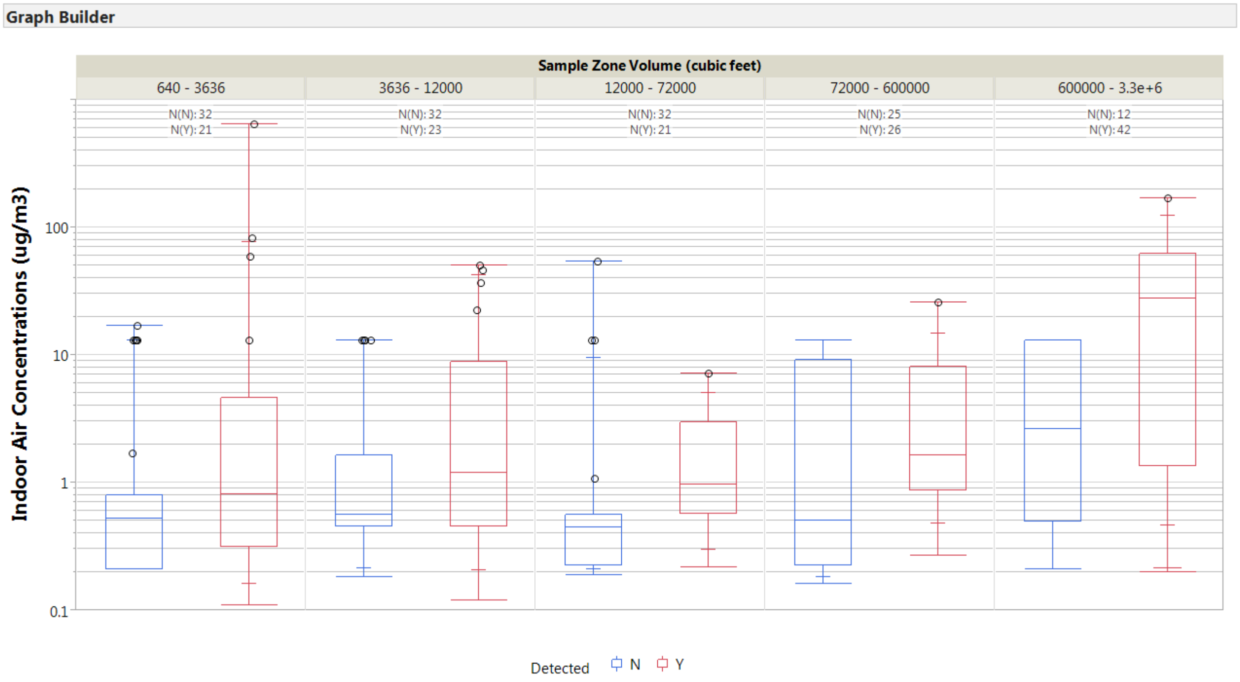

Figure 19

Trichloroethene Indoor Air Results as Related to Sample Zone Volume

NESDI Vapor Intrusion Project

Figure 20
Tetrachloroethene Indoor Air Results as Related to Presence or Absence of Exterior Wall
NESDI Vapor Intrusion Project

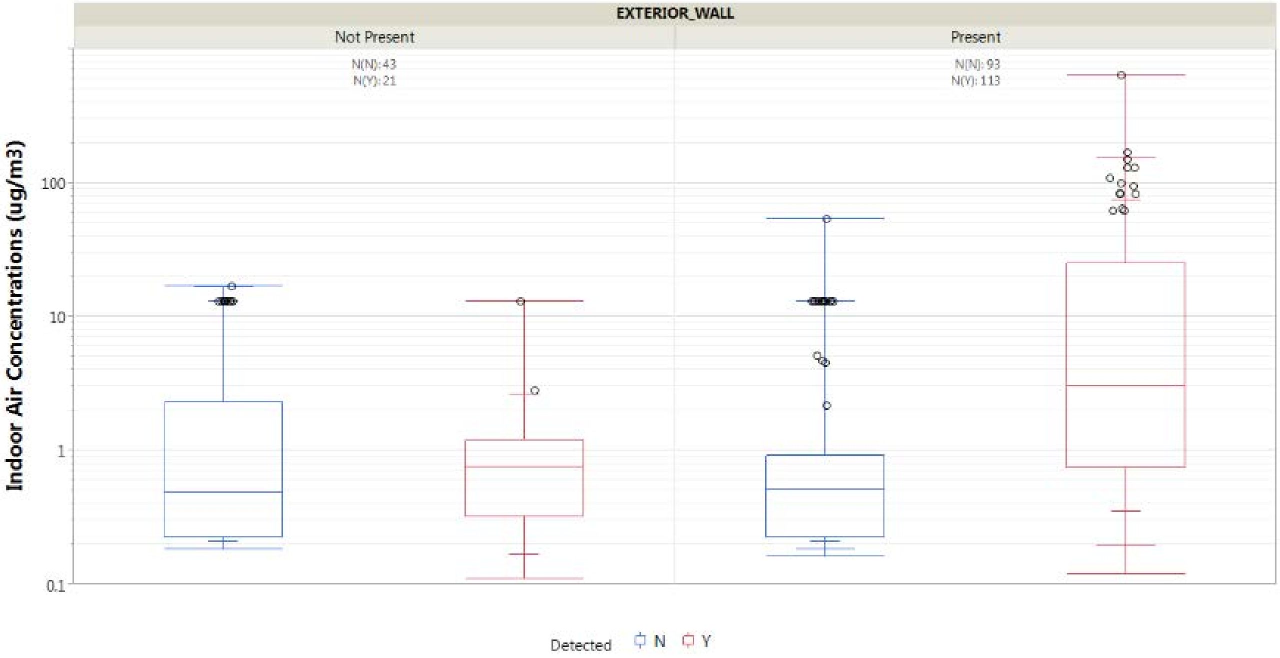

Figure 21
Trichloroethene Indoor Air Results as Related to Presence or Absence of Exterior Wall
NESDI Vapor Intrusion Project

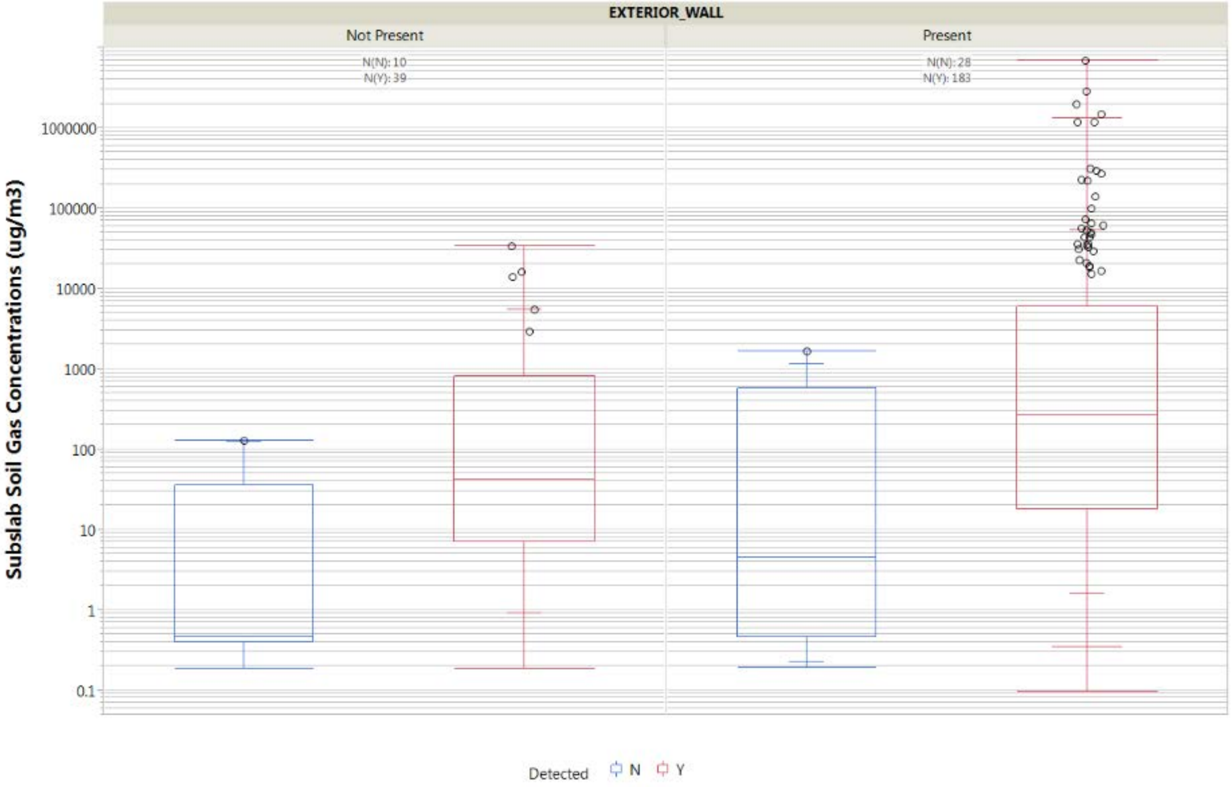

Figure 22
Tetrachloroethene and Trichloroethene Subslab Soil Vapor Results as Related to Presence or Absence of Exterior Wall
NESDI Vapor Intrusion Project

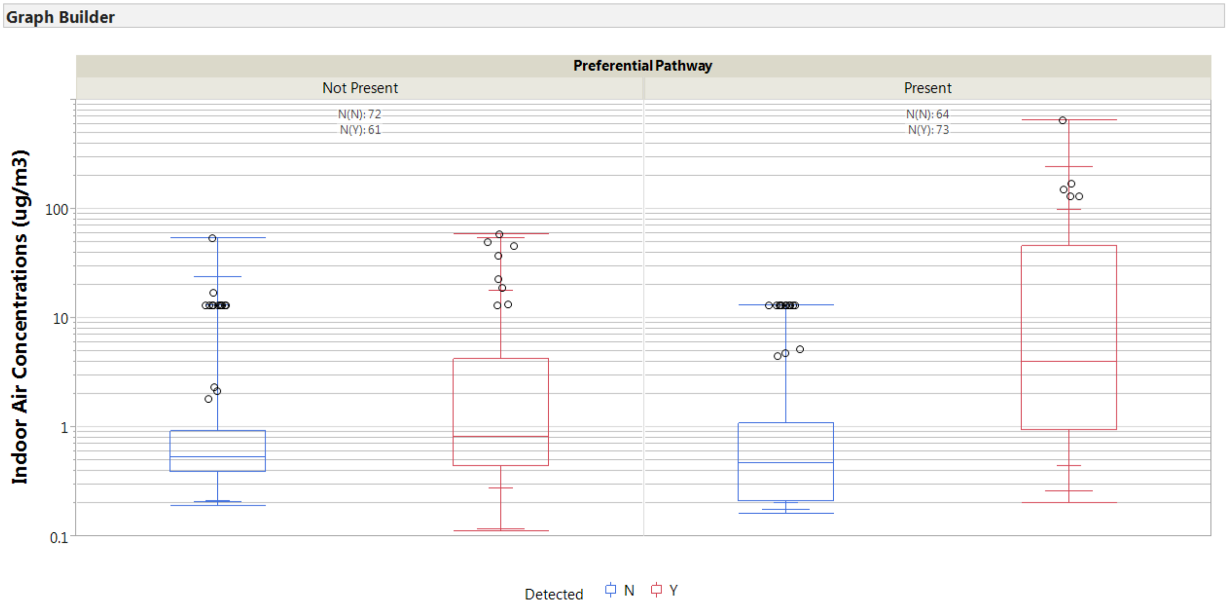

Figure 23
Trichloroethene Indoor Air Results as Related to Presence or Absence of Preferential Pathways
NESDI Vapor Intrusion Project

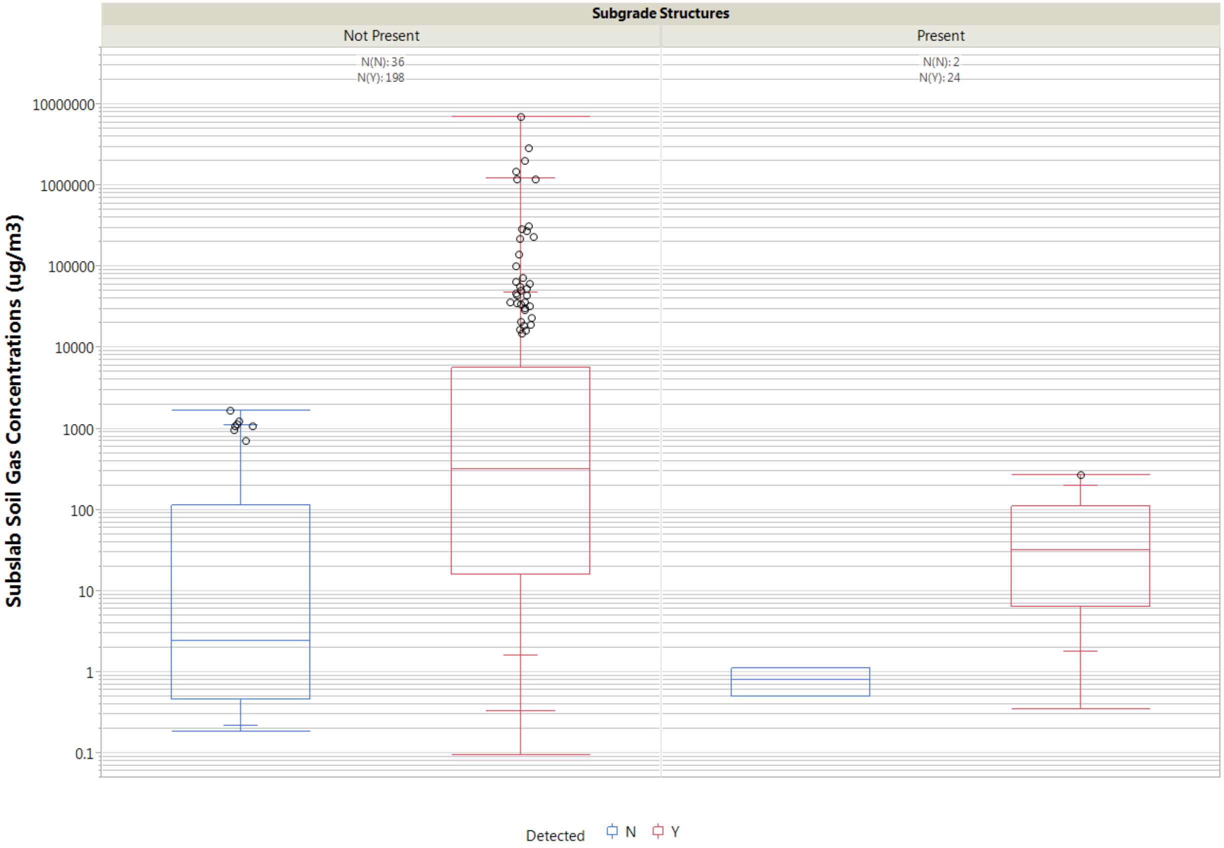

Figure 24
Tetrachloroethene and Trichloroethene Subslab Soil Vapor Results as Related to Presence or Absence of Subgrade Structures
NESDI Vapor Intrusion Project

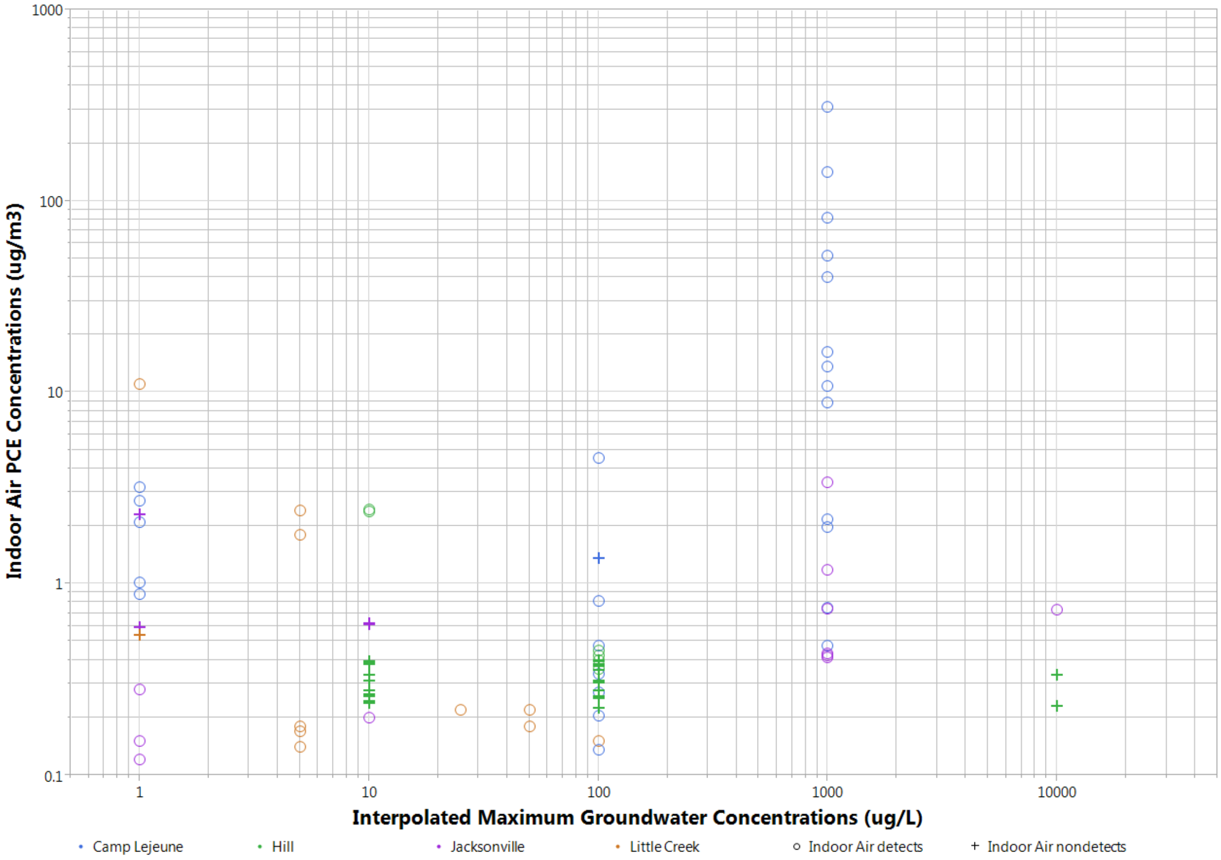

Figure 25
Tetrachloroethene Indoor Air Concentrations as a Function of Interpolated Maximum Groundwater Concentrations
NESDI Vapor Intrusion Project

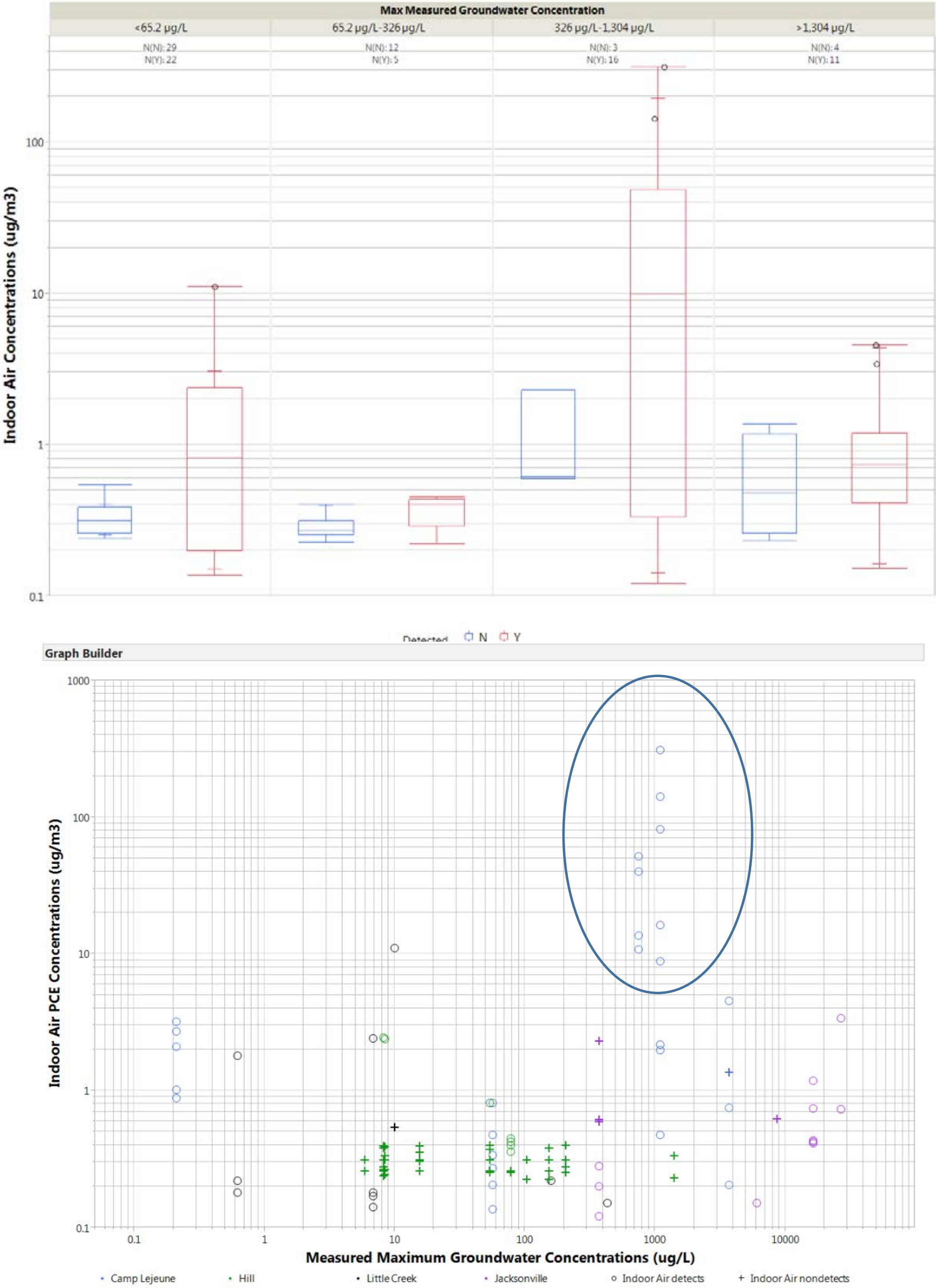

Figure 26
Tetrachloroethene Indoor Air Concentrations as a Function of Measured Maximum Groundwater Concentrations
NESDI Vapor Intrusion Project

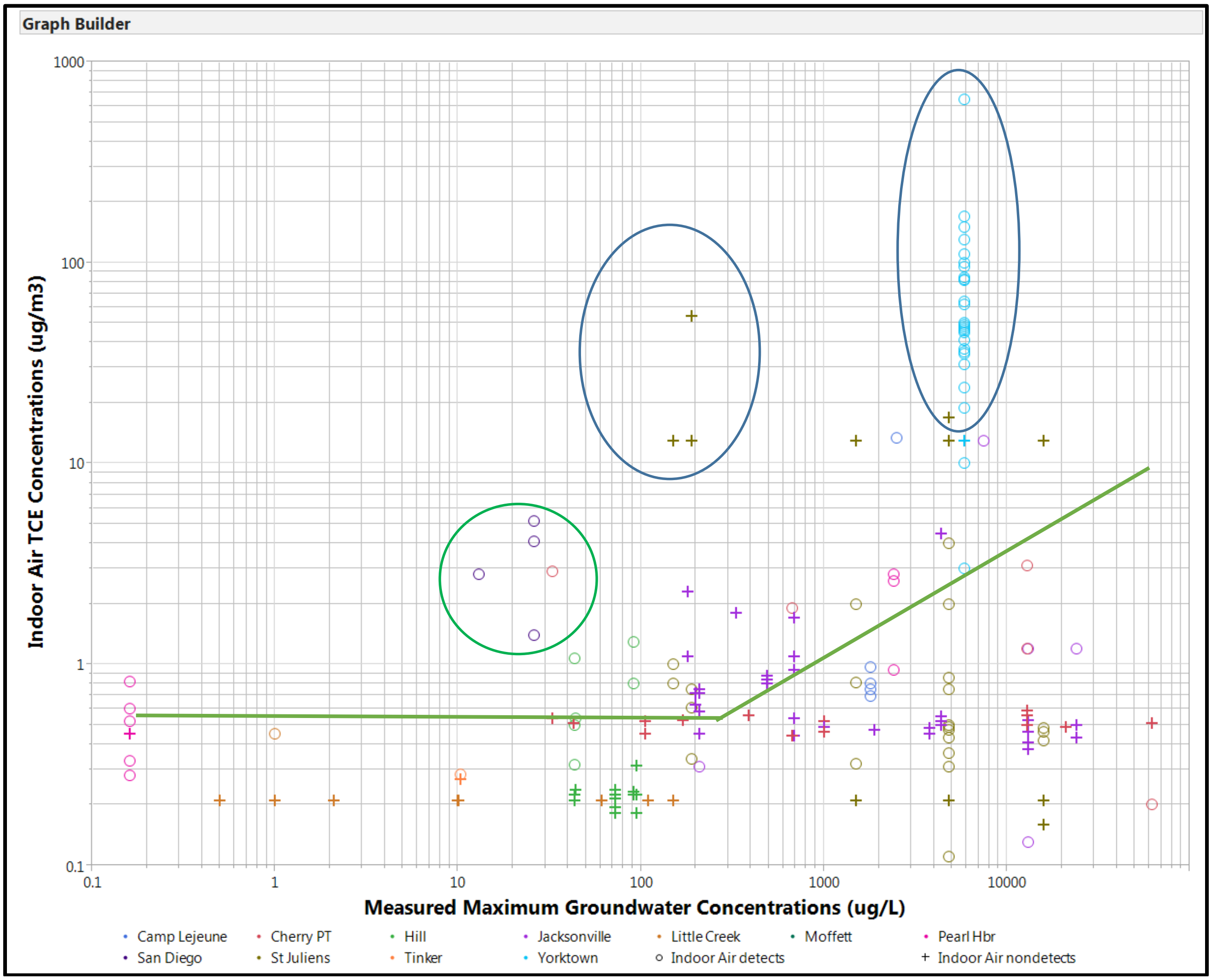

Figure 27
Trichloroethene Indoor Air Concentrations as a Function of Measured Maximum Groundwater Concentrations
NESDI Vapor Intrusion Project

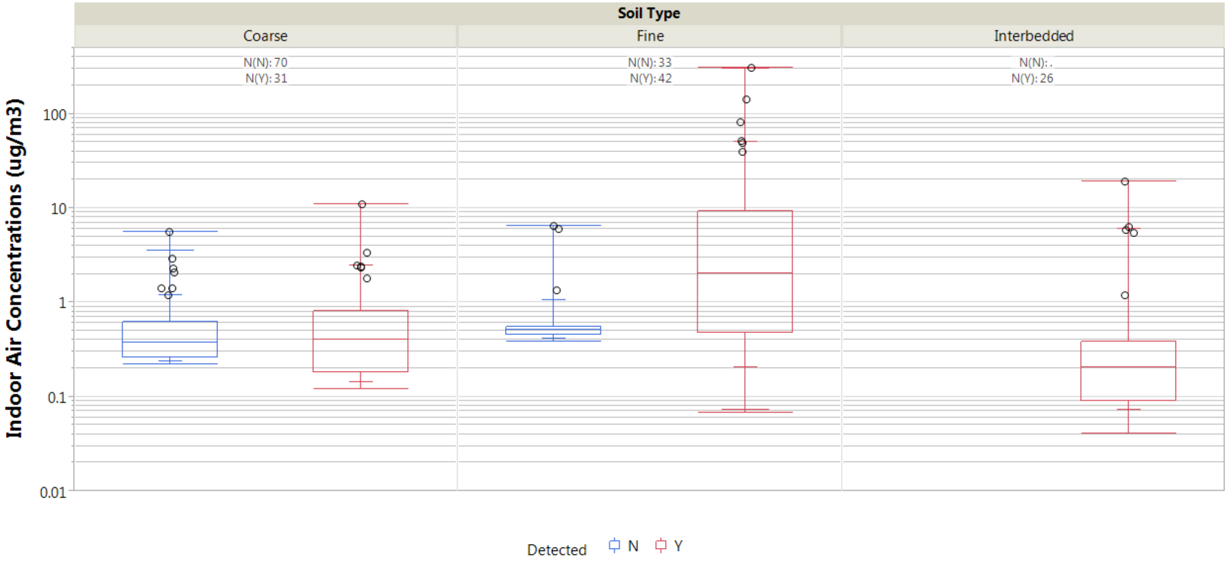

Figure 28
Tetrachloroethene Indoor Air Concentrations as Related to Soil Type
NESDI Vapor Intrusion Project

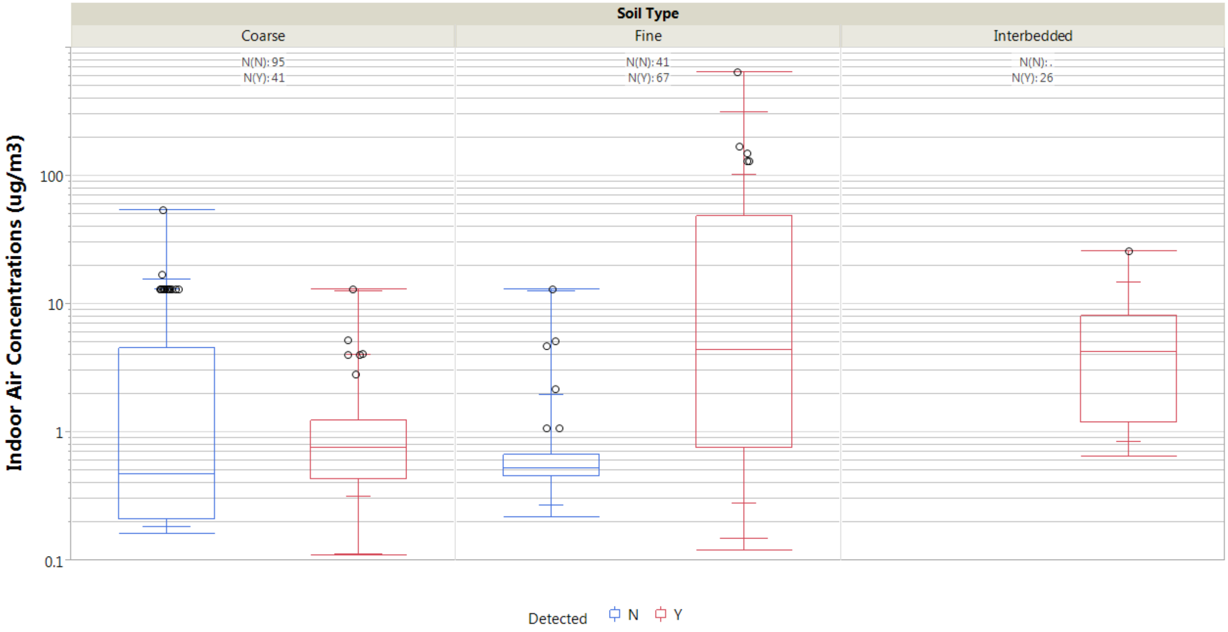

Figure 29
Trichloroethene Indoor Air Concentrations as Related to Soil Type
NESDI Vapor Intrusion Project

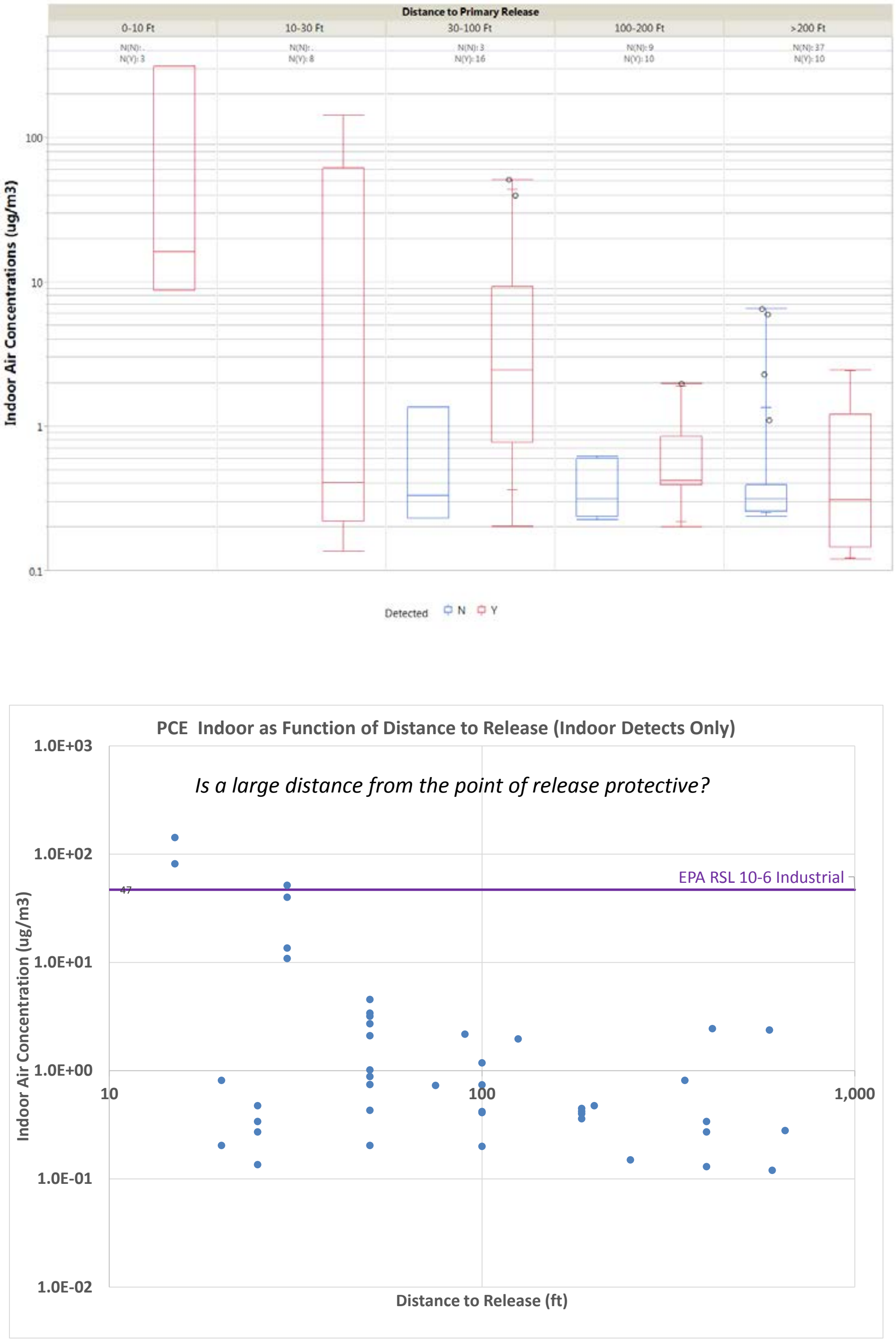

Figure 30
Tetrachloroethene Indoor Air Concentrations as Related to Distance from Primary Release (above box and whisker; bottom XY)
NESDI Vapor Intrusion Project

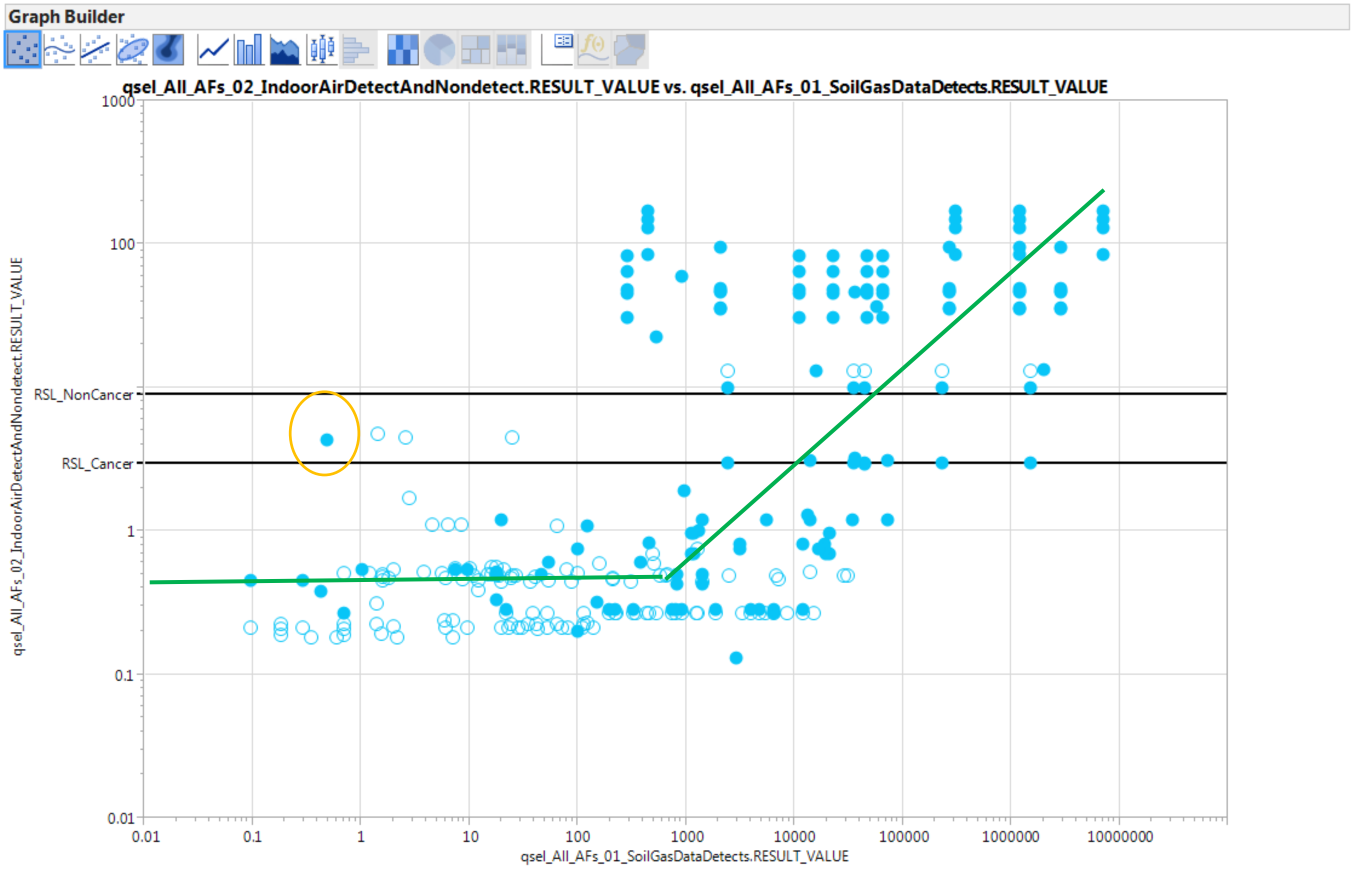

Figure 31
Trichloroethene Indoor Air Concentration Soil Gas Concentration; detected results filled circles, ND results outlined circles
NESDI Vapor Intrusion Project

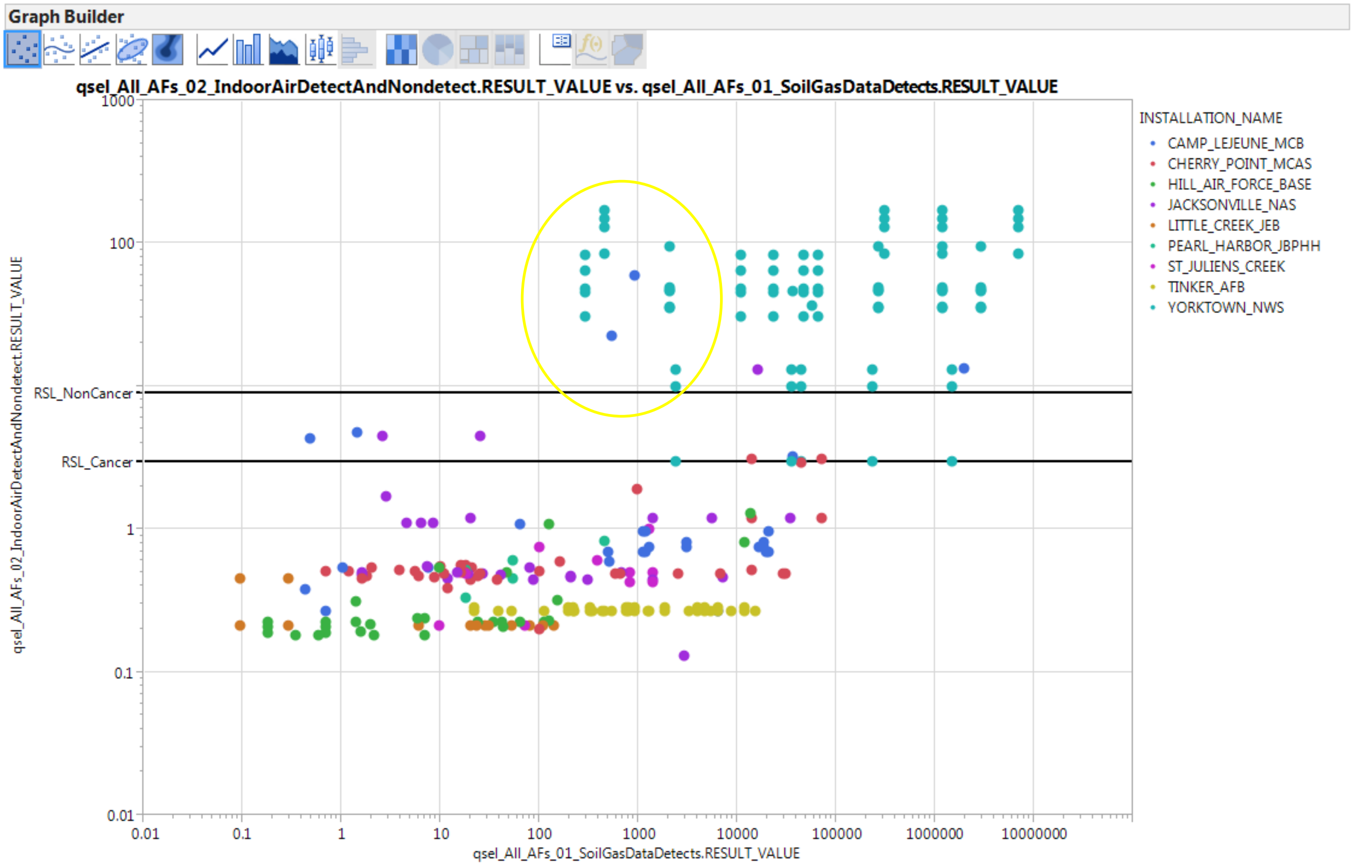

Figure 32
Trichloroethene Subslab Concentration vs. Indoor Air Concentration by Base
NESDI Vapor Intrusion Project

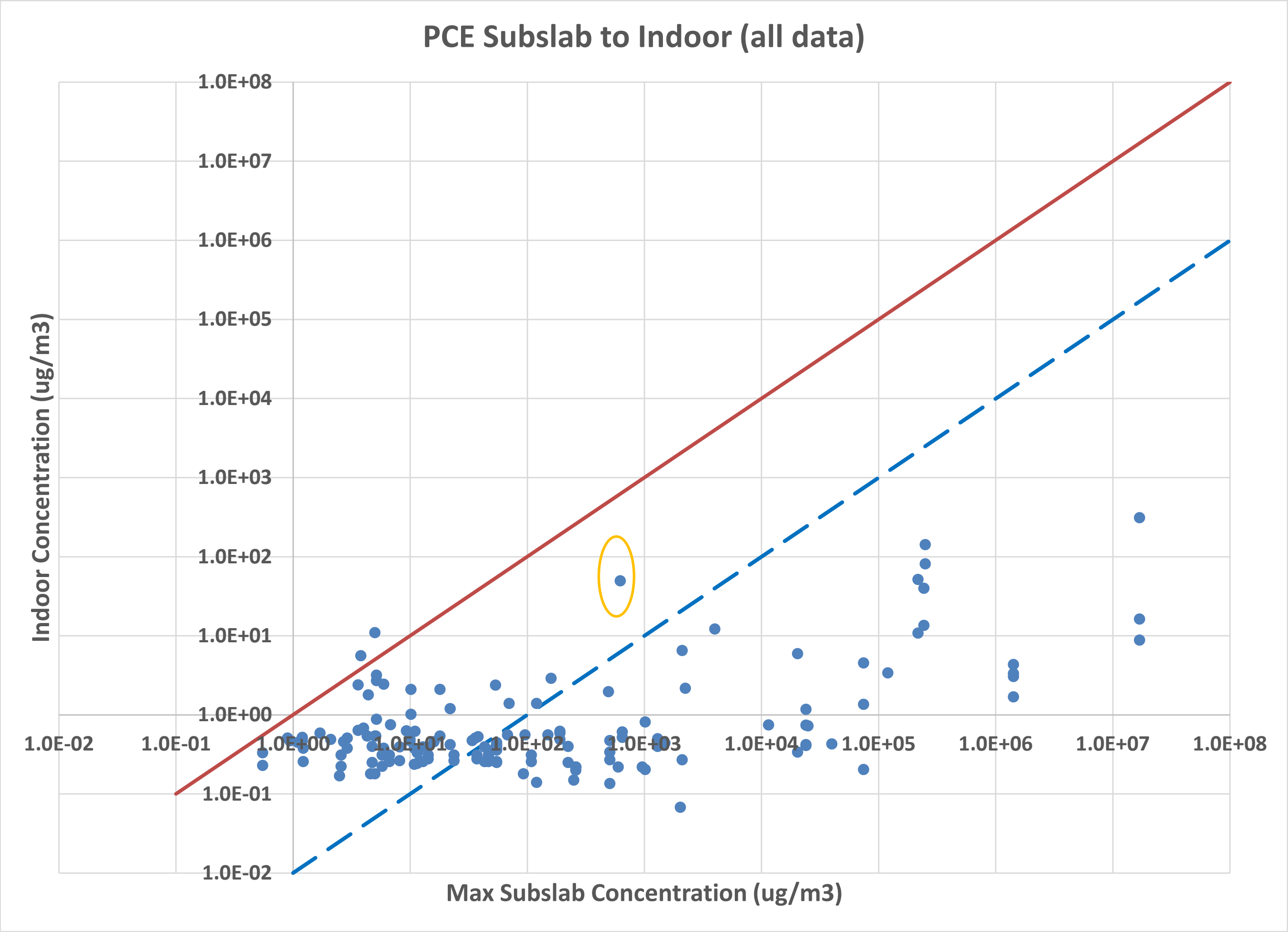

Figure 33
Tetrachloroethene Attenuation Across the Building Envelope. (Red line is an attenuation factor of 1, Blue Line corresponds to an attenuation factor of 0.01)
NESDI Vapor Intrusion Project

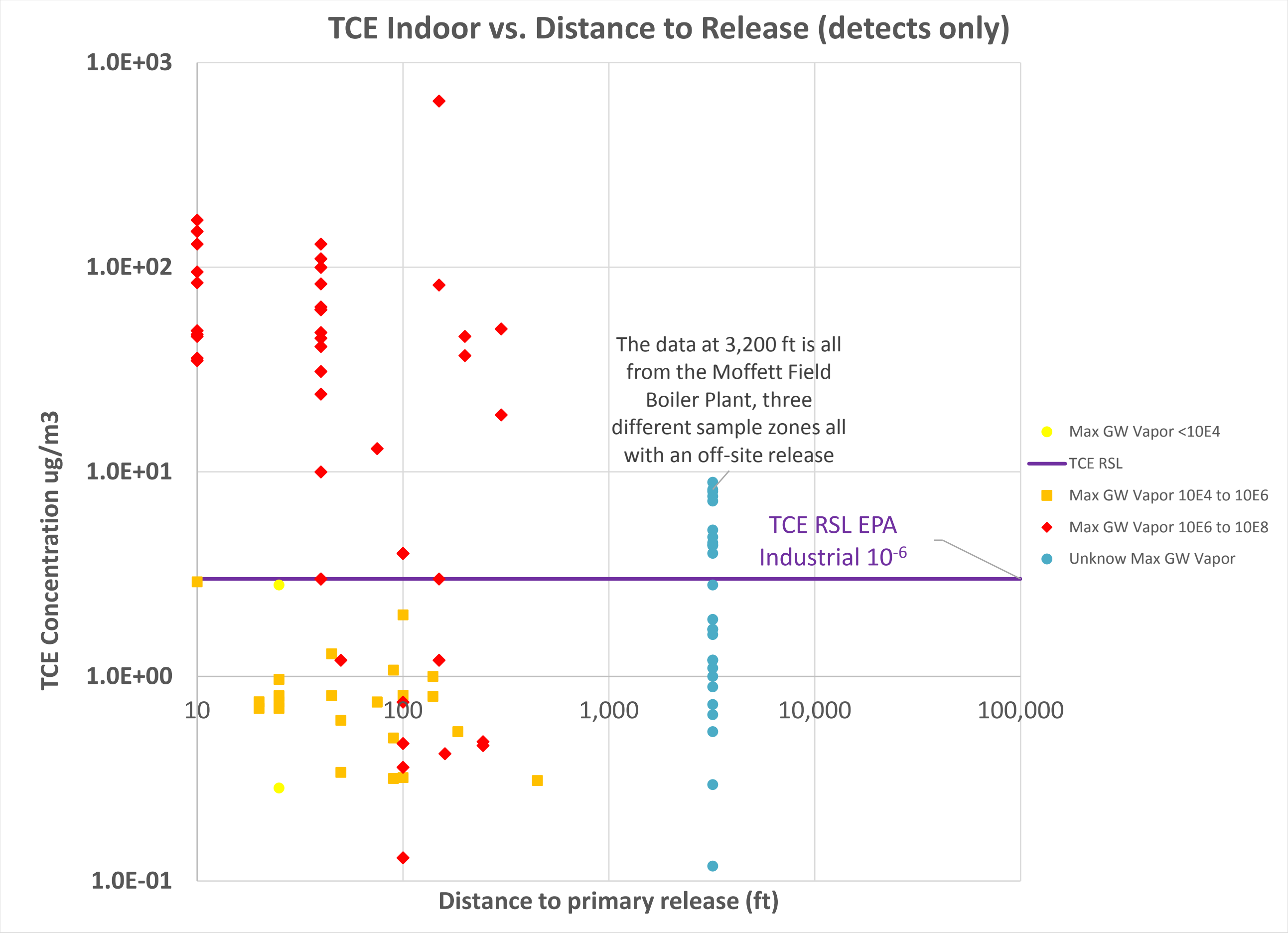

Figure 34

Trichloroethene Indoor Air Concentration as a Function of Groundwater Source Strength and Distance to Release Point

NESDI Vapor Intrusion Project

Appendix E – Additional Results from Exploratory & Statistical Data Analysis

Appendix E

Additional Results from Exploratory and Statistical Data Analysis

Contents

Figures

APPENDIX E

Introduction

The purpose of this appendix is to present results from analyses performed for this project that did not prove sufficiently valuable to describe in the main text or use as part of the foundation of the quantitative decision framework. However, these results can be potentially used to:

- Evaluate how indoor air concentrations or sub-slab soil gas concentrations vary with certain other variables that may be predictive or causative;
- Identify intriguing hints in the dataset that may inform further research efforts; and
- Better understand the underlying data set used in the main text analyses.

E.1 Indoor Air Analyses

This section focuses on graphs produced as part of the indoor air analyses.

E.1.1 Measured Maximum Groundwater Concentration

As part of exploring the source strength and distance focus areas and groundwater to indoor air focus area, single variable analyses were conducted using measured groundwater vapor concentration (calculated from the measured groundwater concentration using Henry's Law) and individual results using a series of filtering/screening approaches. As shown in **Figures E1** through **E4**, this did not yield a monotonic relationship, regardless of which screens were applied. The deviation from the expected monotonic relationship was not solely attributable to data from any one DoD facility. The zone averages provided a more interpretable dataset and are included in the main text.

In the main text, sample zone averaged plots were presented relating groundwater vapor concentration to indoor air concentration. In this appendix, the corresponding plots for PCE and TCE without the zone averaging (**Figures E5** to **E8**) are included. Data plots are presented which included all available data and data with groundwater depths greater than 5 feet only.

E.1.2 Overall Characteristics of Indoor Air Data Set

Table 2-2 in the main text shows the frequency of detection for each compound in indoor air. Based on these frequencies of detection, and the frequencies of exceedances of conservative risk based screening levels, the data presentation focuses on PCE, TCE, cis-1,2-DCE, trans-1,2-DCE and 1,2-DCA.

TCE and PCE were the most commonly detected chlorinated constituents in the indoor air data set, at 50 and 49 percent, respectively. These percentages are similar to those reported in the USEPA (2011) background indoor air data set for residences (43 and 63 percent, respectively). The distribution of TCE at the DoD buildings contains a skewed upper tail, with a maximum value of 650 µg/m^3. The distribution of PCE also shows a skewed upper tail, with a maximum value of 312 µg/m^3. Exceedances of the risk-based industrial screening level[1] for PCE of 47 µg/m^3 were infrequent in the data set, while exceedances for TCE were more frequent.

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[1] Unless otherwise specified, all references in this document to risk-based industrial screening levels refer to the USEPA Regional Screening Level Table May 2014, TR=1E-6, HQ=1, and to the industrial air values. These screening levels may change in future years. Stable compounds that are below screening levels can still provide useful scientific data for the purposes of this project; however, the authors do discuss screening levels here for three purposes. First, a comparison of concentration distributions to screening levels provides a national perspective on the frequency with which concentrations that may be considered problematic, if attributable to subsurface soils in DoD buildings. Second, compounds for which concentrations above screening levels were observed have likely received the greatest attention in the underlying reports. Sampling and analysis strategies are often optimized in an attempt to provide information needed to compare results to compound-specific screening levels. The quality of available information about potential indoor sources and contaminant distributions in environmental media is likely to be best for those compounds approaching or exceeding screening levels. Third, to the extent that the factors controlling transport through the vadose zone and into structures

Cis-1,2-DCE a common biodegradation product of TCE and PCE and had a 27 percent detection frequency in indoor air, which is 5 times higher than the 5 percent frequency of detection in the USEPA (2011) residential background data set. There is no current USEPA risk-based screening level for this compound.

Trans-1,2-DCE was detected in 28 percent of the indoor air samples, twice as frequently as the 14 percent detection frequency reported in the USEPA (2011) indoor residential background data set. Trans-1,2-DCE is more often used industrially than either cis-1,2-DCE or the commercial mixture of the two isomers (ATSDR, 1996). There is no current USEPA risk-based screening level for this compound.

1,1-DCE was detected in 14 percent of the indoor air samples, which is similar to the 13 percent frequency of detection in the USEPA (2011) indoor residential background data set. Each of the detected concentrations in the database were well below the current risk-based industrial screening level of 880 μg/m^3. The distribution appears to be bimodal.

Vinyl chloride was only detected in 6 percent of the indoor air samples, compared with 9 percent of the samples in the USEPA (2011) residential background data set. Vinyl chloride is aerobically degradable (AFCEE 2004). One hypothesis is that the aerobic degradation of vinyl chloride limits the migration into indoor air at significant concentrations.

1,1,1-TCA was detected in 11 percent of the indoor air samples, which was much lower than the 53 percent detection frequency in the USEPA (2011) background residential indoor air data set. Each of the detected concentrations in the database were orders of magnitude below the current risk-based screening level for industrial indoor air of 22,000 μg/m^3.

The most common biodegradation product of 1,1,1-TCA is 1,1-DCA, which is also found in plastic products (NJDEP, 2013). 1,1-DCA was detected in 21 percent of the indoor samples, but only 1 percent in the USEPA (2011) background residential data set. None of the detected concentrations in the database exceeded the industrial indoor risk-based screening level of 7.7 μg/m^3.

1,2-DCA was detected in 13 percent of the indoor air samples, similar to the 14 percent detection frequency in the USEPA (2011) indoor residential background data set. 1,2-DCA has a current industrial risk-based screening level of 0.47 μg/m^3, which was exceeded in a few samples. The distribution appears to be bimodal.

E.1.3 Indoor Concentrations Grouped by Preferential Pathway

Figures E9 through **E18** present the data segregated by the presence or absence of atypical preferential pathways for vapor intrusion (by the original or strict definitions). TCE is the only constituent for which a notable effect of preferential pathways was observed in the expected direction (i.e., higher concentrations would be associated with preferential pathways). This effect was only noted for the original definition and not for the strict definition.

E.1.4 Sample Zone and Building Dimension Effects

E.1.4.1 Indoor Air Grouped by Sample Zone Height

Theory would suggest that ceiling height can have two opposite effects:

1) The strength of the stack effect is proportional to the square root of the building height (Hui, 1993; ITRC 2007)
2) All else being equal, increased ceiling height on the ground floor would be expected to result in decreased indoor air concentrations when those concentrations are attributable to VI; because a greater volume of indoor air is available for dilution (ITRC 2007). This concept is included in the Johnson and Ettinger model with a term for the mixing zone height (Environmental Quality Management, 2004).

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differ by compound because of their differing physical properties, those compounds that commonly exceed screening levels merit prioritized scientific attention.

The potential for VI to occur through building walls is an additional complicating factor in this analysis since greater ceiling heights would correspond to more wall area for infiltration. Building walls can be a source of VI in buildings with hollow block construction, for example. Interpretation of these trends may also be confounded in that office uses are typically associated with 8 to 10 ft ceilings and are expected to have the weakest source terms. Similarly, industrial building uses often have high ceilings.

When the unscreened data sets are reviewed as box and whisker plots, the PCE and TCE data sets (**Figures E19** and **E20**) suggest that maximum indoor air concentrations may be associated with intermediate (11- to 30-foot) ceiling heights. Note also that the percentage of indoor air samples with a detectable concentration is greater in sample zones with intermediate ceiling heights. This is a theoretically possible outcome when two separate effects are moving in opposite directions.

When the data has been screened with the baseline, source strength and preferential pathway screens and the normalized indoor air concentration is plotted as a function of ceiling height the overall impression is that while there may be a trend of decreasing attenuation factor with taller ceilings. However, there is a wide degree of scatter in the data; therefore, this single variable does not provide great explanatory power (**Figures E21** through **E23**).

E.1.4.2 Indoor Air Grouped by Sample Zone Volume

A working assumption about the definition of sample zone used in this project is that air is expected to be reasonably well and rapidly mixed throughout the zone (and perhaps over a larger volume, up to and including the full building in some cases). Conceptually, indoor air concentrations should decrease as sample zone volume increases if all other variables are constant and if the source is due to a discrete activity or a preferential pathway, or if vapors are intruding through only a portion of the floor. As shown in **Figure E24**, the maximum, 75th percentile, and median PCE concentrations among detected samples generally appear to decrease with sample zone volume above 12,000 cubic feet (ft^3). Frequency of PCE detection was also highest in the smallest sample zones; 77 percent of the samples from zones under 3,600 ft^3 were detectable, but only 17 percent of the samples collected in the largest zones (over 136,800 ft^3) were detectable. Thus the trends in percentage detectable samples and in the maximum, 75th percentile, and median agree for this parameter. This trend also holds in the screened data set (**Figure E25**).

The trend for TCE, however, was substantially different (**Figure E26**). The group of sample zones with the largest volumes (>600,000 ft^3) had the highest median and 75th percentile concentrations. The group of sample zones with the largest volumes also had the highest frequency of TCE detection (75 percent of 54 total samples). For perspective, this largest group of sample zones in the database can be visualized as being larger than a floor the size of an American football field[2] with a 10-foot ceiling. This conflict between the PCE and TCE trends pointed to a need to further analyze the data set. It is possible, for example, that the trends are being driven by indoor sources or by a small number of buildings in some cases. A strong TCE flux source would be needed to sustain high concentrations of TCE in these large spaces, especially considering that the air exchange rate of large open buildings such as factories, garages, and warehouses tends to be medium to high[3]. Ventilation rates for new DoD buildings are generally required to comply with American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1[4]. Screened data plots (**Figures E27** and **E28**) did not show a clear relationship between TCE concentration and sample zone volume.

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[2] Dimensions of football fields can be found at http://turf.missouri.edu/stat/reports/fielddems.htm

[3] Recommended design air exchange rates for these spaces are typically greater than 2 air exchanges per hour see: http://www.engineeringtoolbox.com/air-change-rate-room-d_867.html. Testing of a series of DoD zones with volumes between 9,900 ft^3 and 27,600 ft^3 using a variety of methods generally showed air exchange rates between 0.5 and 2 per hour. See Tetra Tech "Final Report on Air Exchange Rate Analysis and Protocol Development" submitted to AFCEE, February 2012. http://rd.tetratech.com/vaporintrusion/projects/doc/AER_Study_Report_Final.pdf

[4] Unified Facilities Criteria "Heating, Ventilating and Air Conditioning Systems" UFC 3-410-01, July 1, 2013 http://www.wbdg.org/ccb/DOD/UFC/ufc_3_410_01.pdf

The trends for cis-1,2-DCE and 1,2-DCA are much less pronounced (**Figures E29** and **E30**), suggesting that indoor air concentrations of these compounds are largely independent of sample zone volume. Given that sample zone volume is the product of sampling zone area and height, the detailed quantitative investigation is focused on area and height as separate variables. Sample zone volume was also included as one of the variables tested in the multiple regression analysis discussed in the main text.

E.1.4.3 Indoor Air Grouped By Building Area

Because detailed air exchange rate measurements between sample zones are not available for the studied population of buildings, some degree of air mixing throughout the building volume is presumed to occur. Therefore, given equal source strengths, large buildings would be expected to have a greater capacity for dilution and thus lower indoor air concentrations.

However, several studies (USEPA, 2009; Shen, 2013, USEPA 2012b) indicate that concentrations in soil gas and groundwater beneath a building slab or other lower permeability surface are increased by a capping effect that limits volatilization especially below the center of a large building. This effect would result in higher sub-slab soil gas concentrations beneath large buildings. In turn, the higher sub-slab soil gas concentrations could result in higher indoor air concentrations. Thus, increasing building area could have two opposite effects, depending on whether the dilution effect or capping effect is stronger. Shen et.al. (2013) suggest that the capping effect will be great when the non-dimensional ratio of the “Building Characteristic Size” β to the thickness of the relatively dry soil layer l_o is large (β/l_o between 0 and 8).

The median and 75th percentile detectable PCE indoor concentrations decrease significantly (by up to orders of magnitude) with increasing building size (**Figure E31**). This trend is also clear on an XY graph (**Figure E32**) after filtering/screening (baseline, source strength, and preferential pathway screens applied).This provides relatively strong evidence that larger buildings provide more volume for dilution in cases where either the VI occurs in only a portion of the building or where the strength of indoor sources is not proportional to the size of the building. For example, the same mass of volatiles would result in higher concentrations in a small building compared with a large building because of dilution and mixing.

However the same pattern was not observed for TCE, regardless of filtering/screening (**Figure E33**) or for cis-1,2-DCE (**Figure E34**). In these cases, the highest concentrations appear to be associated with medium building areas between 20,000 and 100,000 sq ft. This unexpected trend is attributable to data from at least three facilities, suggesting it is a reasonably robust finding. For the other analytes, there was generally insufficient data remaining after screening to draw a conclusion on this relationship. One possible physical explanation for the observation of this trend for PCE but not for TCE and cis-1,2-DCE is that TCE and cis-1,2-DCE are often formed as biodegradation productions of PCE under mildly anaerobic conditions. Although petroleum hydrocarbons and other sources of readily biodegradable organic matter where not the focus of this database analysis, the presence of petroleum hydrocarbons is common at DoD chlorinated solvent impacted sites. Modeling studies have shown that at sites with relatively thin vadose zones (5 ft), there are concentrations of petroleum hydrocarbon vapors that will result in an “oxygen shadow” beneath medium and large buildings that is not present beneath small buildings with otherwise identical conditions (Abreu, 2013). The sites in this database are predominantly characterized by relatively thin vadose zones.

There is no apparent trend for 1,2-DCA (**Figure E35**), but an apparent increase in concentration with increasing area for 1,1-DCA (**Figure E36**).

E.1.4.4 Indoor Air Grouped by Maximum Building Ceiling Height

As discussed in E.1.4.1, theory would suggest that ceiling height could have at least two opposite effects:

1) The strength of the stack effect is proportional to the square root of the building height (Hui, 2003; ITRC, 2007)

2) All else being equal, increased ceiling height on the ground floor should decrease indoor concentrations, when those concentrations are attributable to VI; because a greater volume of indoor air is available for dilution (ITRC, 2007).

There appears to be a significant *positive* correlation between sub-slab soil gas concentration and building height in the dataset (**Section E.2.3**). The plots in this section have been normalized for this effect by dividing the indoor concentration by the sub-slab soil gas concentration.

The PCE, TCE and cis-1,2-DCE data sets (**Figures E37** to **E41**) suggest that maximum indoor air concentrations are associated with intermediate ceiling heights in the unscreened data sets. Those plots also suggest that the percentage of detectable indoor air samples is greater with intermediate ceiling heights. This is a theoretically possible outcome if two separate effects are moving in opposite directions. However, there is not a clear observable trend in the screened data sets. No trend is observed for 1,2-DCA (**Figure E42**).

E.1.4.5 Indoor Air Subdivided by Building Volume

Figures E43 to **E48** display the indoor air concentrations grouped by building volume. PCE concentrations for the 75th quantile and for the median are highest for the smallest group of buildings. This trend makes physical sense under the assumption that larger buildings provide more dilution of any single source. However, the effect could be influenced by a larger number of sources (e.g., industrial activities or soil gas entry points) in larger buildings. It is also possible that this effect could be confounded by an association of building size with use. The same trend does not hold for TCE or DCE. 1,2-DCA has a week trend with the highest median in the smallest two groups.

E.1.5 Indoor Air by Presence of Subgrade Structures

The presence of a subgrade structure did not appear to increase indoor concentrations in any of the cases examined. Therefore, these graphs were not presented for brevity.

E.1.6 Indoor Air vs. Soil Type

The soil type directly under the sample zone was included in the database based on this definition:

“If silts or clays are indicated in boring logs or cross sections for the vadose (unsaturated) zone near or beneath the building, the User should enter “Fine” as the soil type. This includes strata containing coarser-grained components such as silty sand, gravelly clay, etc. The “Coarse” soil type should be entered in cases where no fines are indicated or only traces of fines are indicated. The interbedded soil type should be entered in cases where there are two or more layers with different (i.e., coarse and fine) soil types.”

Indoor air concentrations as a function of soil type are presented in **Figures E49** through **E52**. For the highly chlorinated ethane compounds PCE and TCE, higher indoor air concentrations are associated with fine soils (**Figures E49** and **E50**). The effect is statistically significant in the unscreened data set (**Tables E1** and **E2**). The effect is still visible in the screened datasets sorted by facility (**Figures E51** and **E52**). Although in each case the fine soil points above the median are all drawn from one or two facilities, it should be noted that the facilities in question are different for PCE and TCE (**Figures E51** and **E52**).

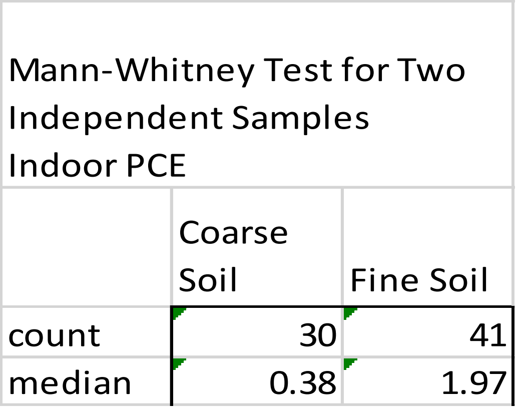
The trend of higher indoor air concentrations in buildings over fine soils appears to hold, but to a lesser extent, for the degradation product cis-1,2-DCE (**Figures E53** and **E54**). However, the number of detectable results included in the analysis is small.

In contrast, fine soils are not associated with higher indoor concentrations for 1,1-DCE (**Figure E55**).

The highly chlorinated ethane 1,1,1-TCA and its degradation product 1,1-DCA appear to show higher and more frequently detected concentrations overlying fine soils (**Figures E56** and **E57**). However, the number of detectable results is small and the Fisher-exact test does not reach statistical significance.

No effect is suggested with 1,2-DCA (**Figure E58**).

TABLE E1
Mann-Whitney Test for Two Independent Samples
PCE Indoor Air Concentration vs Soil Type

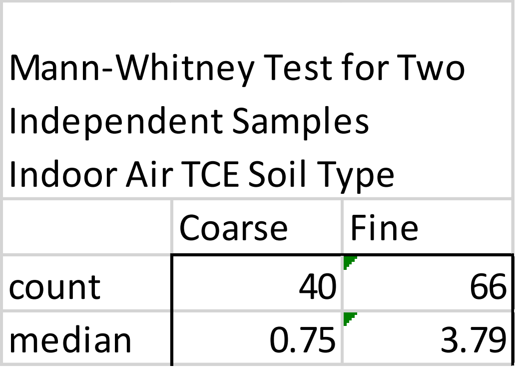


Mann-Whitney Test for Two
Independent Samples
Indoor PCE

	Coarse Soil	Fine Soil
count	30	41
median	0.38	1.97

p value, 2 tailed =0.0003

TABLE E2
Mann-Whitney Test for Two Independent Samples
TCE Indoor Air Concentration vs Soil Type



Mann-Whitney Test for Two
Independent Samples
Indoor Air TCE Soil Type

	Coarse	Fine
count	40	66
median	0.75	3.79

p value, 2 tailed = 3.5e-6

E.1.7 Indoor Concentrations Grouped by Preferential Pathways, Specific Preferential Pathway Types and Subgrade Structures

A consistent pattern is not observed when the data is reviewed using the original preferential pathway definition with the unscreened data sets. A slight tendency to higher indoor air concentrations with preferential pathways with TCE is observed with the original definition but this tendency is less clear with the strict definition.

Similarly, consistent patterns are not observed when the indoor air data is sorted by the presence or absence of floor drains. However, a somewhat higher indoor air concentration is observed for TCE in the presence of floor drains.

No clear indoor air concentration trends are observed when the data is sorted by the presence or absence of vault pits, nor was there a clear trend when subgrade structures were sorted into the categories of none, utility corridor or vault.

E.1.8 Indoor Air Data Subdivided by Facility

Figures E59 through **E64** present the indoor air concentration data by facility. The facilities with the highest concentrations are different by compound, which could reflect either differing release histories or differing biogeochemical environments in the subsurface. The clustering of results by facility suggests some caution is needed in interpreting the statistical analyses of the overall data set, since the sampling locations are not randomly selected.

PCE and TCE were detectable in some samples at almost all facilities. Vinyl chloride was detectable at only two facilities, and in very low concentration.

E.1.9 Indoor Air Data Subdivided by Facility and Specific Building

Figures E65 to **E71** show the distribution of key contaminants in indoor air at specific buildings, grouped by facility. The data is clustered by building, which could be reflective of either subsurface or indoor sources. For PCE and TCE, the facilities with the highest indoor air concentrations each have more than one building where high concentrations were detected.

E.1.10 Indoor Air Data Subdivided by Building Use

Figures E72 through **E79** show concentrations of key contaminants by building use (note that buildings may include multiple sample zones and multiple uses). The PCE concentration is highest among the offices (which could possibly suggest that dry cleaning is an important source). However, the other compounds (TCE, cis-1,2-DCE, and trans-1,2-DCE) are highest in workshop and warehouse building uses, which may include original release points.

E.1.11 Indoor Air Data Subdivided by Sample Zone Use

Sample zones are more likely to have a single type of use then buildings as a whole. **Figures E80** through **E87** show the indoor air data distributions subdivided by sample zone use. These distributions show substantial overlap between use categories. For PCE, some of the highest values are found in both the industrial/shop and office categories. Warehouse uses show the highest concentrations for cis-1,2-DCE and 1,2-DCA. 1,2-DCA is often associated with plastic products. 1,2-DCA can also be found as a solvent and a dilutent for pesticides, paints, coatings and adhesives (Howard, 1990). All of the “kitchen/break” spaces that exhibit high concentrations in this dataset (>1 $\mu g/m^3$) are in shop buildings.

E.1.12 Indoor Air Concentrations Grouped by HVAC Type

Figure E88 and **E91** show indoor air concentrations grouped by sample zone HVAC type. In the VI field as a whole, there is a widespread expectation that engineered central HVAC systems used in commercial buildings provide a protective effect for vapor intrusion (ITRC, 2007). It is assumed that these centralized HVAC systems are operated with some percentage of fresh air intake and could therefore be setup to provide continuous positive pressurization, preventing VI (Mosely, et.al., 2008). However in this data set, a correlation between indoor air concentrations and engineered HVAC systems is not apparent.

E.1.13 Indoor Air Subdivided by Flooring Type

The database contains information about the floor covering type, compiled at the sample zone level. For three of the constituents (PCE, TCE and 1,1,1-TCA; **Figures E92** to **E95**), the highest indoor concentrations are usually found associated with bare concrete or vinyl sheet flooring. It is unclear if this could be a causative mechanism (for example sorption by the carpet, carpet backing or wood) or whether this is a confounded observation. Confounding could occur because bare concrete and vinyl tile are flooring types typically associated with more industrial and utilitarian spaces, which are also more likely to have indoor sources or be proximate to the point of release. While new building materials can also be sources of VOCs, this would not be expected in the majority of these buildings, given their ages. For most non-polar VOCs, carpet would provide higher sorption than either vinyl or wood flooring. In one test reported in the literature, wood flooring sorption for PCE was not observed although some sorption to vinyl flooring was observed (Won, et.al., 2001). Interestingly, all of the detectable vinyl chloride cases appear to be in sample zones with bare concrete floors (**Figure E95**).

E.2 Sub-slab Data

E.2.1 Sub-slab Soil Gas Data Analysis by Facility and Building

PCE concentrations in sub-slab soil gas were detectable at eight facilities. PCE concentrations in sub-slab soil gas are highest at three particular (geographically separated) facilities whether measured by the maximum, 75th percentile or median (**Figure E96**). The other five facilities have similar distributions; with median PCE sub-slab soil gas concentrations between 10 and 60 $\mu g/m^3$. When viewed at a building level (**Figure E97**), three buildings stand out with the highest sub-slab soil gas concentrations of PCE located at three geographically dispersed facilities. In contrast to the indoor air data set, few nondetectable concentrations of PCE are present in the sub-slab soil gas dataset. This clustering by building suggests that the calculated p-values should be viewed with some caution since the sample locations are not independent.

Sub-slab soil gas TCE concentrations by facility are shown on **Figure E98**. Relatively few nondetectable concentrations are observed for TCE in sub-slab soil gas. Although detection limit issues pose significant challenges in interpreting the indoor air data, this is not a significant concern in the sub-slab soil gas evaluation. Buildings with median TCE sub-slab soil gas concentrations above the USEPA screening level of 30 $\mu g/m^3$ (10^{-6} target risk for carcinogens, HQ=1) are numerous in this dataset (**Figure E99**). At least one building with a median TCE concentration above the USEPA commercial sub-slab soil gas screening level is found at all ten facilities with TCE data in the database.

Sub-slab soil gas concentrations of cis-1,2-DCE are shown by facility in **Figure E100** and by building in **Figure E101**. Since no current risk based screening levels for cis-1,2-DCE are available from USEPA in the regional risk table or the VISL calculator, the data is compared to USEPA's former sub-slab soil gas VISL of 186 $\mu g/m^3$. Nondetectable sub-slab soil gas samples with reporting limits greater than the screening level are more frequent for this compound than for PCE and TCE.

Viewed by building (**Figure E102**) the highest detectable concentrations, well above the conservative screening level are seen in three buildings. There are five buildings with nondetects for cis-1,2-DCE above the screening level.

None of the sub-slab soil gas samples collected contain concentrations of 1,1,1-TCA above the current screening level of 220,000 $\mu g/m^3$; therefore, graphs showing this compound are omitted for brevity. However, the common degradation product, 1,1-DCA has a much lower screening level of 77 $\mu g/m^3$ and more 1,1-DCA concentrations are present above the screening level (**Figures E103** and **E104**).

E.2.2 Building Area and Volume

It has been suggested that larger area buildings should have higher sub-slab soil gas concentrations due to a capping effect. However, there is not a consistent, monotonic relationship observed between the building area and the sub-slab soil gas concentration in this dataset. Nor was a consistent, monotonic relationship observed between the building volume and the sub-slab soil gas concentration in the dataset (**Figures E105 to E112**).

E.2.3 Building Height

There is not an obvious mechanistic linkage between building height and sub-slab soil gas concentration. Empirically however, the box and whisker plots showed a trend of increasing sub-slab soil gas concentration with increasing building height at least above 10 ft. The trend is apparent in the data sets for PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, 1,1,1-TCA, 1,1-DCA, and 1,1-DCE (**Figures E113 to E129**). For 1,2-DCA and vinyl chloride, there are not enough detectable sub-slab soil gas samples present in the dataset to suggest a trend. A statistically significant relationship was observed between the maximum building height and:

- log of cis-1,2-DCE sub-slab soil gas concentration ($r^2 = 0.23$, $p<0.001$) ,

- log of trans-1,2-DCE sub-slab soil gas concentration (r^2=0.12, p<0.001),
- log of 1,1,1-TCA sub-slab soil gas concentration (r^2 = 0.06, p=0.014),
- log of 1,1-DCE sub-slab soil gas concentration (r^2=0.20 and p=0.0019).

A weakly statistically significant relationship was observed between building height and:

- log of PCE sub-slab soil gas concentration (r^2 = 0.019, p=0.045),
- log of TCE sub-slab soil gas concentration (r^2=0.023, p=0.024),
- log of 1,1-DCA sub-slab soil gas concentration (r^2= 0.079, p=0.031).

Given the observed empirical relationship, there are several possible mechanisms that could be explanatory:

1) High ceilings are typically needed for shop/industrial operations while ceilings <10 ft are typical for office occupancies. Therefore, the association of high ceilings with high sub-slab soil gas concentrations may be confounded, since the shop/industrial buildings are more likely to be located near the original release.

2) Increased building height should lead to increased strength of the stack effect, all else being equal, according to the defining equation.

3) Taller buildings on average require deeper foundations. As discussed previously the coarse backfill along deeper footings could provide a mechanism for mass transport to the sub-slab. Thais effect could be particularly noticeable in this dataset given the relatively shallow groundwater typical of coastal, Naval sites.

To test whether this was a confounding effect of building use or a physical effect the analysis is repeated for certain subsets of buildings by use.

- For PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, 1,1,1-TCA and 1,1-DCA among industrial/shop buildings, there was no statistically significant height effect trend (log concentration vs. height for PCE p=0.26; TCE p=0.25; cis-1,2-DCE p=0.10 trans-1,2-DCE p= 0.89; 1,1,1-TCA p= 0.37; 1,1-DCA p= 0.69)

- For 1,1-DCE among industrial/shop building uses there was a statistically significant height effect (r^2 =0.19 and p=0.004) (**Figure E137**)

- For PCE and TCE, there was a statistically significant height effect for office building uses (PCE log concentration vs. height r^2=0.15, p=0.014; TCE log concentration vs. height r^2=0.22 p=0.026) (**Figures E128 and E129**).

- Additional subsets by building use were not analyzed because of small sample sizes.

This analysis suggests that much of the apparent height effect on sub-slab soil gas concentration is caused simply by tall buildings commonly being used for industrial or shop purposes. Some residual effect is present in some cases even when segregated by building use.

E.2.4 Building Construction Date

From historical reasoning, one might expect to find higher sub-slab soil gas concentrations beneath buildings constructed before modern environmental regulation and awareness. Older buildings would also be expected to have more slab cracking. For certain contaminants – such as 1,1,1-TCA (**Figure E130**), 1,1-DCA (**Figure E131**), 1,1-DCE (**Figure E132**) - there appears to be a clear pattern of higher concentrations and more frequent detections beneath buildings constructed before 1960. This pattern was either absent or less clear for the other contaminants studied.

E.2.5 Preferential Pathway

There isn't a consistent relationship observable between sub-slab soil gas concentrations with and without preferential pathways (**Figures E133** to **E146**, original and strict definitions separately presented). However in some cases, the concentrations in soil gas associated with strict preferential pathways being present appeared to be lower or not detectable in comparison to than at locations with strict preferential pathways absent. Note however that the number of cases of strictly defined preferential pathways and thus sample size is small for this group.

E.2.6 Floor Drains

Floor drains are frequently suspected as routes of contaminant migration to the subsurface. However, in this data set there was only weak evidence for such an association. The most visually persuasive relationship with floor drains was observed for 1,1,1-TCA which showed a higher frequency of detection, higher median, and higher 75th percentile concentrations in the presence of floor drains (**Figure E147**). In contrast, vinyl chloride is more frequently observed in sample zones without floor drains. This observation could be attributable to a greater exchange of oxygen with the sub-slab in buildings with floor drains or merely be an artifact of the small number of cases where vinyl chloride was observable (**Figure E148**).

E.2.7 HVAC Type

For several contaminants, the concentrations in sub-slab soil gas beneath zones with engineered HVAC systems (as compared to zones with no HVAC system or only zone specific HVAC) were notably higher:

- 1,1-DCA and 1,1-DCE (50th and 75th and higher percentiles) (**Figures E149 and E150**)
- PCE and 1,1,1-TCA (75th and higher percentiles) (**Figures E151** and **E152**)

A possible mechanistic explanation for these observations is that positively pressurized indoor environments minimize physical attenuation of VOC concentrations in the sub-slab via volatilization, which would also be consistent with the interpretation above of the sub-slab soil gas data as a function of preferential pathways. However, the statistical power of this observation is limited, because the engineered HVAC systems are by far the most frequent case in the dataset.

The trend was less distinct for cis- and trans 1,2-DCE (**Figures E153** and **E154**). A possible explanation for this difference is that positively pressurized indoor environments inhibit volatilization but enhance aerobic degradation for these compounds.

TCE concentrations were highest in association with zones with no HVAC system (**Figure E155**)

There was insufficient data to reach a conclusion on this point for 1,2-DCA and vinyl chloride.

E.2.8 Building Use

Building use was coded in the database based on current building use. For almost all of the studied contaminants except PCE, sub-slab soil gas concentrations were highest beneath industrial/shop or mixed use buildings. This trend holds for TCE, cis-1,2-DCE, trans-1,2-DCE, vinyl chloride, 1,1,1-TCA, 1,1-DCE and 1,2-DCE (**Figures E156** to **E163**). This observation most likely reflects the proximity of these building uses to points or areas of contaminant release, suggesting that building use will be a useful variable for building prioritization for VI investigations.

The one clear exception to this pattern is PCE where the maximum and 75th percentile of the office sub-slab soil gas data exceed the corresponding values for the shop use. The PCE exception is entirely due to two small buildings at one facility. These buildings have as their primary source an industrial sewer. There is one called the “motor trans and cobbler shop” where the name suggests a quite different historical use than the current noted use of office space and locker room. The second is currently being used as an office but the history is unknown.

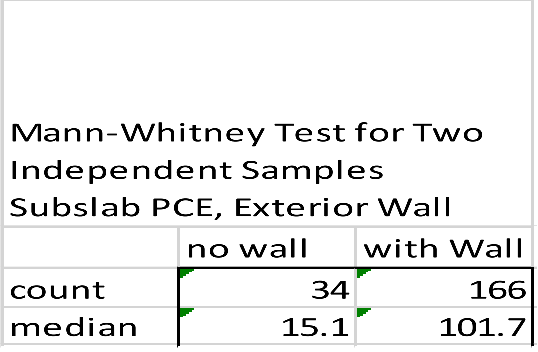
Too few observations for 1,2-DCA were available in sub-slab soil gas for a productive analysis.

E.2.9 Exterior Wall (Present in Sample Zone)

For the compounds in the data set most commonly used as solvents (PCE, TCE, and 1,1,1-TCA) median concentrations are substantially higher in sample zones with exterior walls (**Figures E164** to **E166** and Tables **E3** to **E5**). For PCE and 1,1,1-TCA, the result is statistically significant. 1,1-DCE and 1,1-DCA (**Figures E167** and

E168) were also significantly more likely to be detected beneath sample zones with an exterior wall (2-way contingency table analysis using probability of detection as effect, 1,1-DCE: odds ratio 6.58; significant in a two tailed test of odds ratio, p=0.002; 1,1-DCA: odds ratio 7.34, p=0.003). This trend is not observed or is less prominent for other compounds including those that are primarily formed in-situ as degradation products (cis-1,2-DCE, trans-1,2-DCE, and vinyl chloride). There are infrequent detections of 1,2-DCA so it is difficult to draw conclusions for this compound.

TABLE E3
PCE Sub-slab Soil Gas Concentration vs. Exterior Wall, Mann-Whitney Test for Independent Samples

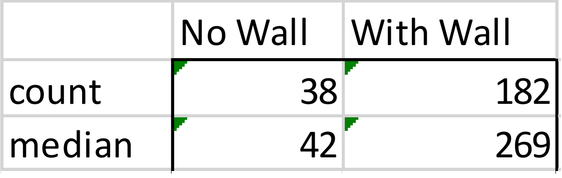


Mann-Whitney Test for Two Independent Samples Subslab PCE, Exterior Wall

	no wall	with Wall
count	34	166
median	15.1	101.7

p value, 2 tailed =0.0027

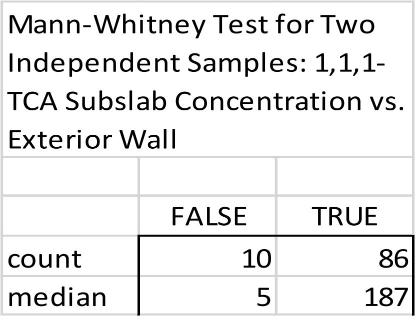
TABLE E4
TCE Sub-slab Soil Gas Concentration vs. Exterior Wall Presence, Mann-Whitney Test for Two Independent Samples



	No Wall	With Wall
count	38	182
median	42	269

p value, 2 tailed =0.213

TABLE E5
1,1,1-TCA Sub-slab Soil Gas Concentration vs. Exterior Wall, Mann-Whitney Test for Independent Samples



Mann-Whitney Test for Two Independent Samples: 1,1,1-TCA Subslab Concentration vs. Exterior Wall

	FALSE	TRUE
count	10	86
median	5	187

two-tailed p = 0.0035

This relationship has not been previously systematically discussed in the VI literature, although guidance occasionally refers to differences in sub-slab soil gas concentration near exterior walls. For example, the Massachusetts Department of Environmental Protection states "*Two to four probes are recommended for a typical single family home; more may be needed in larger buildings or if soil or groundwater contamination is high or variable. At least one of the sub-slab soil gas samples should be obtained near the center of the building footprint to offset any type of "edge effect"* (MDEP, 2014). The California Environmental Protection Agency guidance discourages sub-slab soil gas sampling near the edge of the building due to wind effects (CalEPA, 2011).

There are several possible explanations for the observed trend in the data:

- Exterior walls are typically associated with deeper foundation elements such as load beams, footings etc. These foundation elements are also typically associated with gravel layers that could conceivably facilitate contaminant movement toward the slab. There are also typically perimeter cracks or capillary breaks between the slab and wall/foundation through which flow induced by the stack effect or building exhaust ventilation might move (**Figure E169**). VI modelers have often modeled this crack as the primary point of entry. In that conceptualization, depressurization is maximized at the crack and thus flow moves toward it (**Figure E170**).

- USEPA's conceptualization of VI (USEPA, 2004) shows convective cells in the sub-slab area bounded by the foundation (**Figure E171**). This appears to be supported by literature, which shows a role for these load beams and footings in heat transfer between the building and soil system (Hagentoft 1988; Zhong, 2007).
- Anecdotal information/professional experience suggests that historic waste disposal practices often occurred just outside the building where the waste was generated. It has also been suggested that industrial/shop functions tend to be located on exterior walls where loading docks are available. Either of these historical mechanisms could cause an association between exterior walls and higher VOC concentrations in soil.
- Two related authors Schmidt (2012) and Cox (2013) have collected and analyzed high spatial resolution sub-slab soil gas data sets. These authors suggest that an important factor in understanding the distribution of contaminants beneath large commercial buildings is an understanding of the historical evolution of the building through multiple expansion cycles. These authors suggest that waste disposal locations near the exterior of historic buildings can become sub-slab sources over time.

E.2.10 Distance to Primary Release

As indicated in the main text, although significant relationships were seen for PCE, TCE and 1,1-DCA, insufficient information is available about distance to primary release and/or detectable sub-slab data to reach a reliable conclusion regarding cis-1,2-DCE, vinyl chloride, 1,1,1-TCA and 1,2-DCA. However, graphs for the first two compounds are presented as box and whisker plots (**Figures E172** and **E173**), to suggest that this variable may be worth exploring for additional compounds when a larger data set is available.

Figures

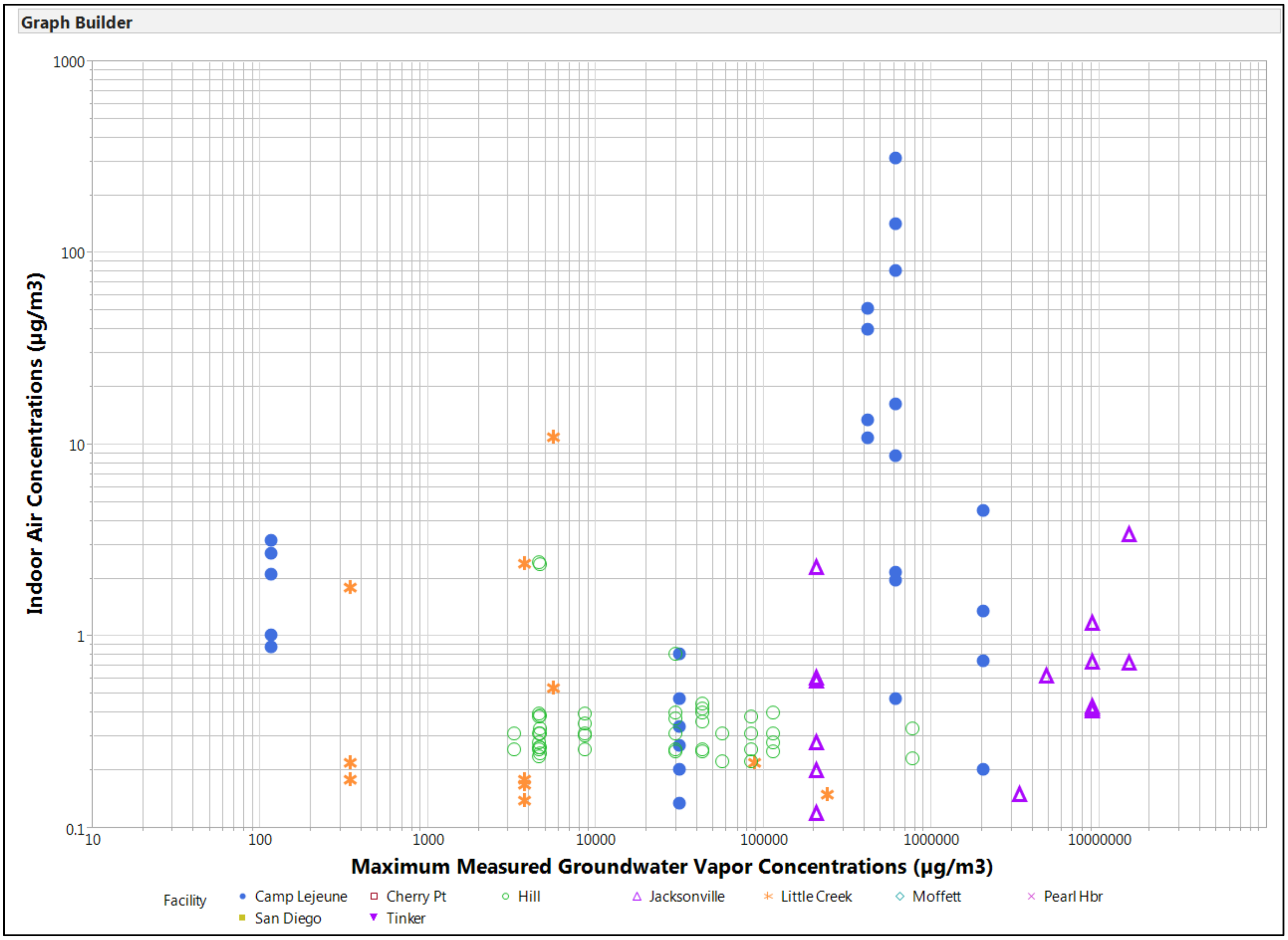


FIGURE E1
PCE Indoor Air Concentration vs Measured Maximum Groundwater Vapor Concentration
No Screens Applied
NESDI Project #476

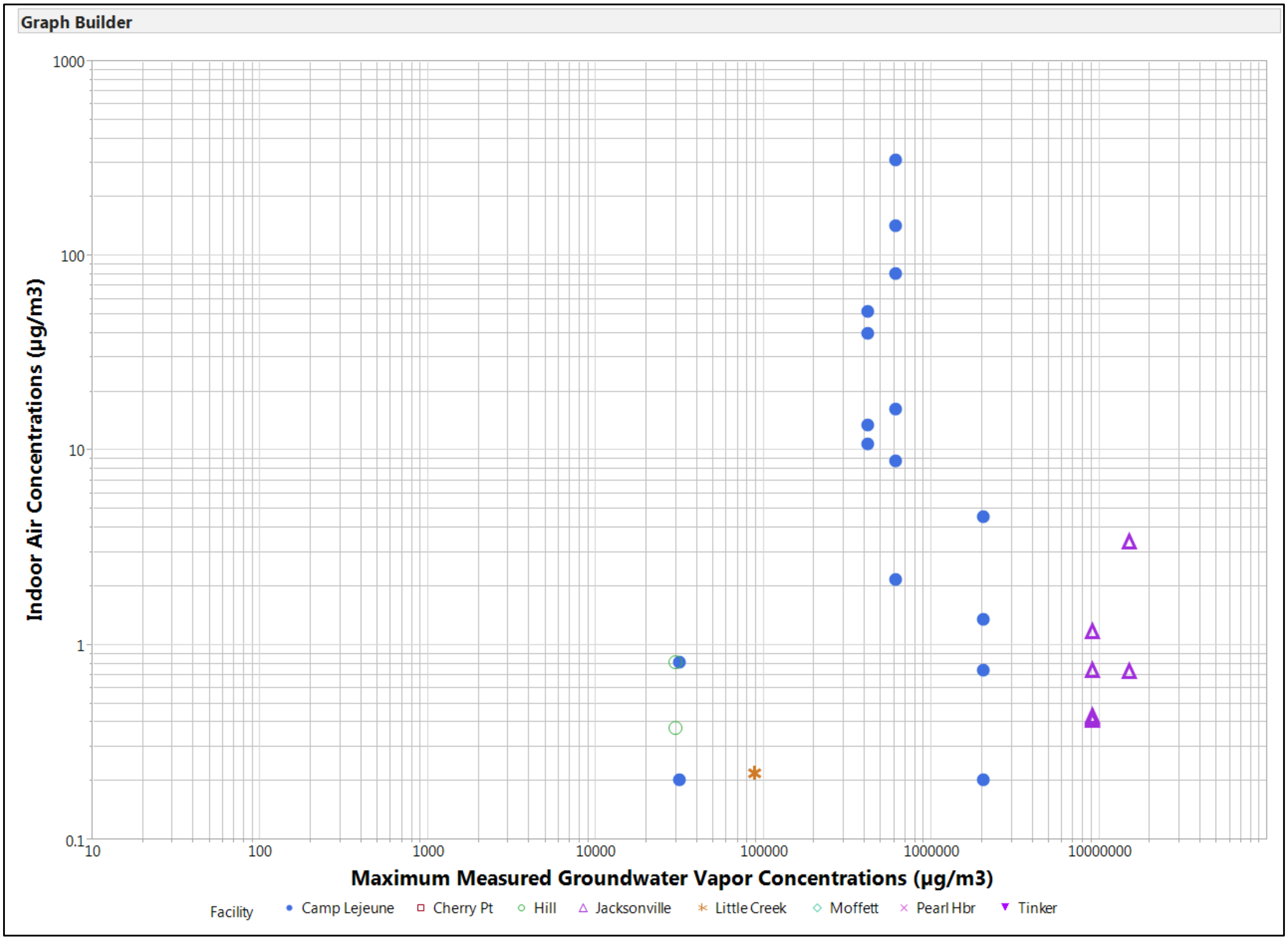


FIGURE E2
PCE Indoor Air Concentration vs Measured Maximum Groundwater Vapor Concentration
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

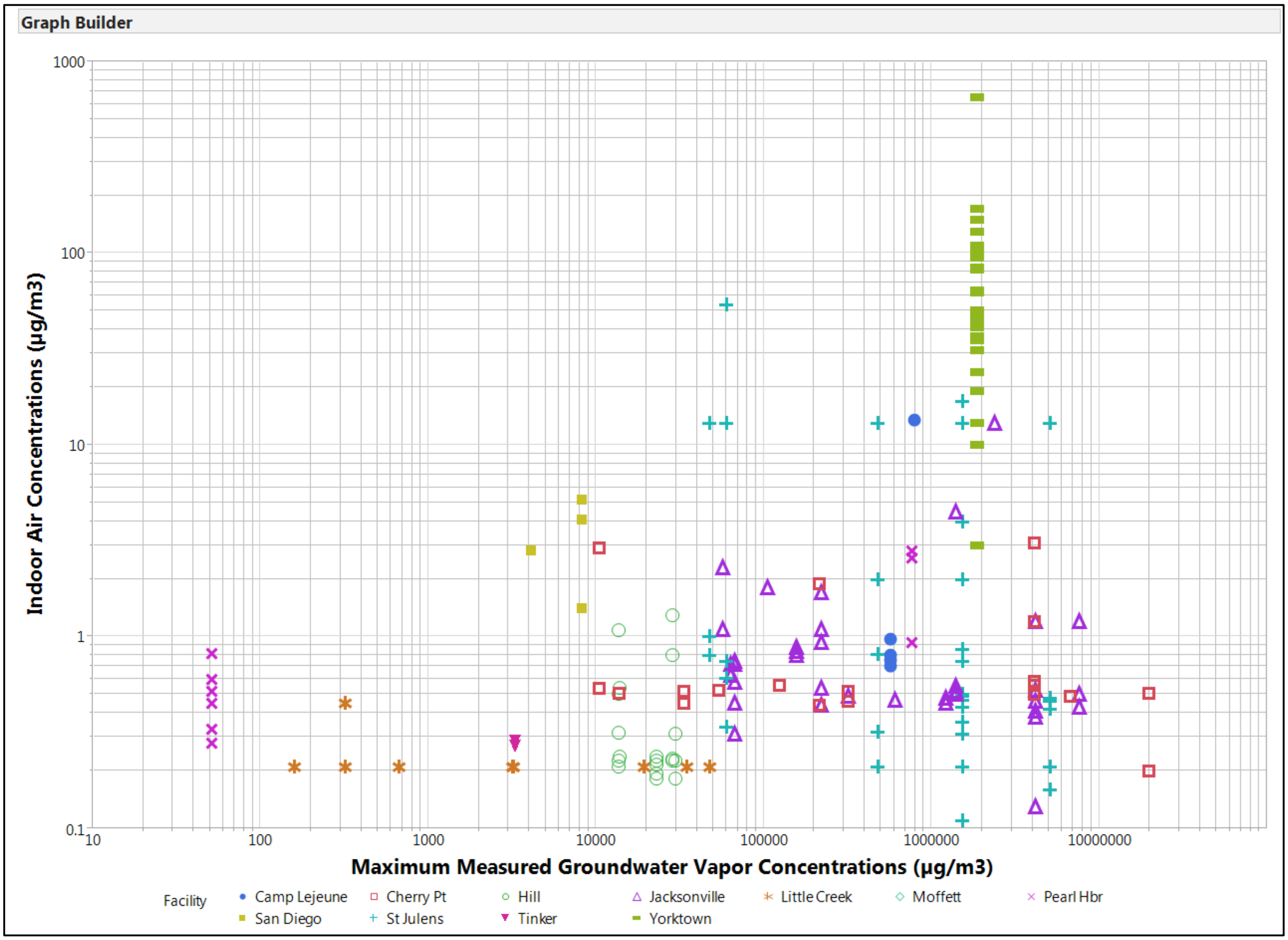


FIGURE E3
TCE Indoor Air Concentration vs Maximum Measured Groundwater Vapor Concentration
No Screens Applied
NESDI Project #476

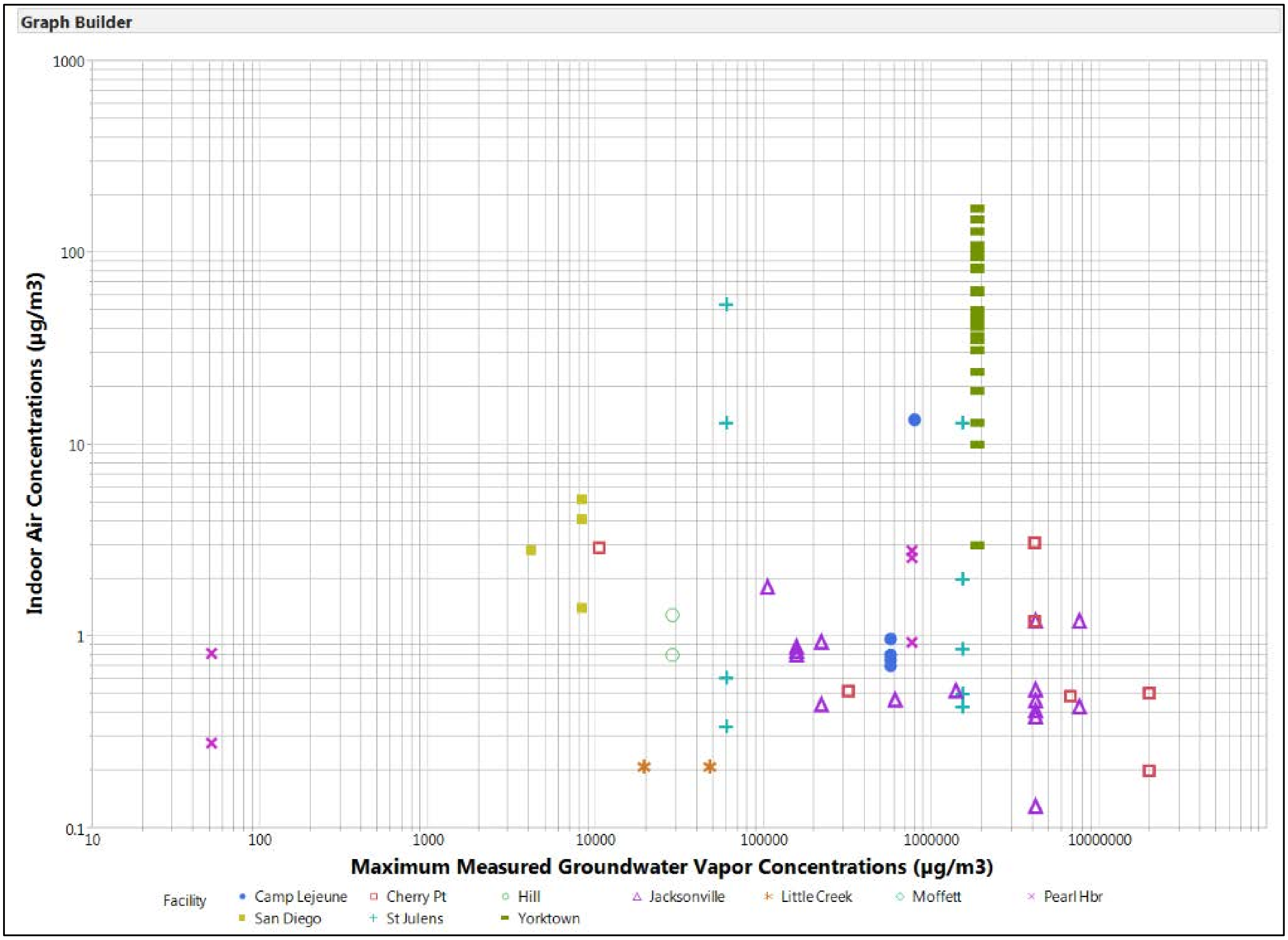


FIGURE E4
TCE Indoor Air Concentration vs Maximum Measured Groundwater Vapor Concentration
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

In the main text, sample zone averaged plots were presented relating groundwater vapor concentration to indoor air concentration. In this appendix, the corresponding plots for PCE and TCE without the zone averaging (Figures E5 to E8) are included. Data plots are presented for all data and also data with groundwater depth >5 ft, which if often used as a minimum criteria for using vapor intrusion screening levels.

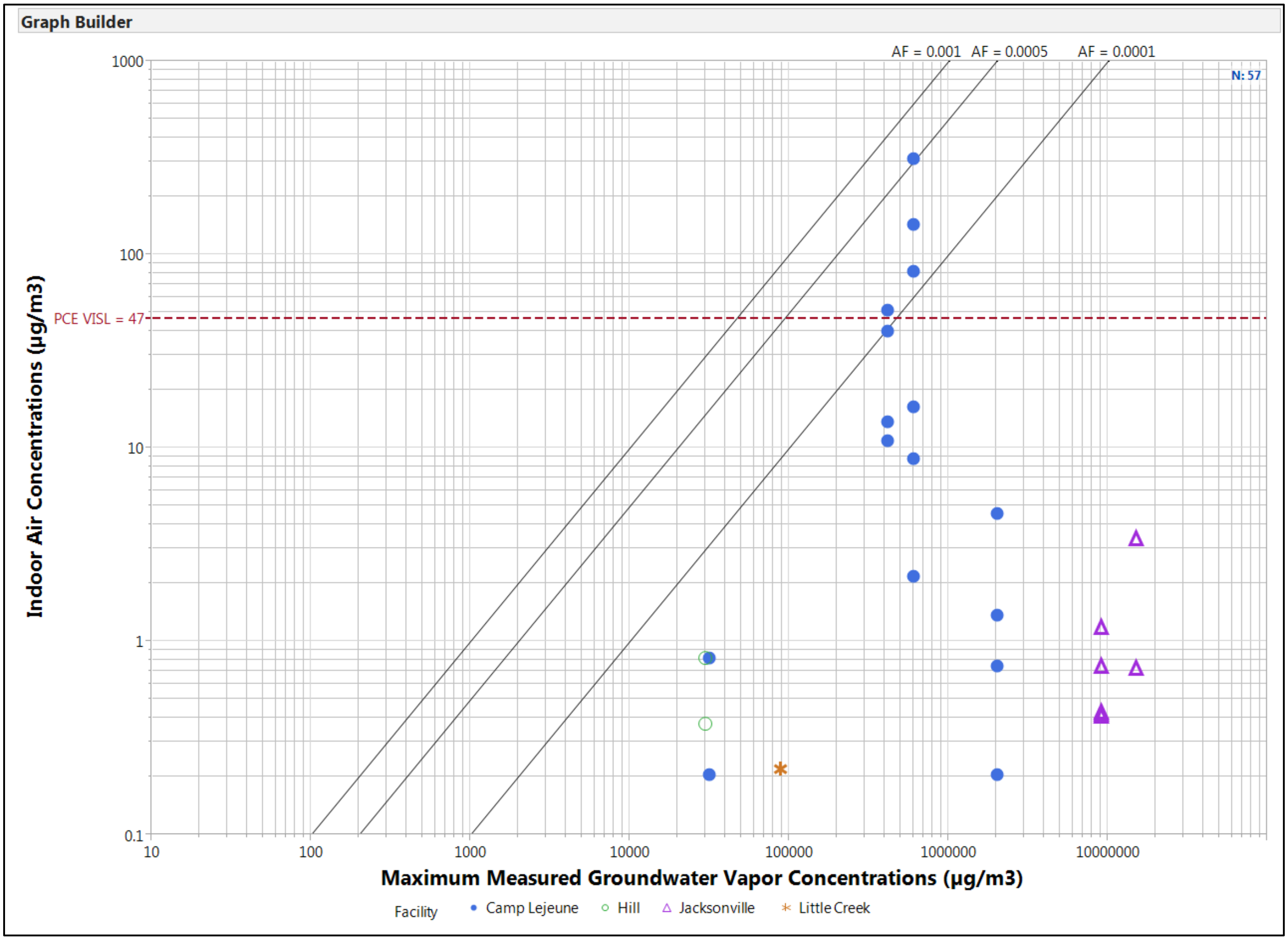


FIGURE E5

PCE Indoor Air Concentration vs Groundwater Vapor Concentration; Detectable Data Only
Baseline, Source Strength and Preferential Pathway Screens Applied; All GW Depths
NESDI Project #476

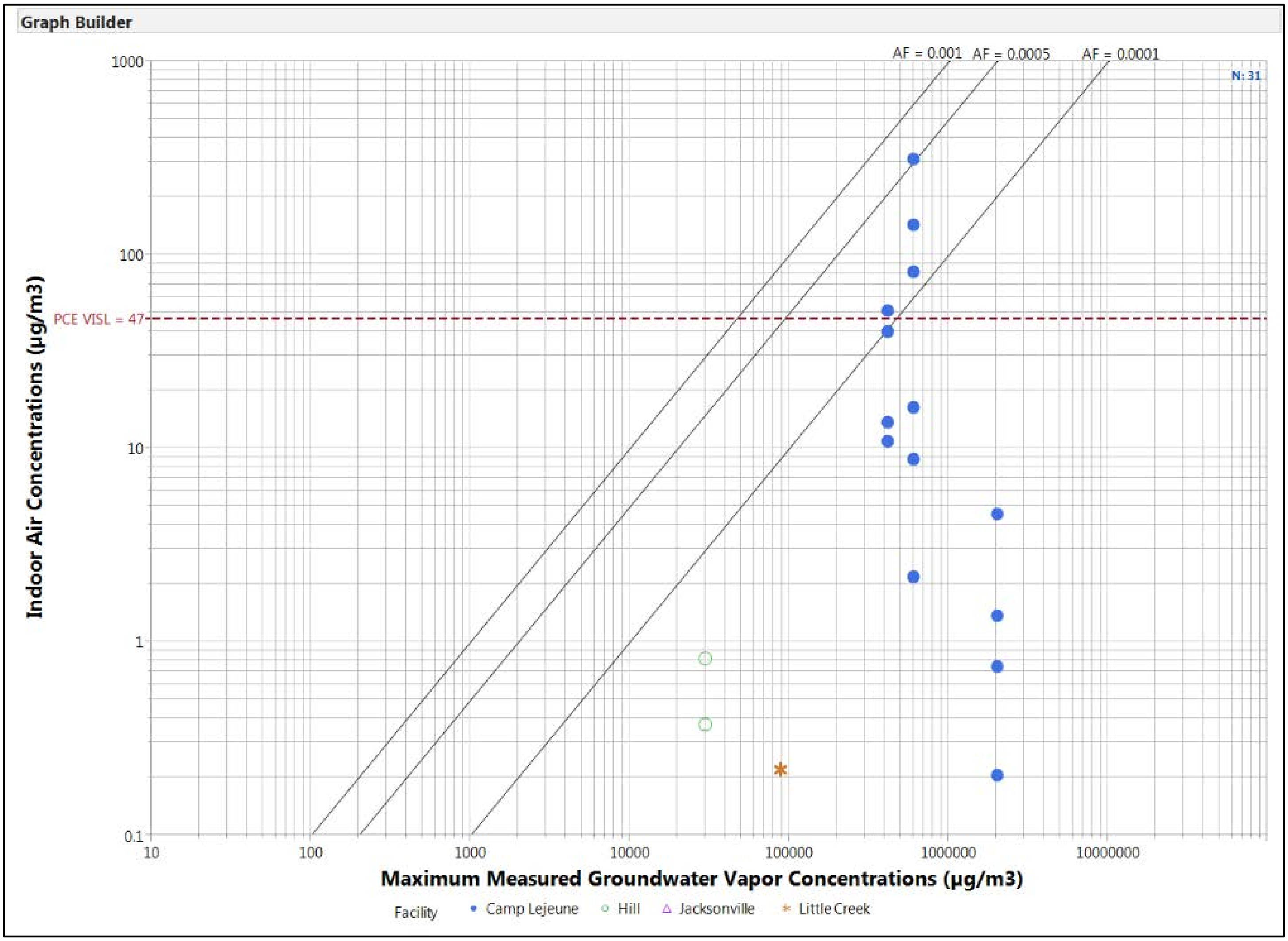


FIGURE E6

PCE Indoor Air Concentration vs Groundwater Vapor Concentration Detectable Data Only Baseline, Source Strength and Preferential Pathway Screens Applied; GW Depths >5 ft

NESDI Project #476

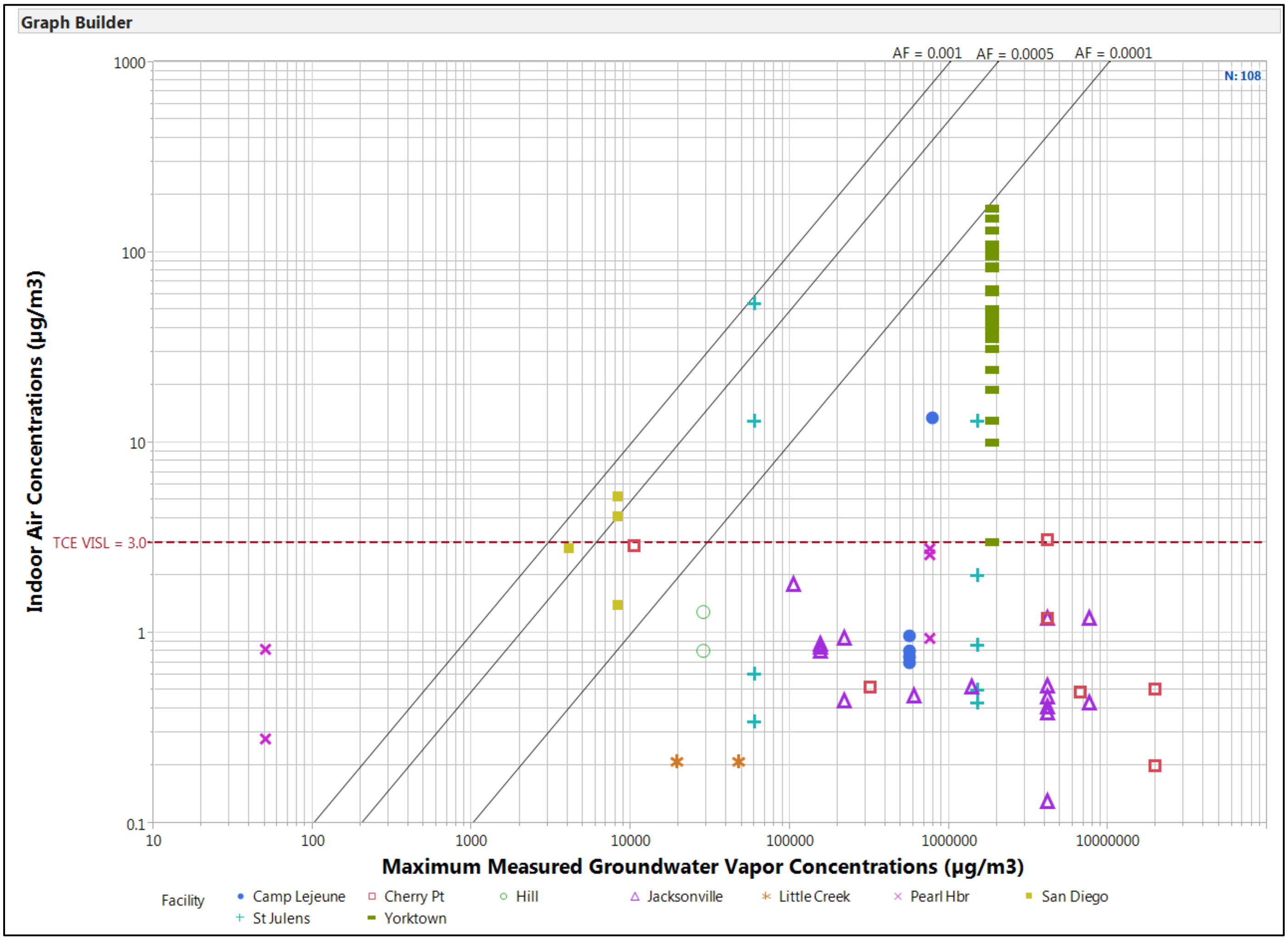


FIGURE E7

TCE Indoor Air Concentration vs Groundwater Vapor Concentration; Detectable Data Only
Baseline, Source Strength and Preferential Pathway Screens Applied; All GW Depths
NESDI Project #476

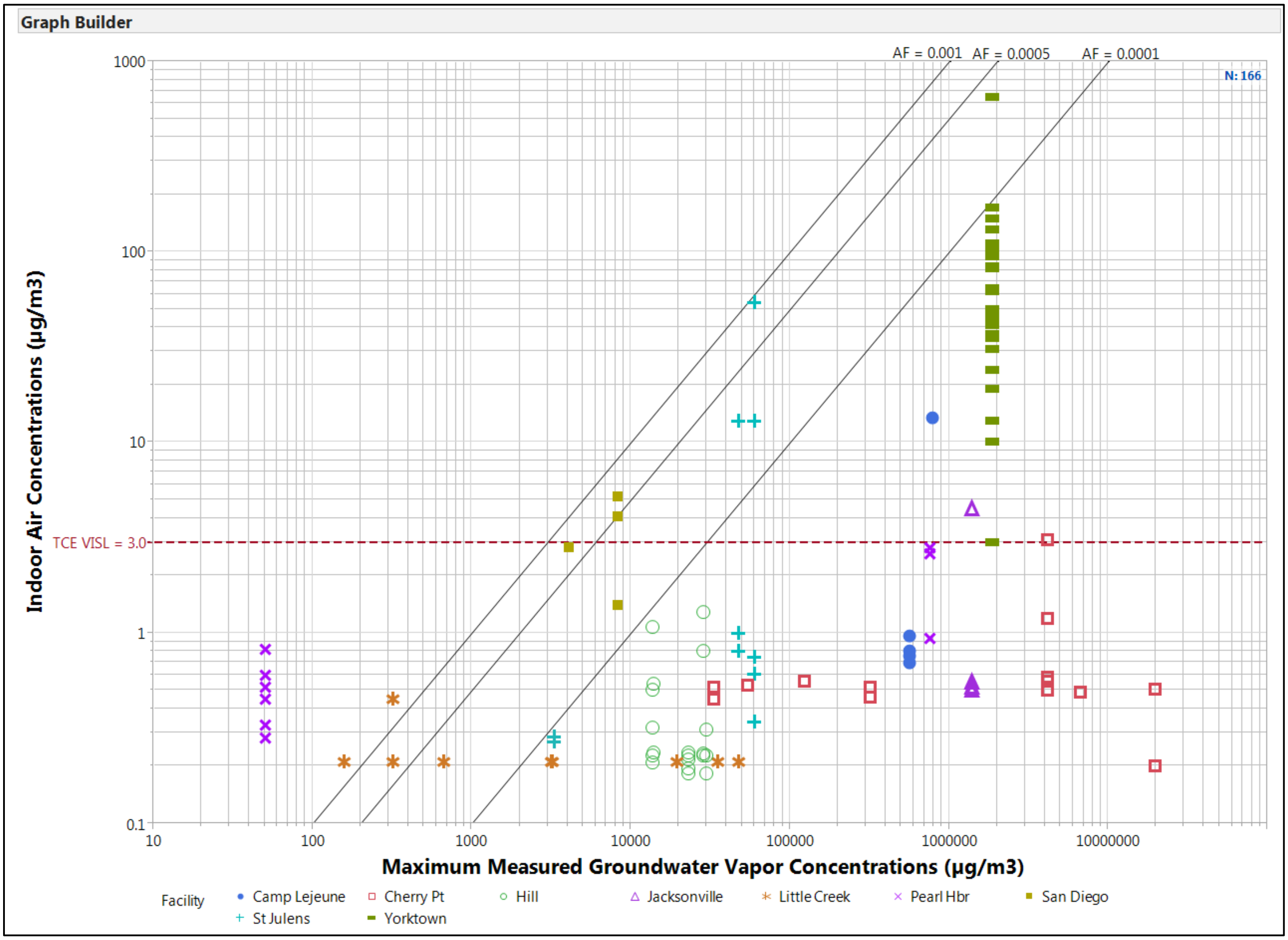


FIGURE E8
TCE Indoor Air Concentration vs Groundwater Vapor Concentration; Detectable Data Only
Baseline, Source Strength and Preferential Pathway Screens Applied; GW Depth > 5 ft
NESDI Project #476

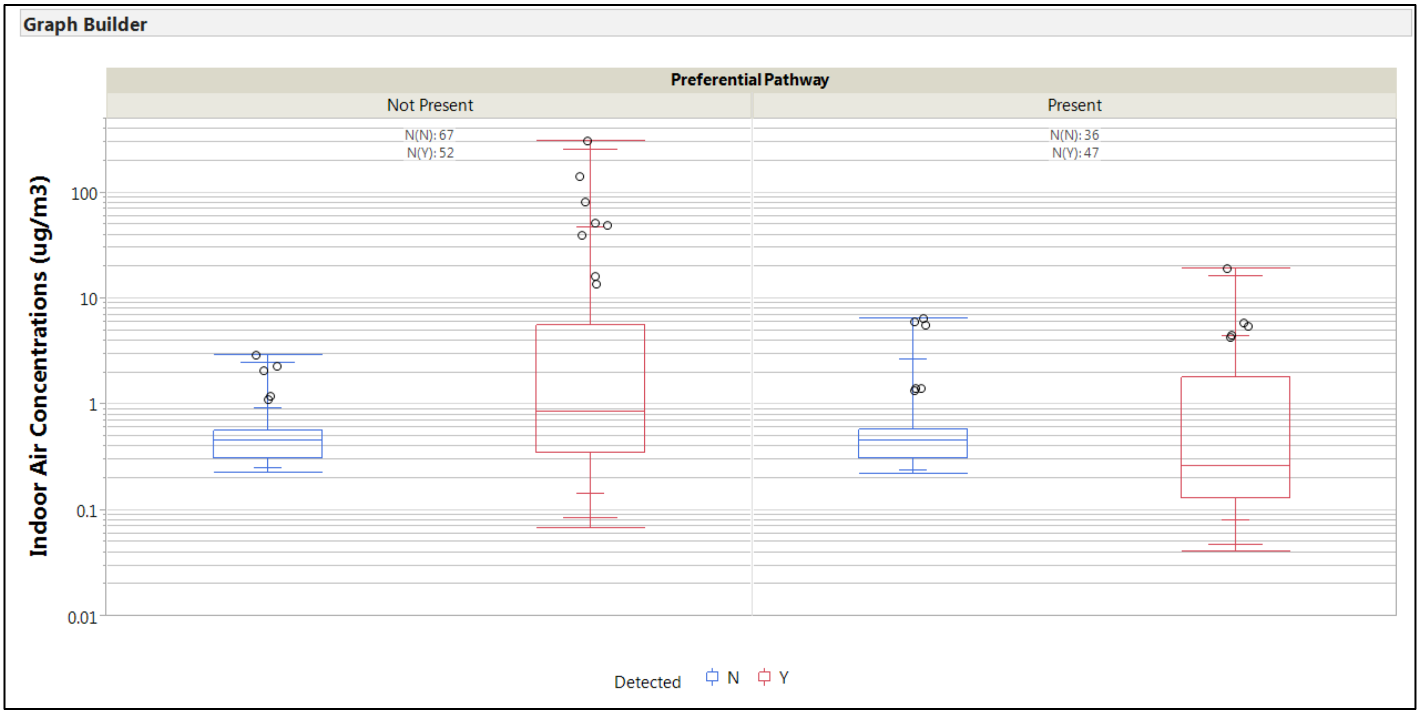


FIGURE E9

PCE Indoor Air Concentration by Preferential Pathway Presence (Original Definition)

NESDI Project #476

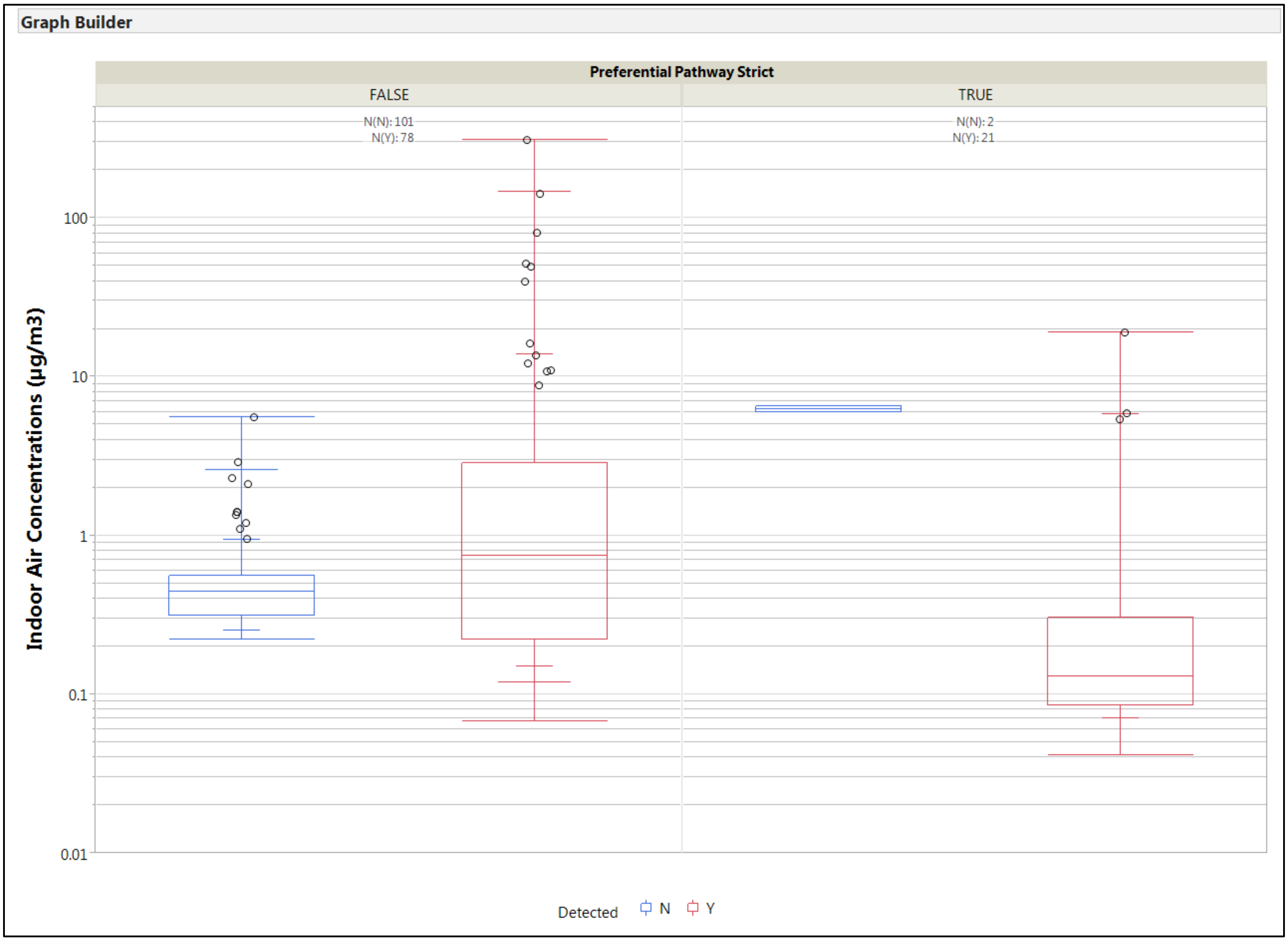


FIGURE E10
PCE Indoor Air Concentration by Preferential Pathway Presence (Strict Definition)
NESDI Project #476

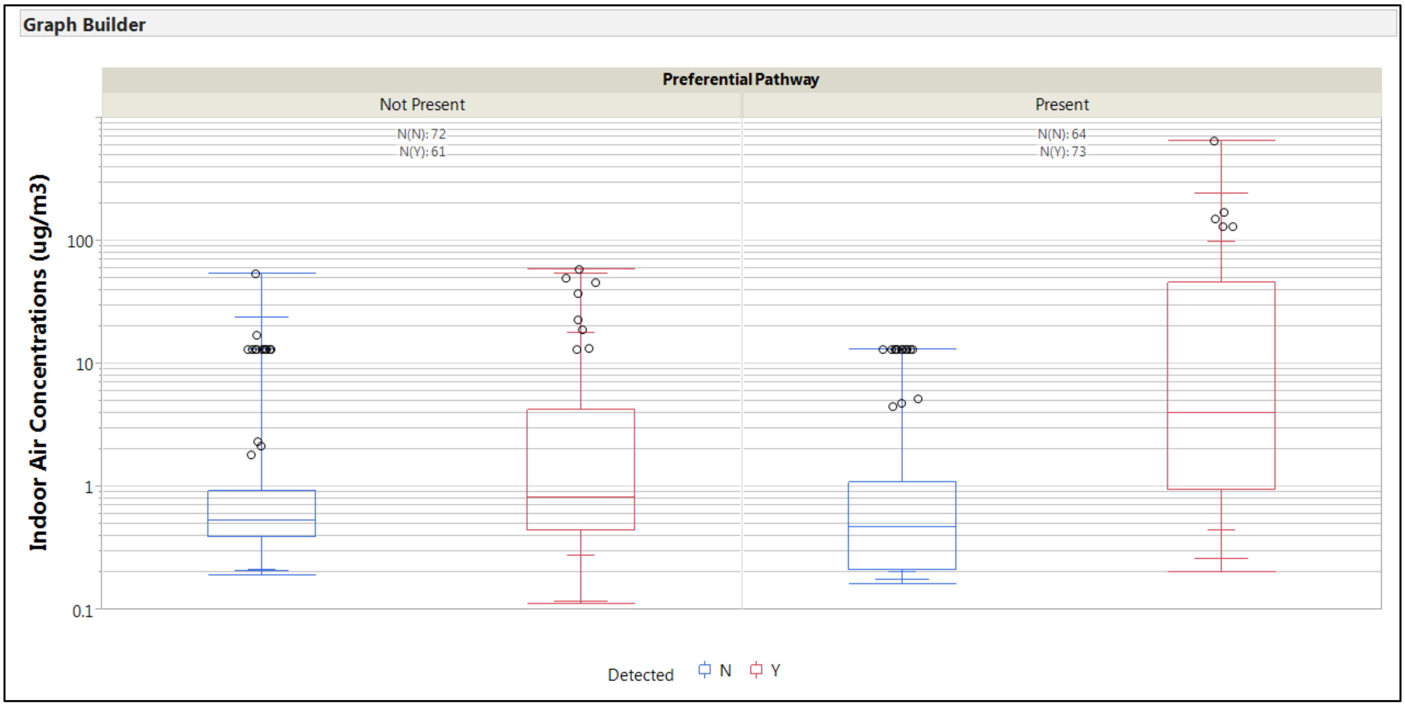


FIGURE E11
TCE Indoor Air Concentration by Preferential Pathway Presence (Original Definition)
NESDI Project #476

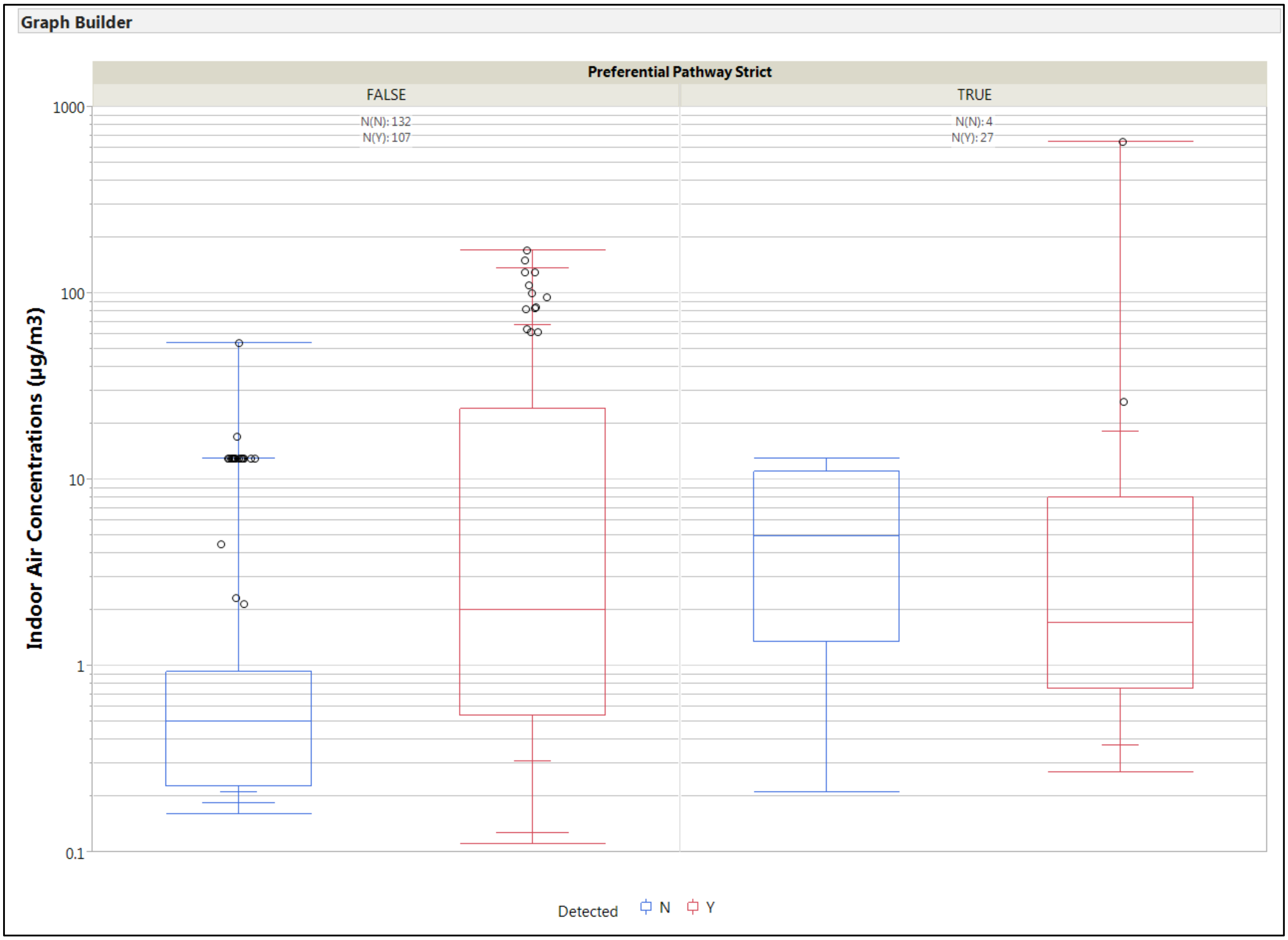


FIGURE E12
TCE Indoor Air Concentration by Preferential Pathway Presence (Strict Definition)
NESDI Project #476

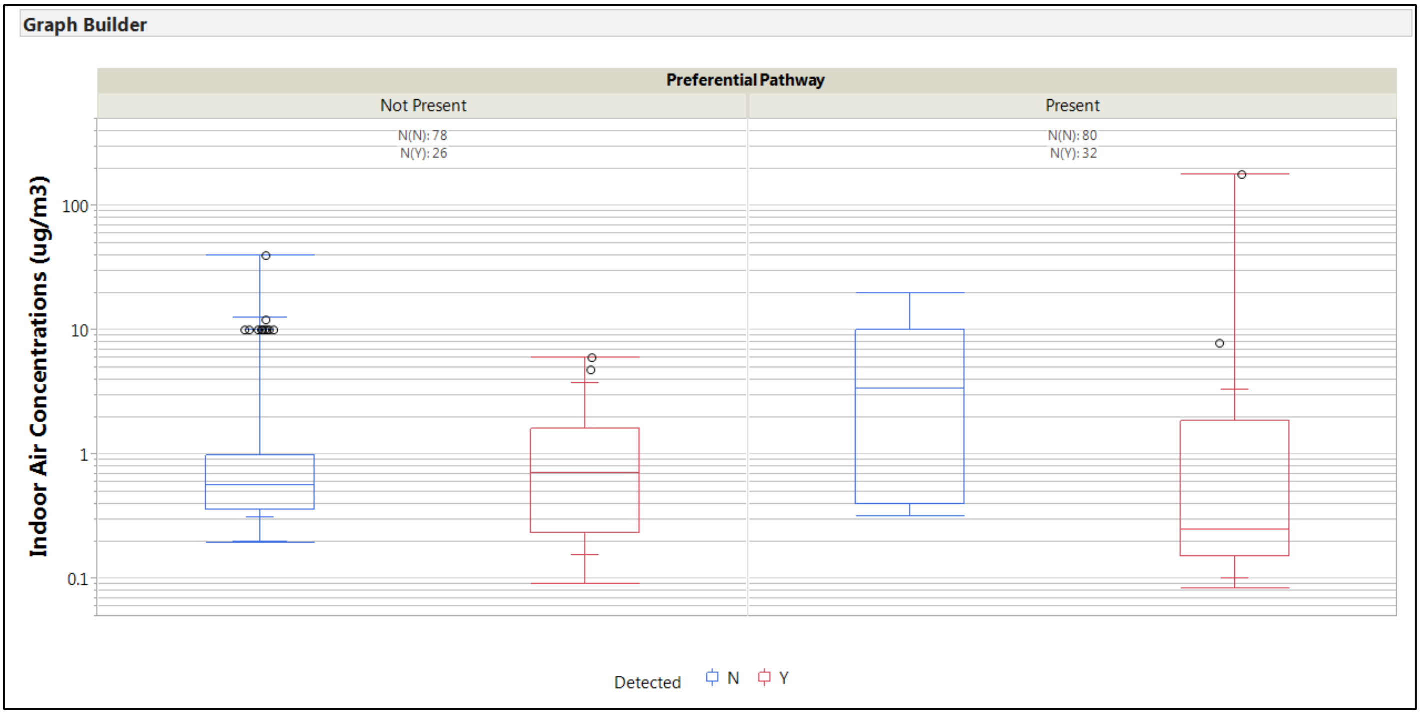


FIGURE E13
Cis-1,2-DCE Indoor Air Concentration by Preferential Pathway Presence (Original Definition)
NESDI Project #476

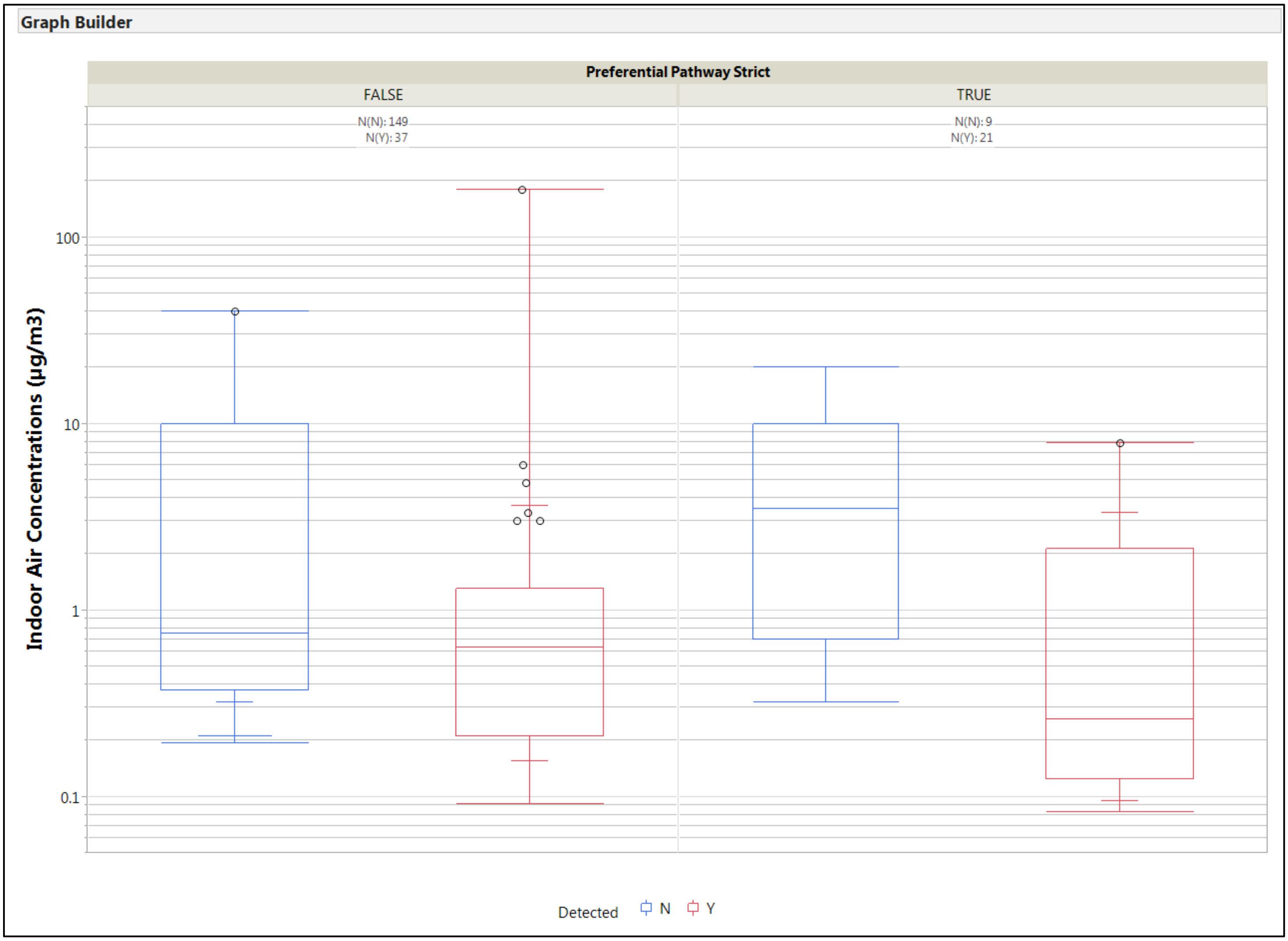


FIGURE E14
TCE Indoor Air Concentration by Preferential Pathway Presence (Strict Definition)
NESDI Project #476

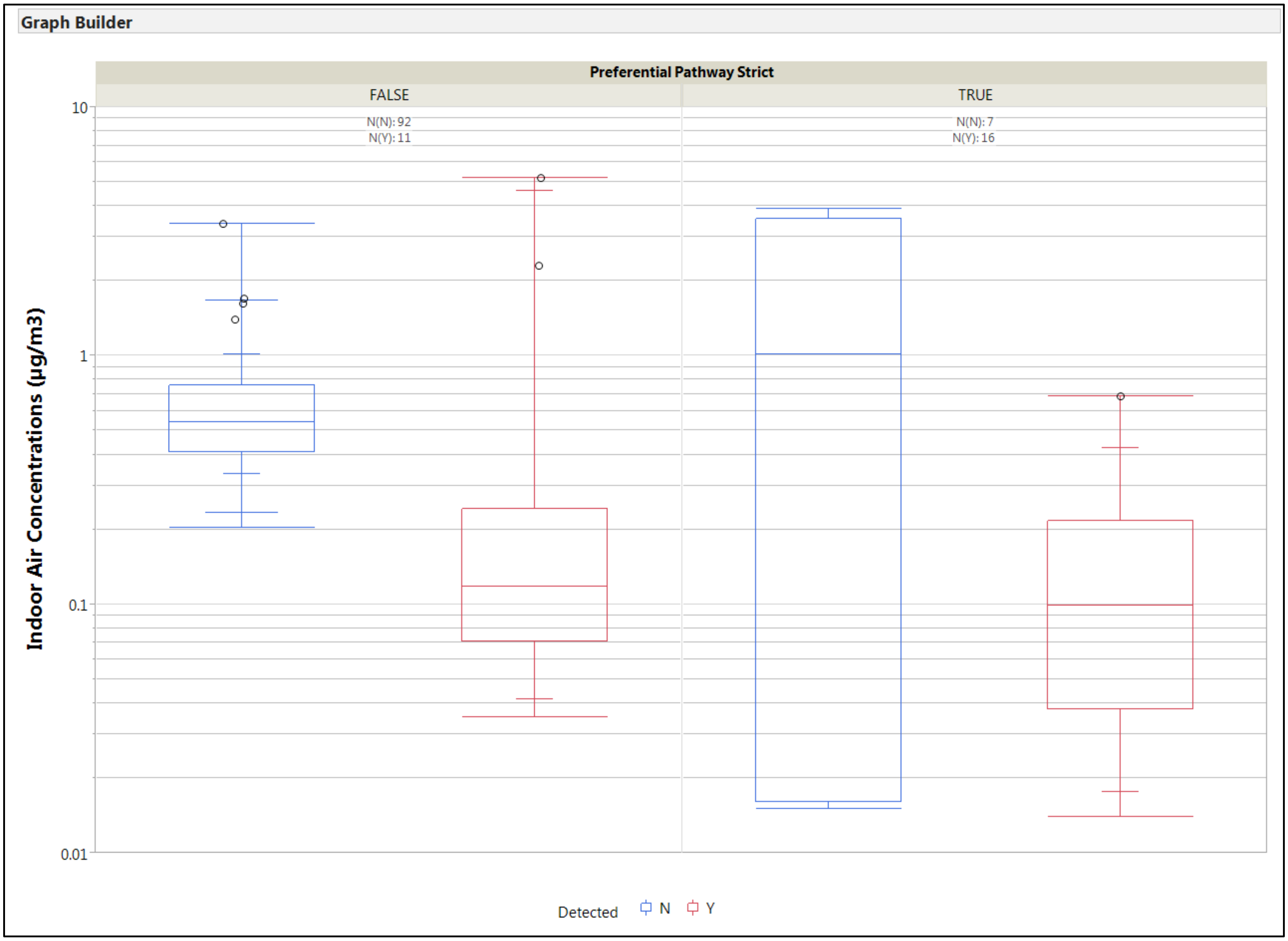


FIGURE E15

1,1-DCA Indoor Air Concentration by Preferential Pathway Presence (Original Definition)

NESDI Project #476

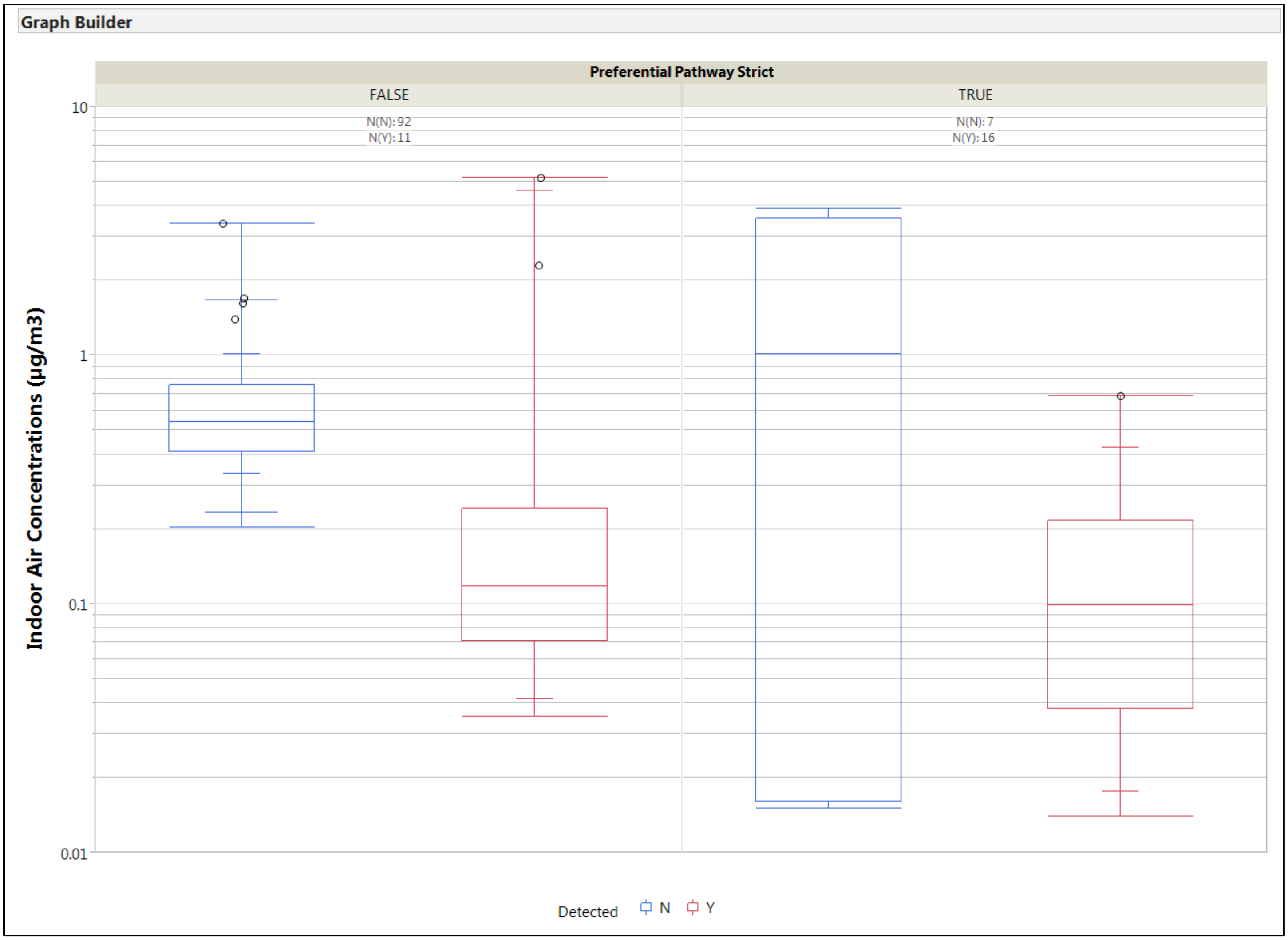


FIGURE E16
1,1-DCA Indoor Air Concentration by Preferential Pathway Presence (Strict Definition)
NESDI Project #476

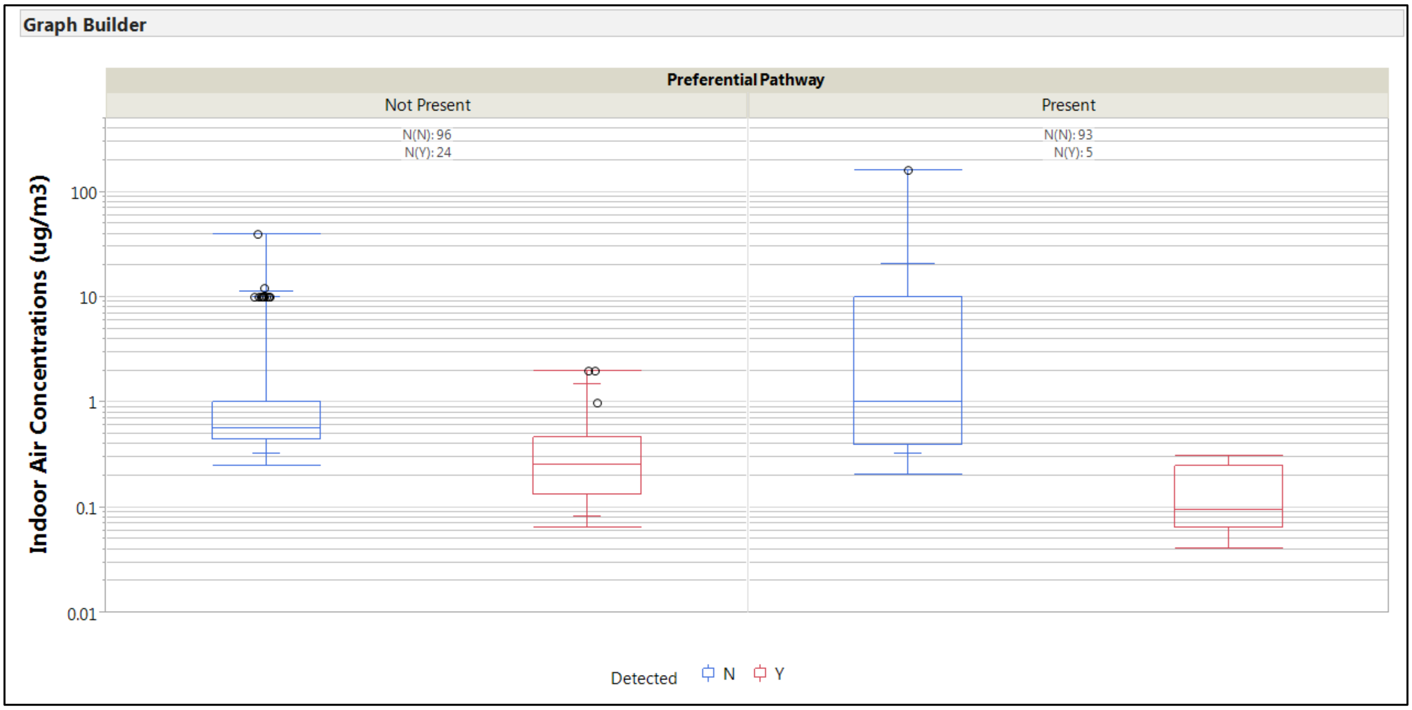


FIGURE E17
1,2-DCA Indoor Air Concentration by Preferential Pathway Presence (Original Definition)
NESDI Project #476

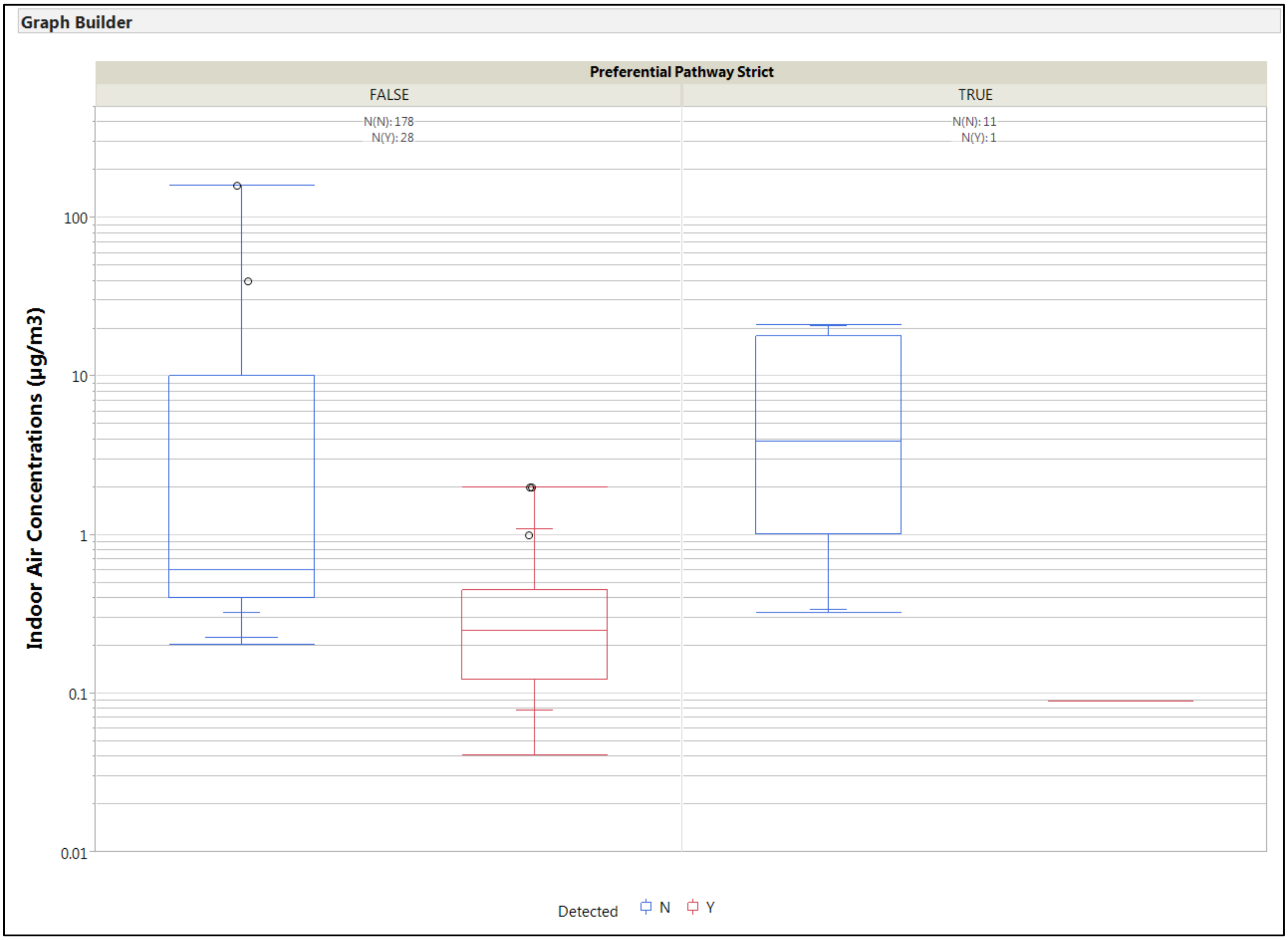


FIGURE E18
1,2-DCA Indoor Air Concentration by Preferential Pathway Presence (Strict Definition)
NESDI Project #476

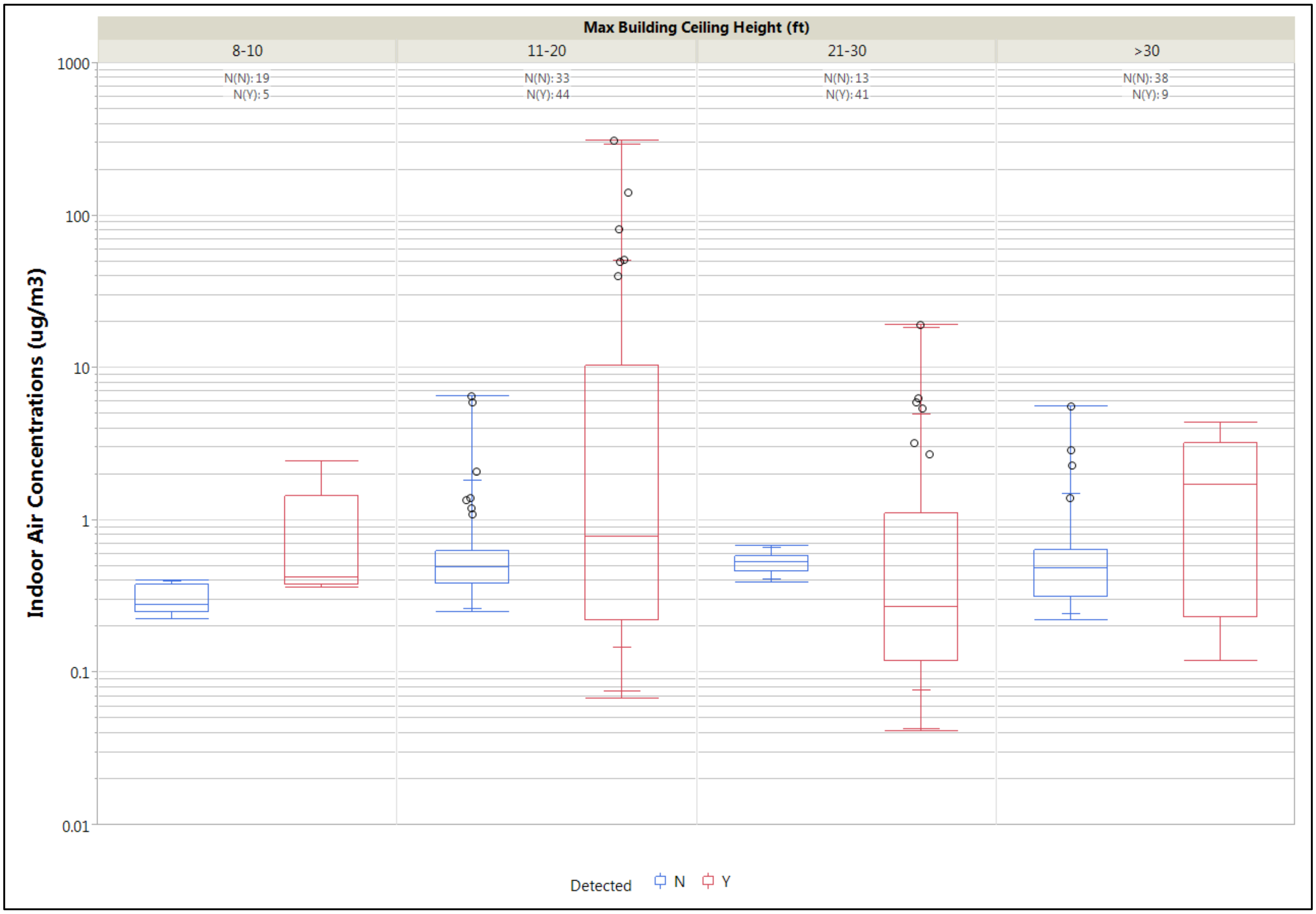


FIGURE E19
PCE Indoor Air Concentration by Maximum Ceiling Height
NESDI Project #476

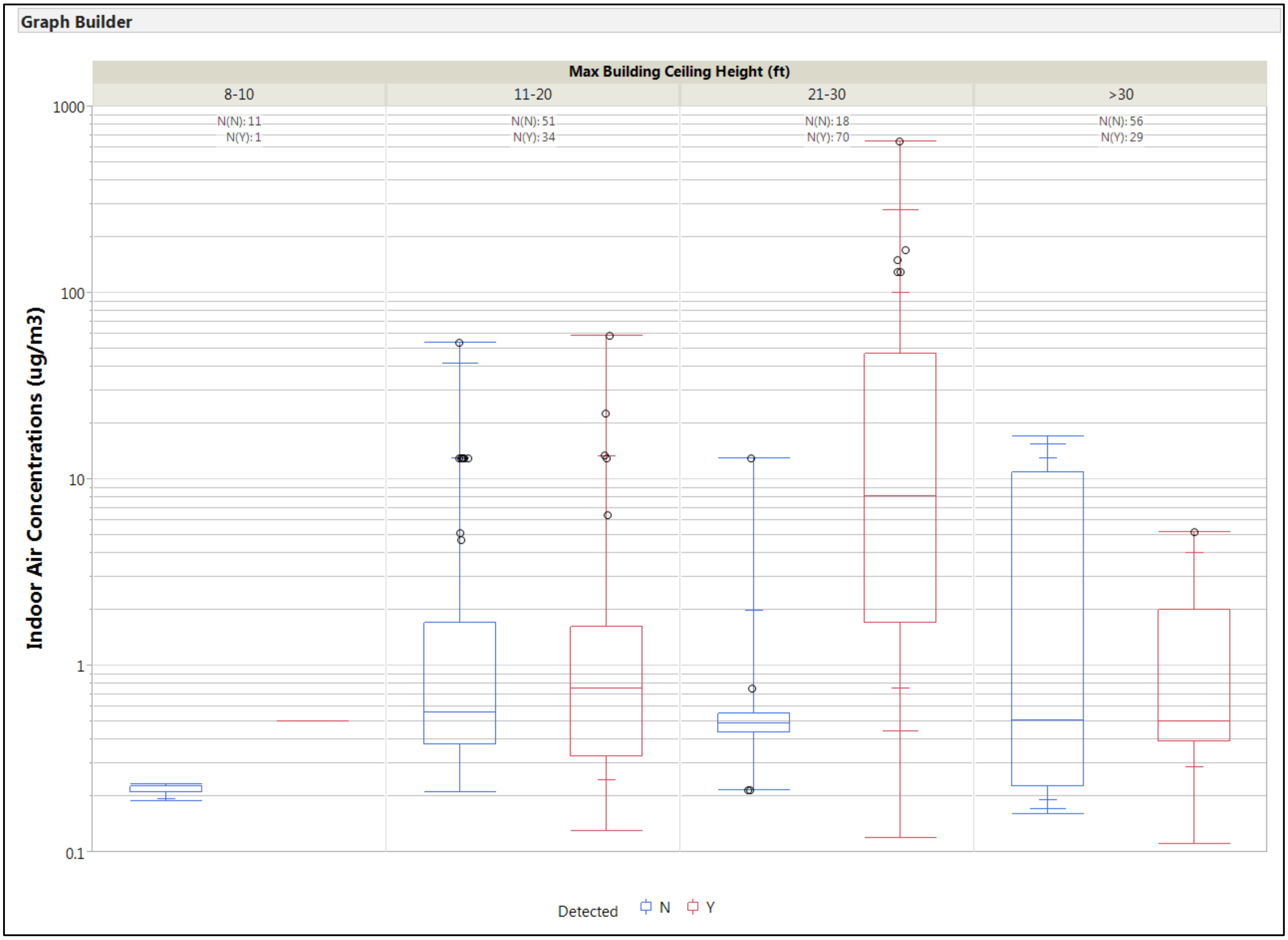


FIGURE E20
TCE Indoor Air Concentration by Maximum Ceiling Height
NESDI Project #476

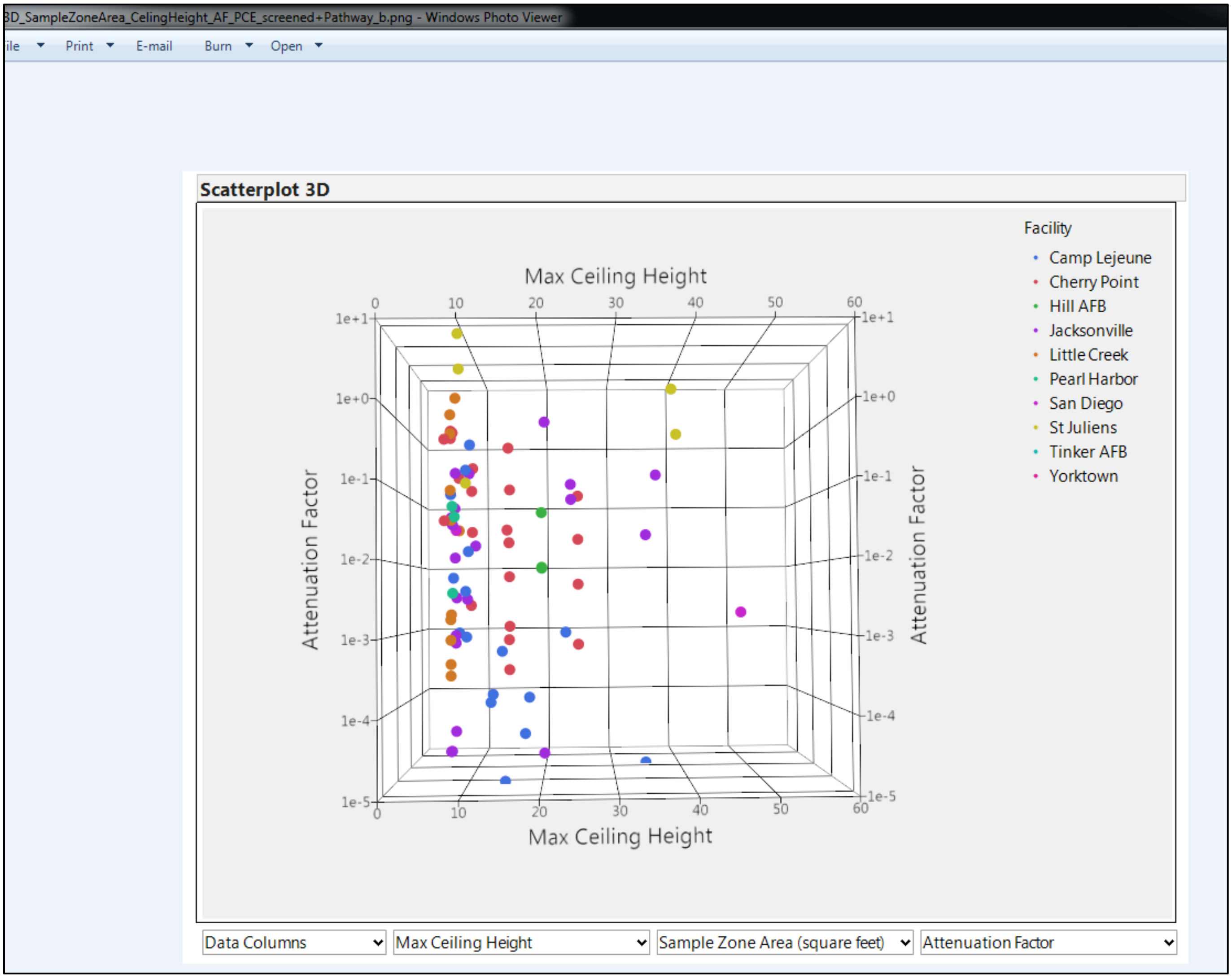


FIGURE E21

PCE Normalized Indoor Air Concentration by Maximum Ceiling Sample Zone Height
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

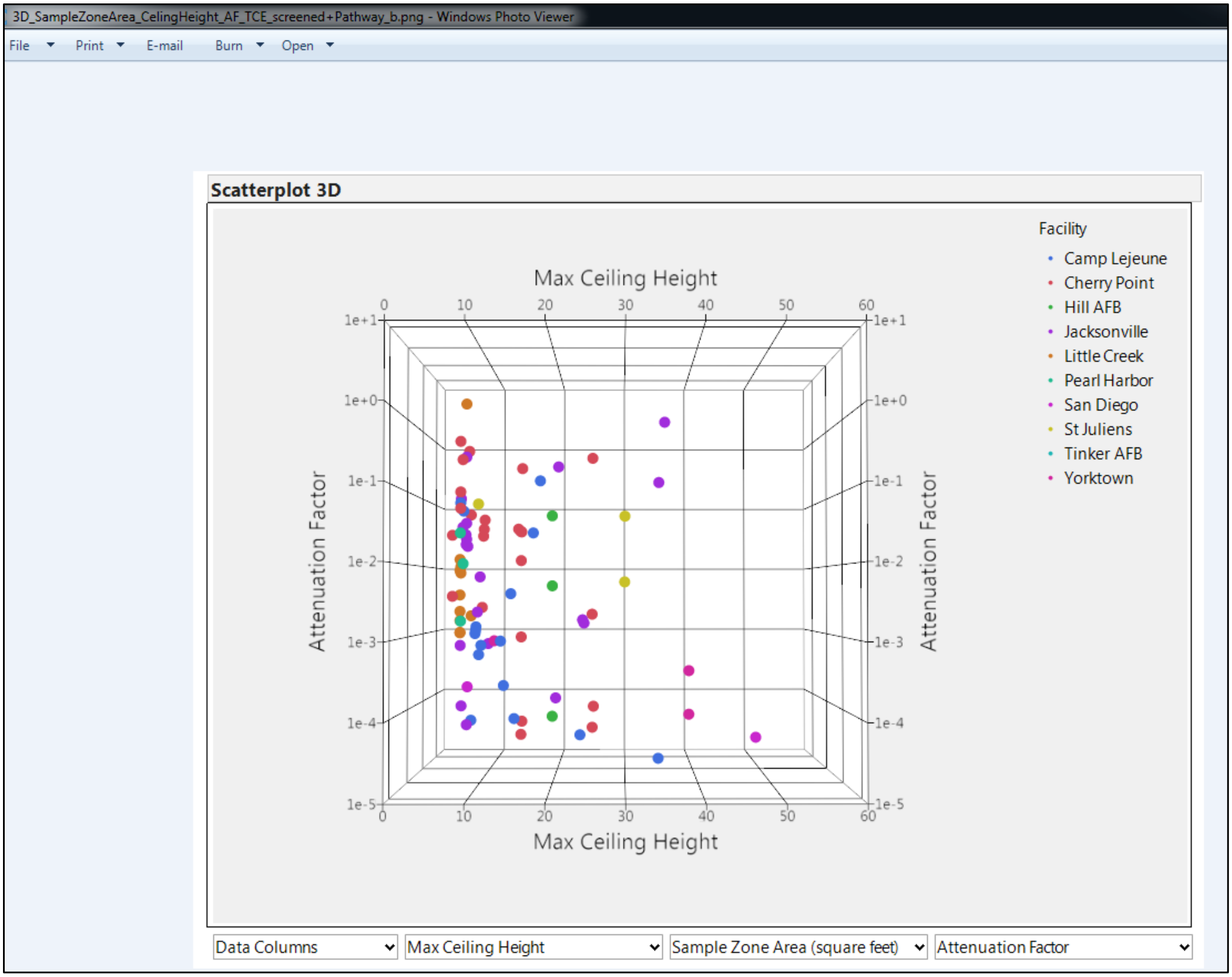


FIGURE E22
TCE Normalized Indoor Air Concentration by Maximum Ceiling Sample Zone Height
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

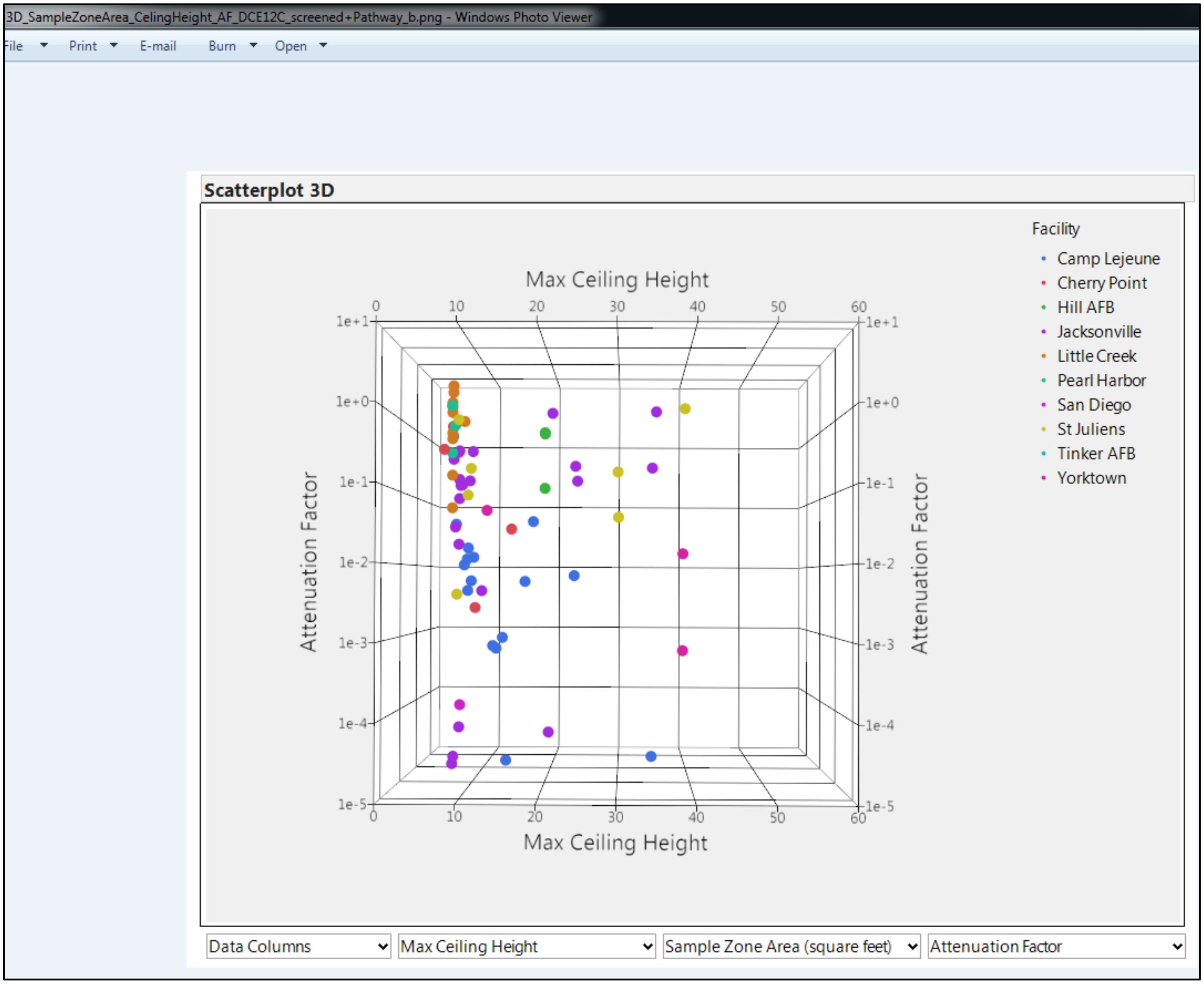


FIGURE E23
Cis-1,2-DCE Normalized Indoor Air Concentration by Maximum Ceiling Sample Zone Height
Baseline, Source strength and Preferential Pathway Screens Applied
NESDI Project #476

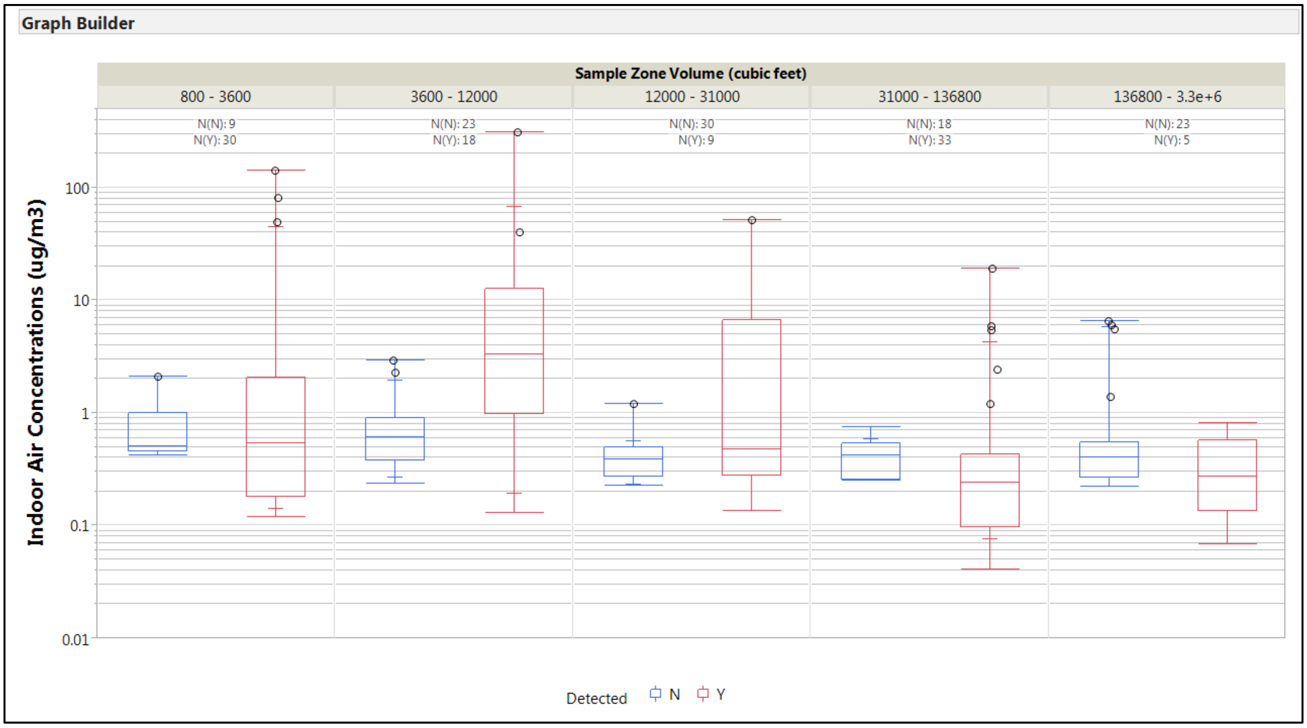


FIGURE E24
PCE Indoor Air Concentration by Sample Zone Volume
No Screens Applied
NESDI Project #476

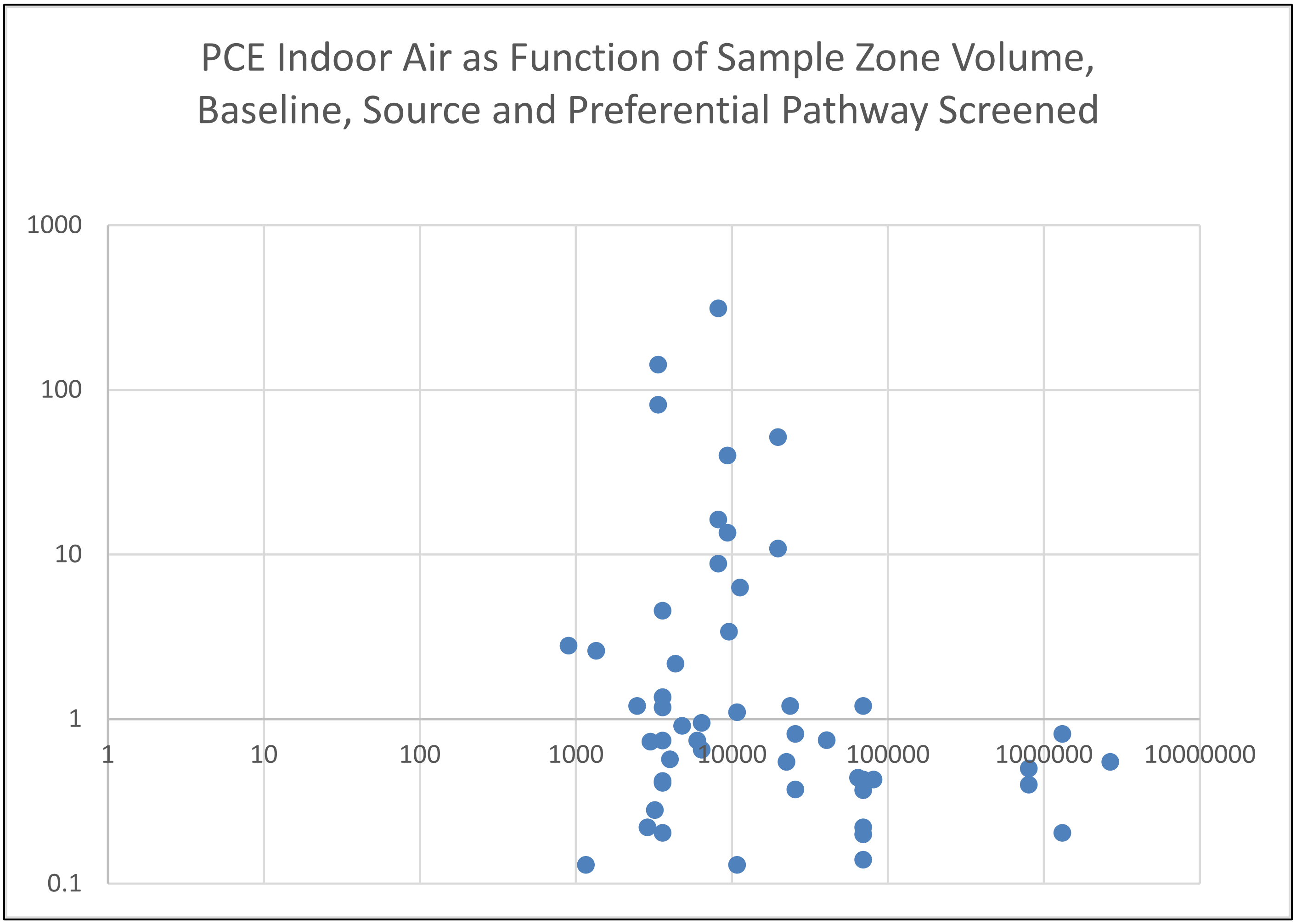


FIGURE E25
PCE Indoor Air Concentration by Sample Volume
Baseline, Source and Preferential Pathway Screens Applied
NESDI Project #476

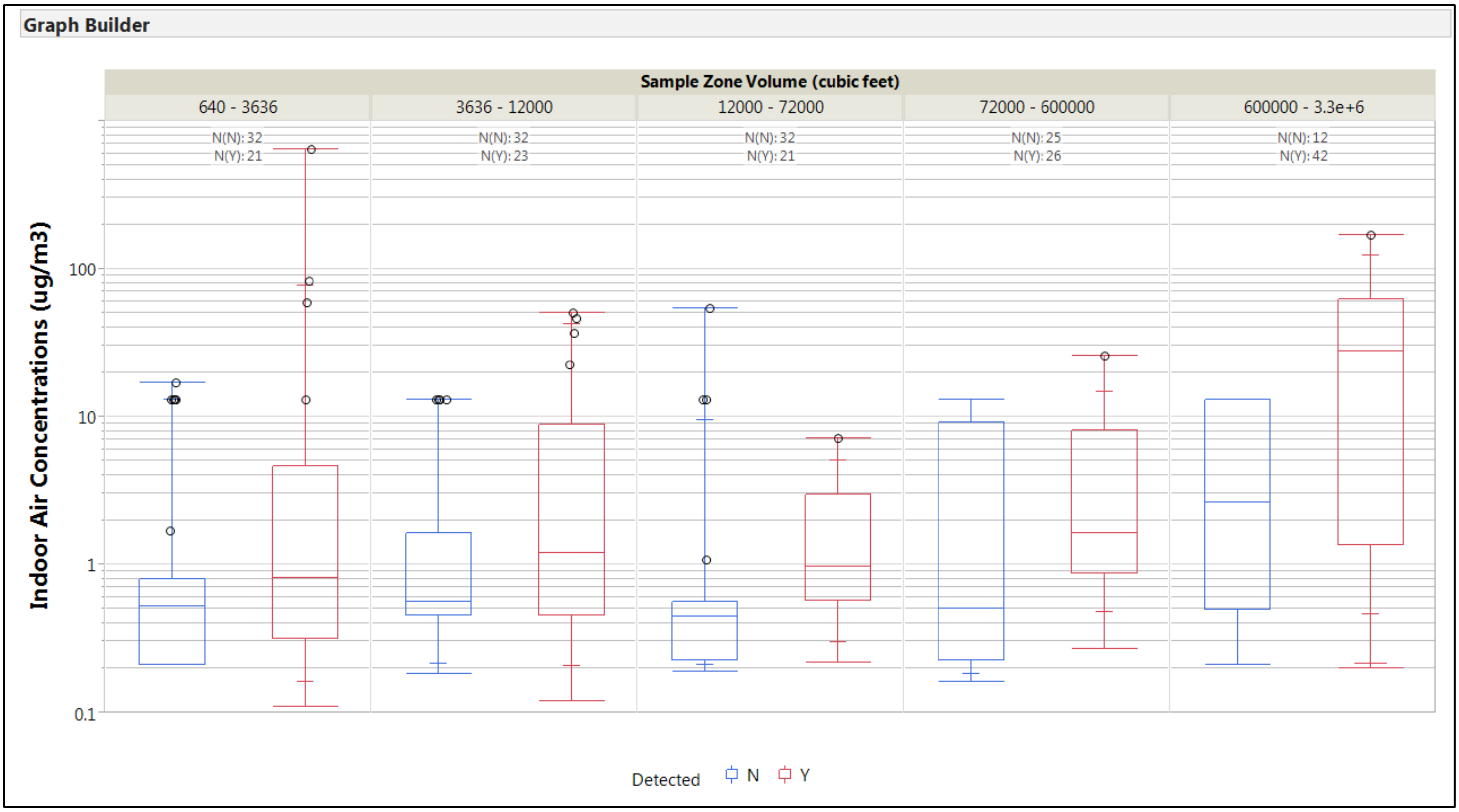


FIGURE E26
TCE Indoor Air Concentration by Sample Zone Volume
No Screens Applied
NESDI Project #476

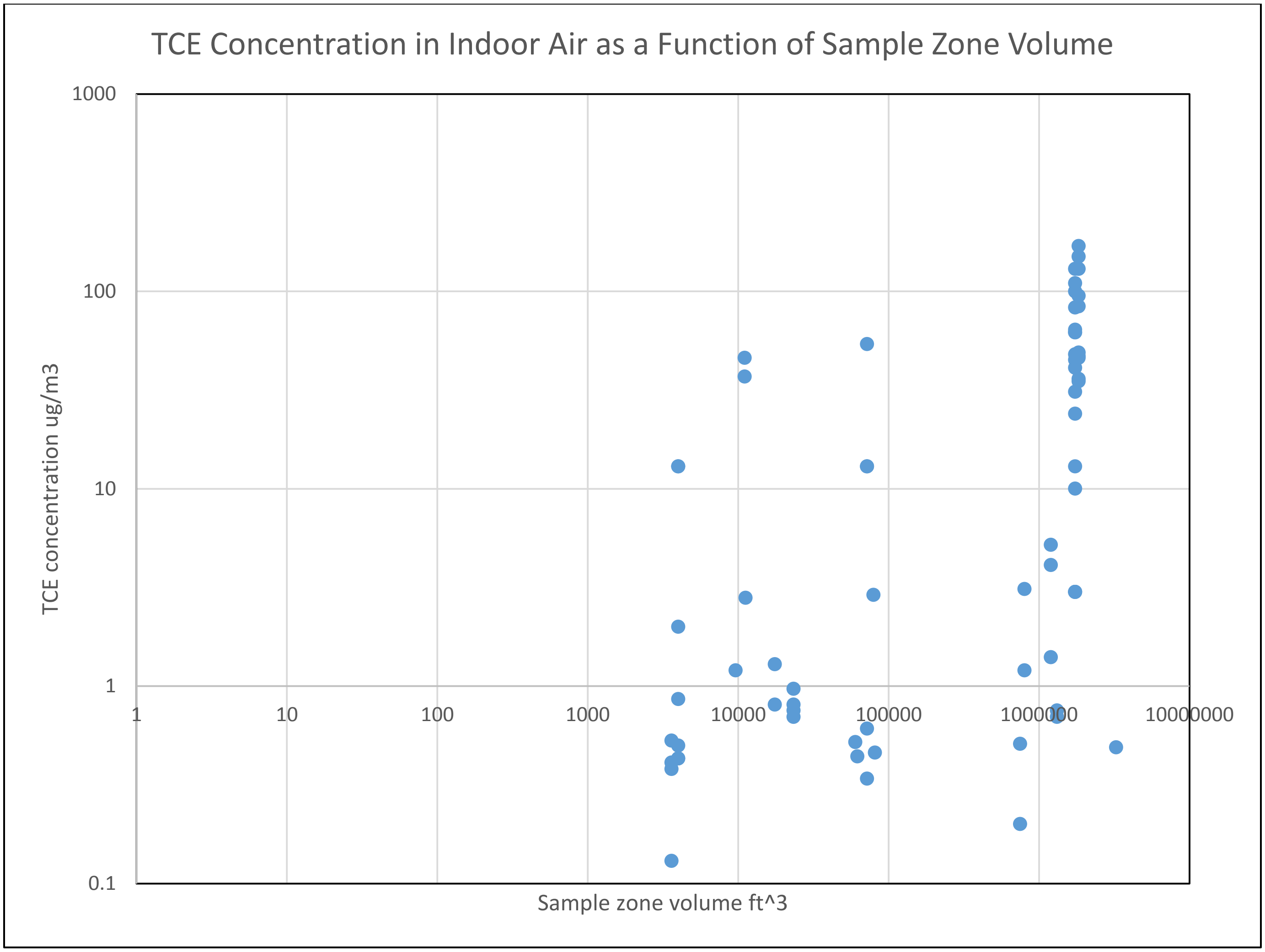


FIGURE E27
TCE Indoor Air Concentration by Sample Zone Volume
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

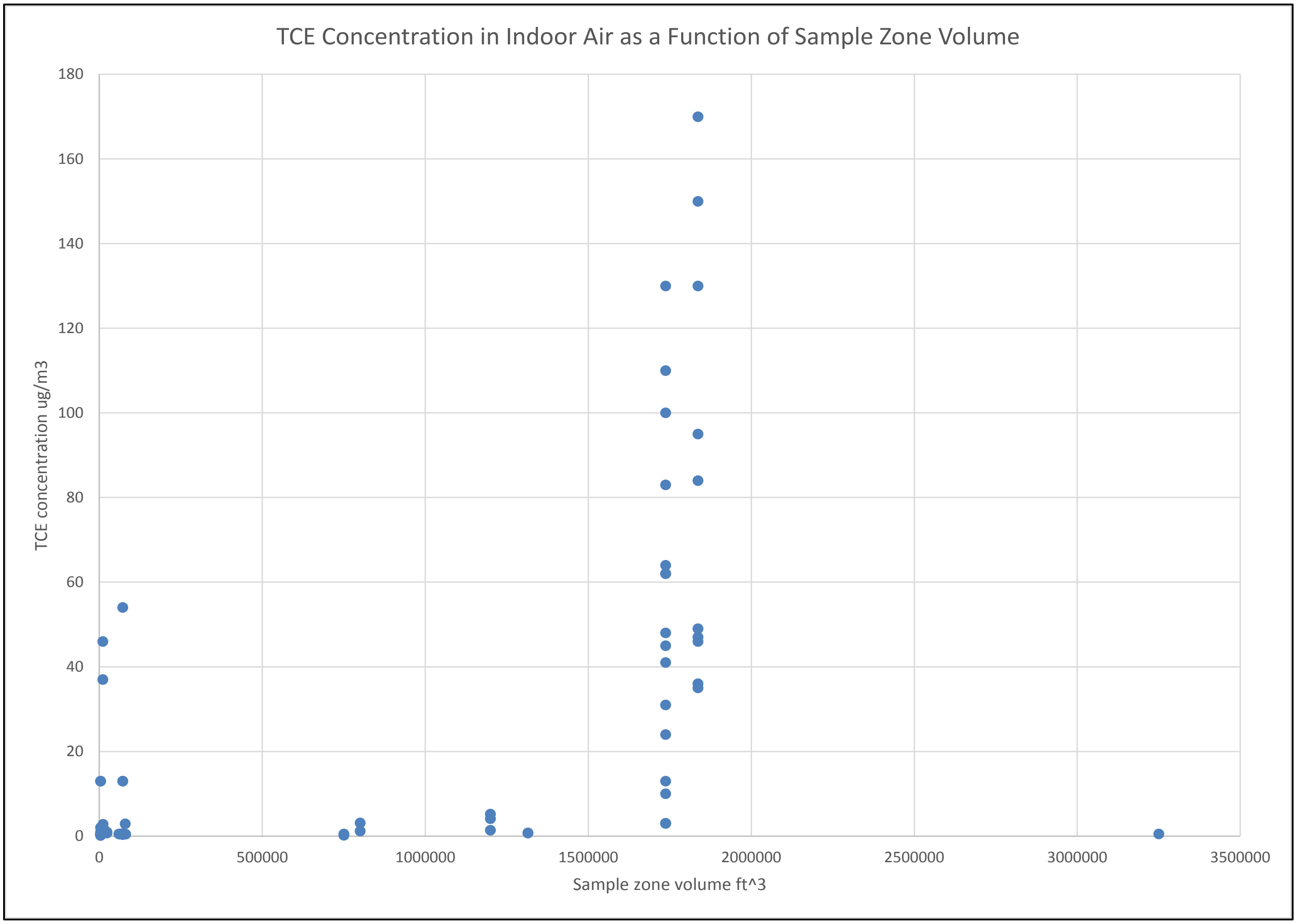


FIGURE E28
TCE Indoor Air Concentration by Sample Zone Volume
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

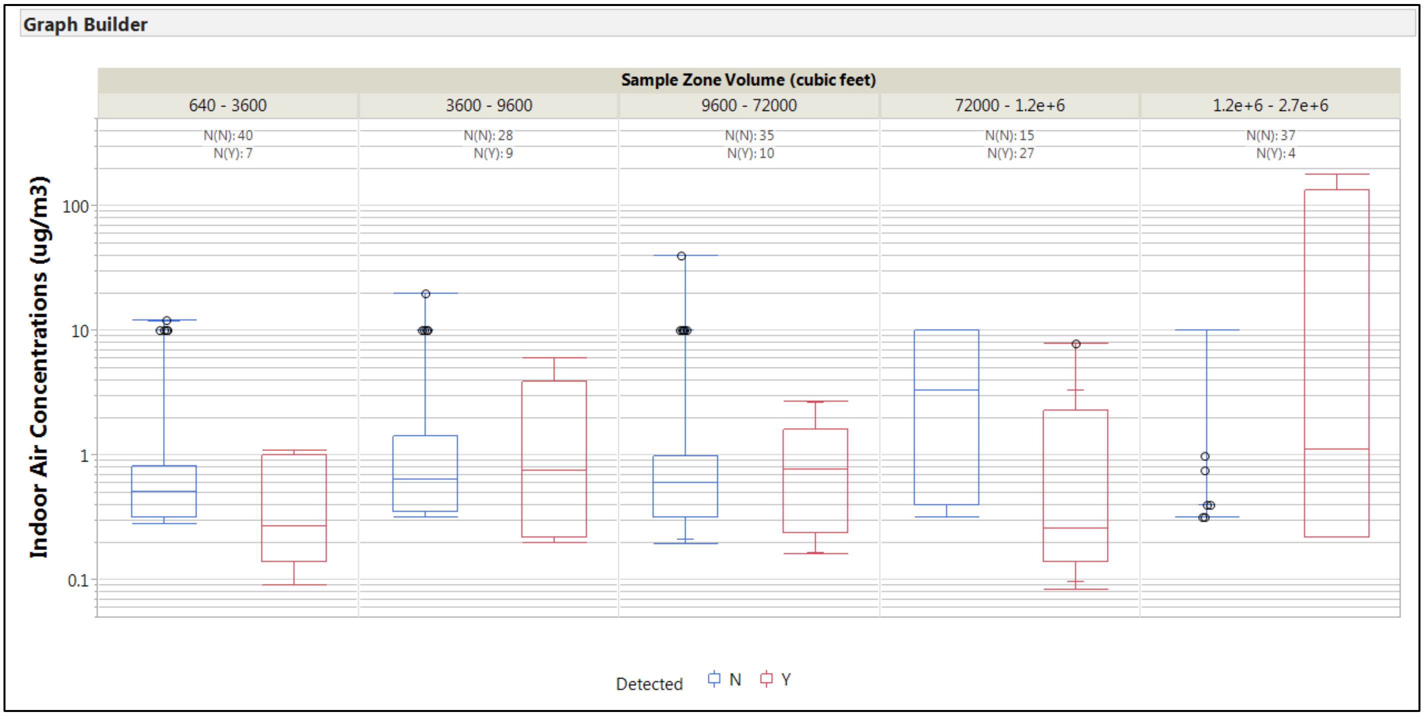


FIGURE E29
Cis-1,2-DCE Indoor Air Concentration by Sample Zone Volume
NESDI Project #476

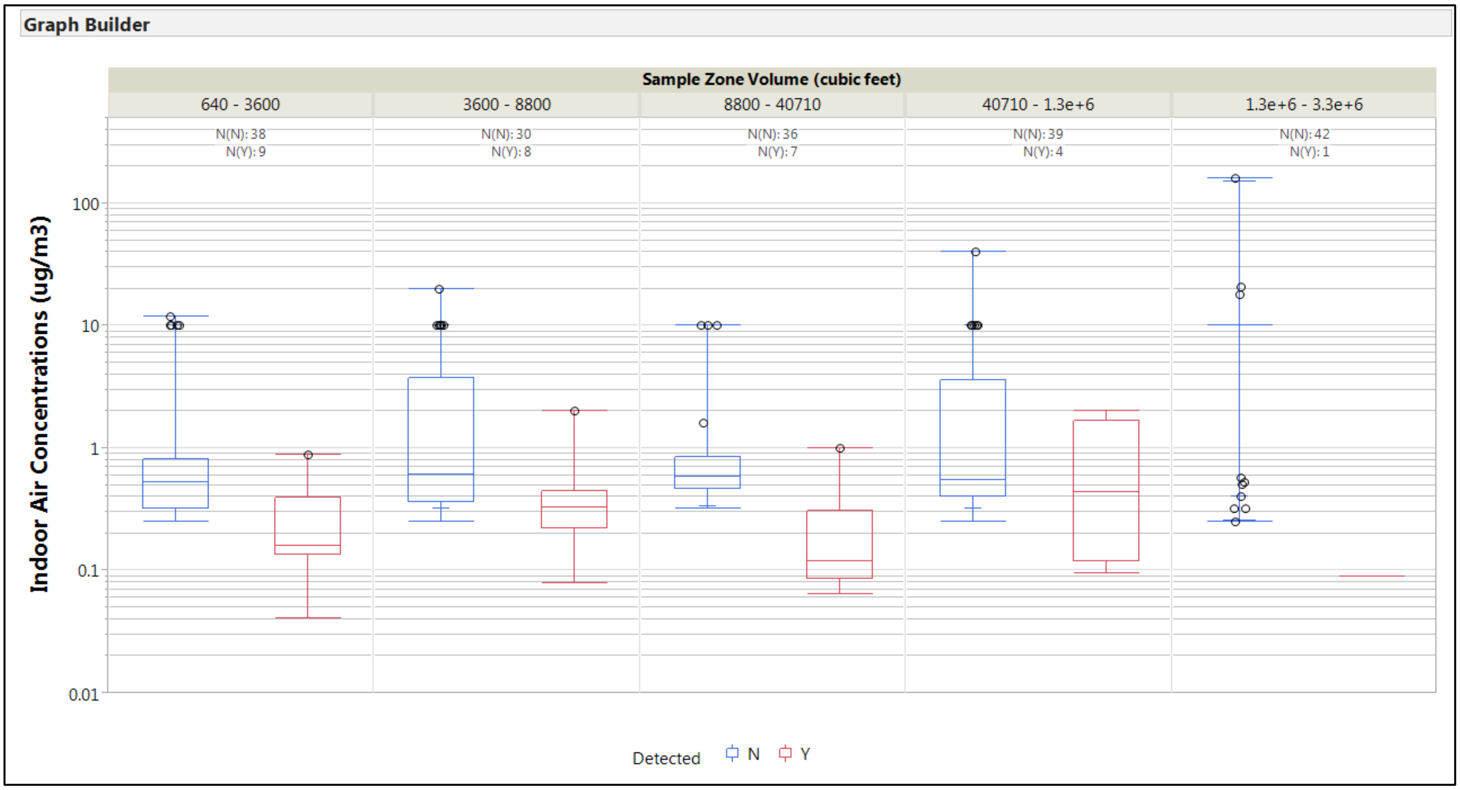


FIGURE E30
1,2-DCA Indoor Air Concentration by Sample Zone Volume
NESDI Project #476

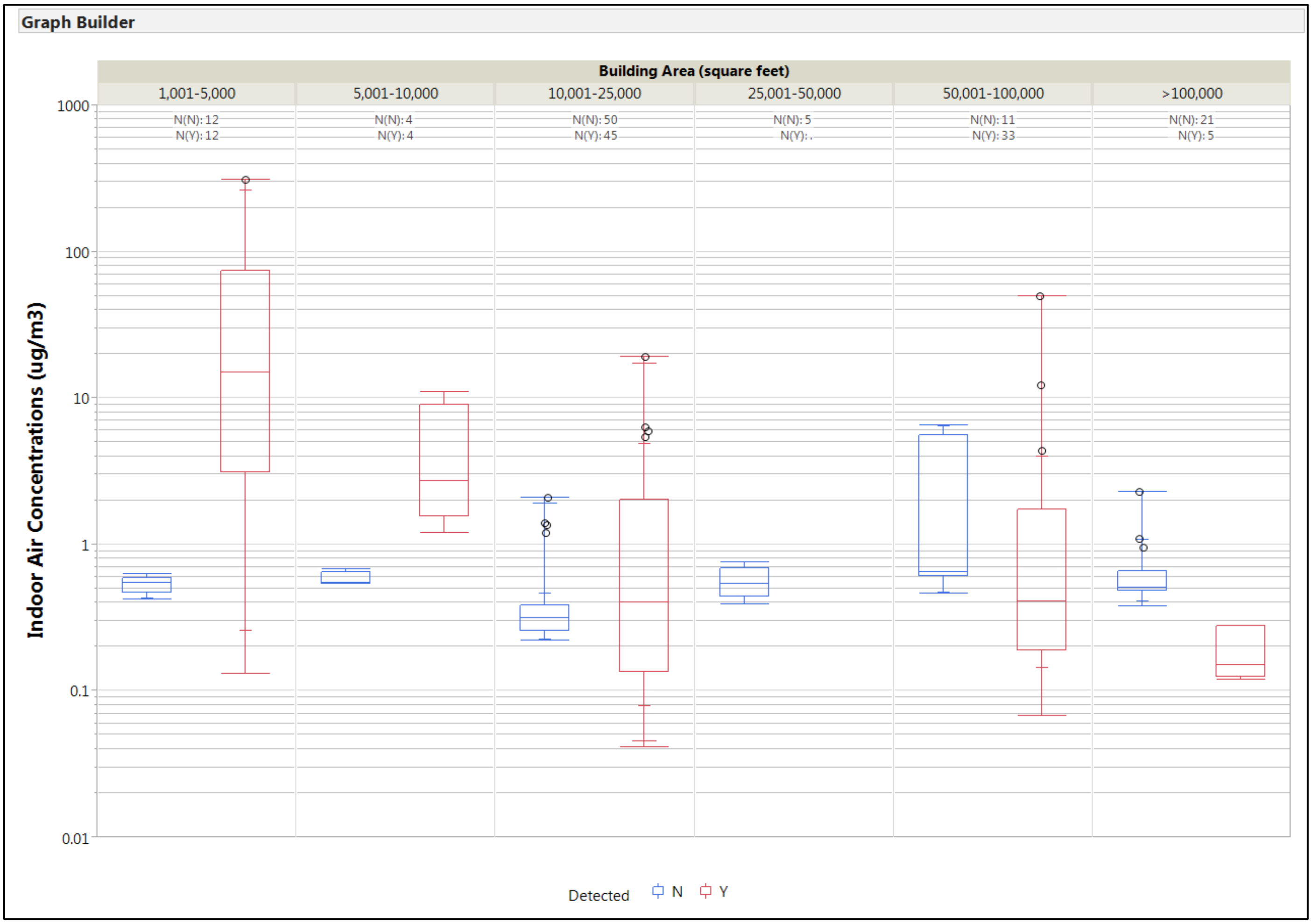


FIGURE E31
PCE Indoor Air Concentration by Building Area
No Screens Applied
NESDI Project #476

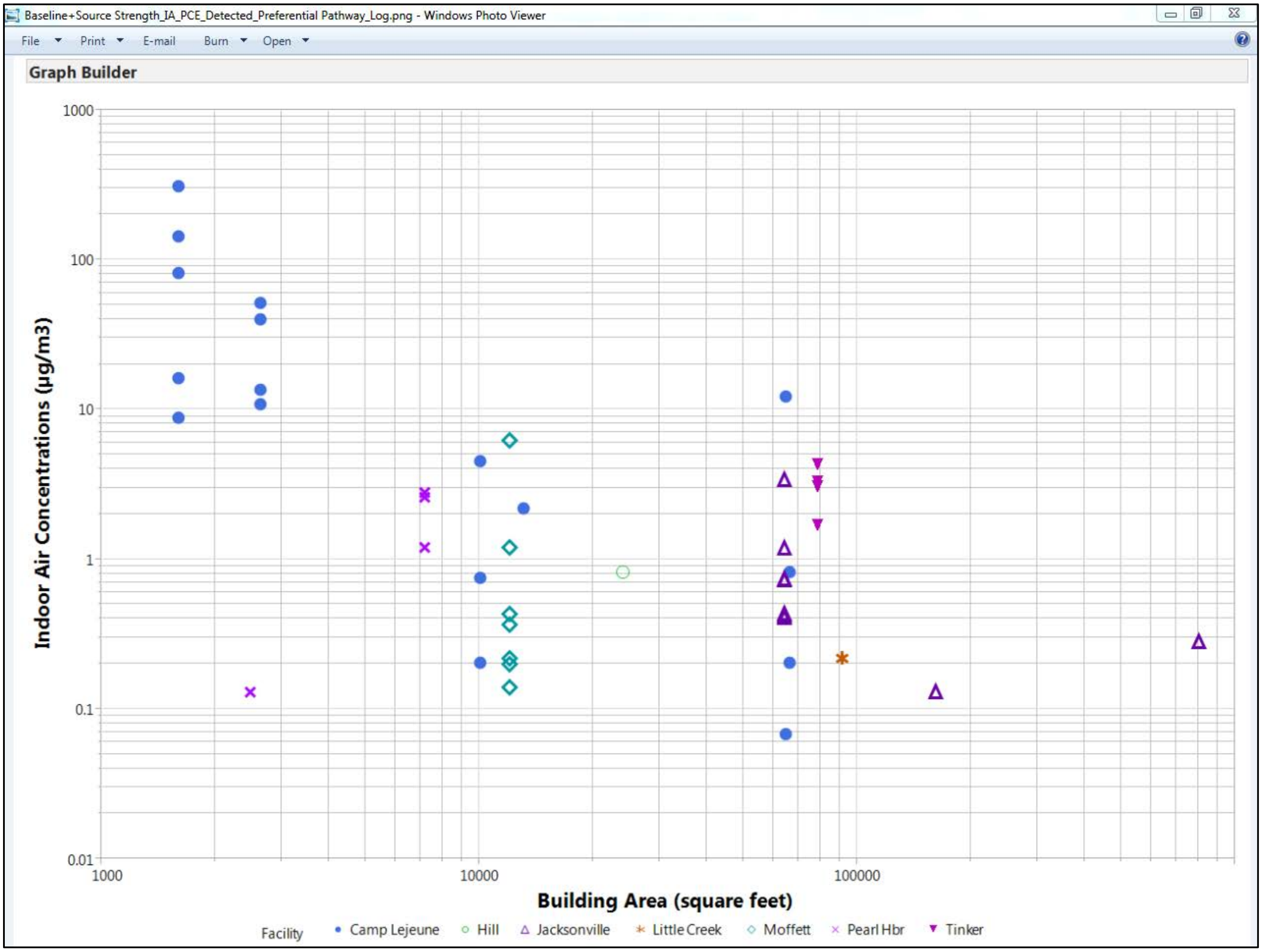


FIGURE E32
PCE Indoor Air Concentration vs Building Area
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

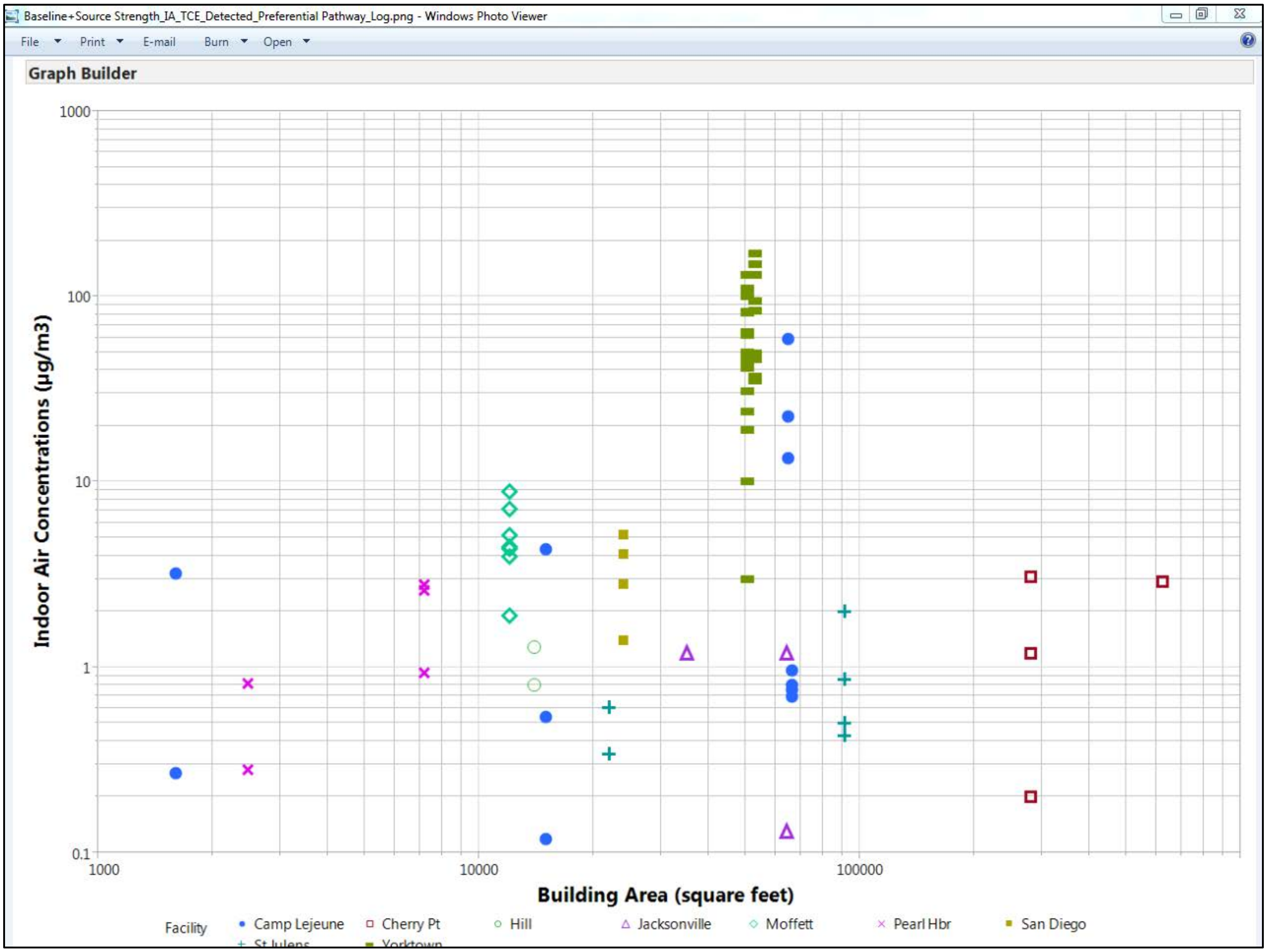


FIGURE E33
TCE Indoor Air Concentration vs Building Area
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

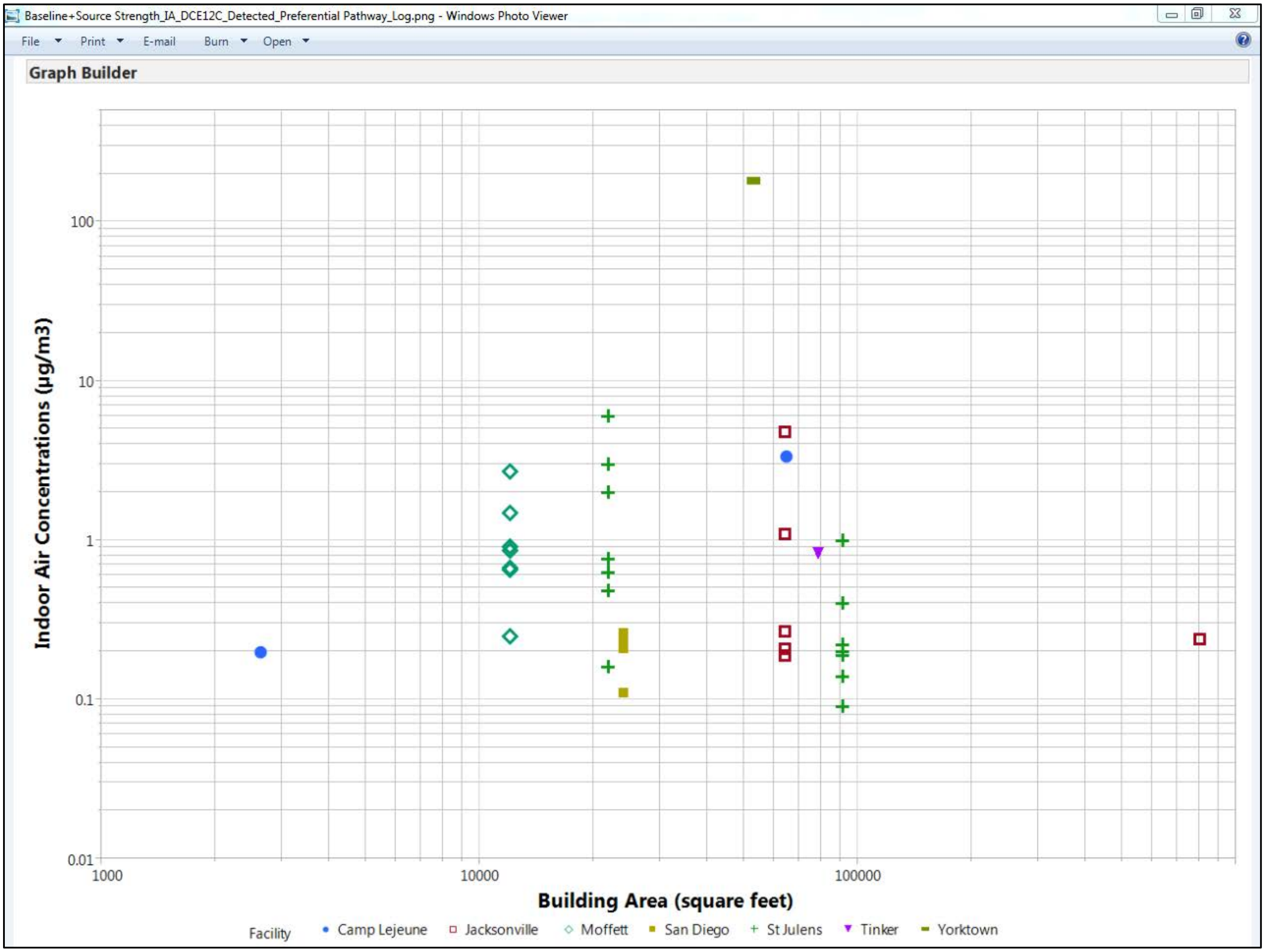


FIGURE E34
Cis-1,2-DCE Indoor Air Concentration vs Building Area
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

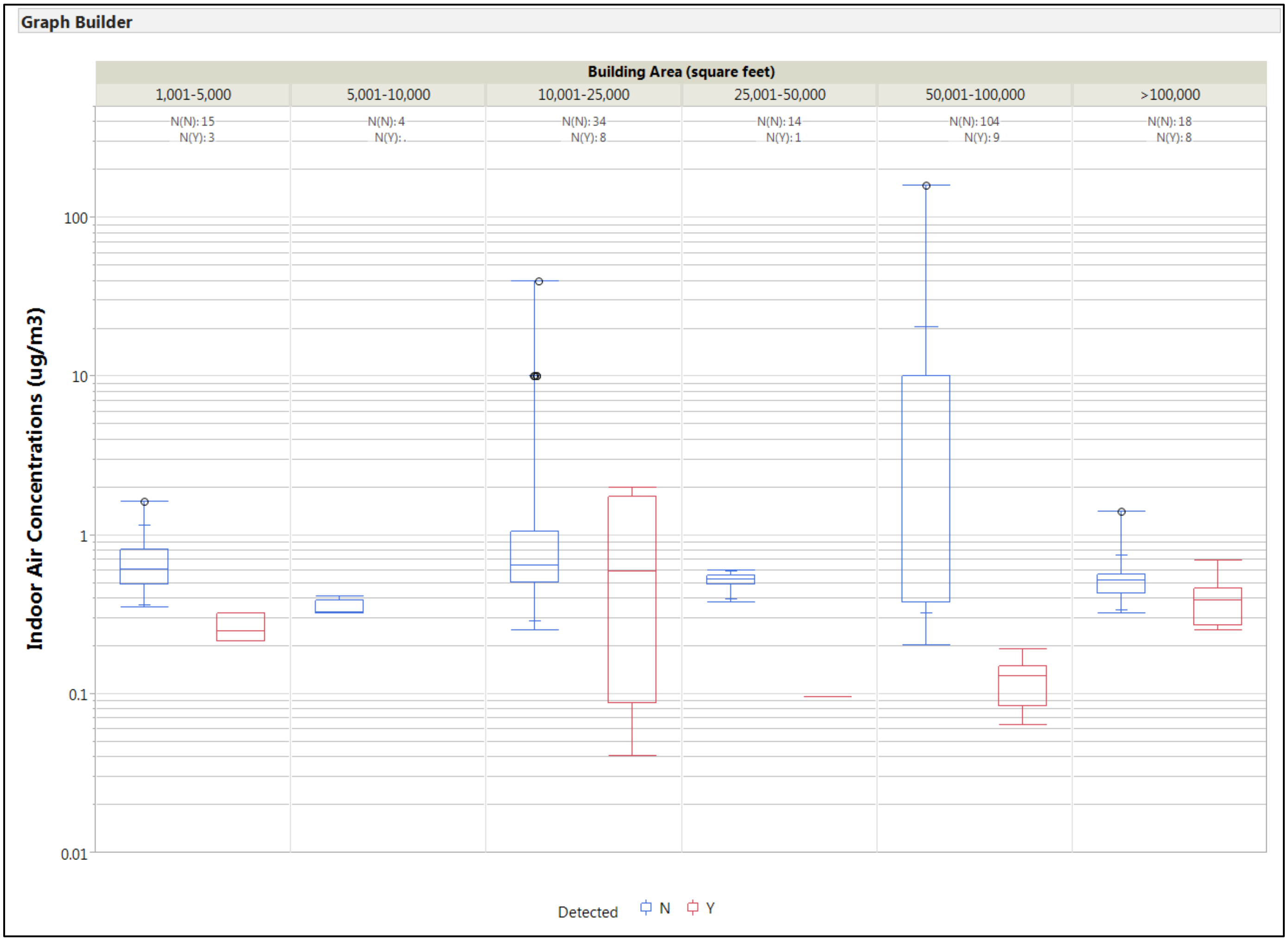


FIGURE E35
1,2-DCA Indoor Air Concentration by Building Area
NESDI Project #476

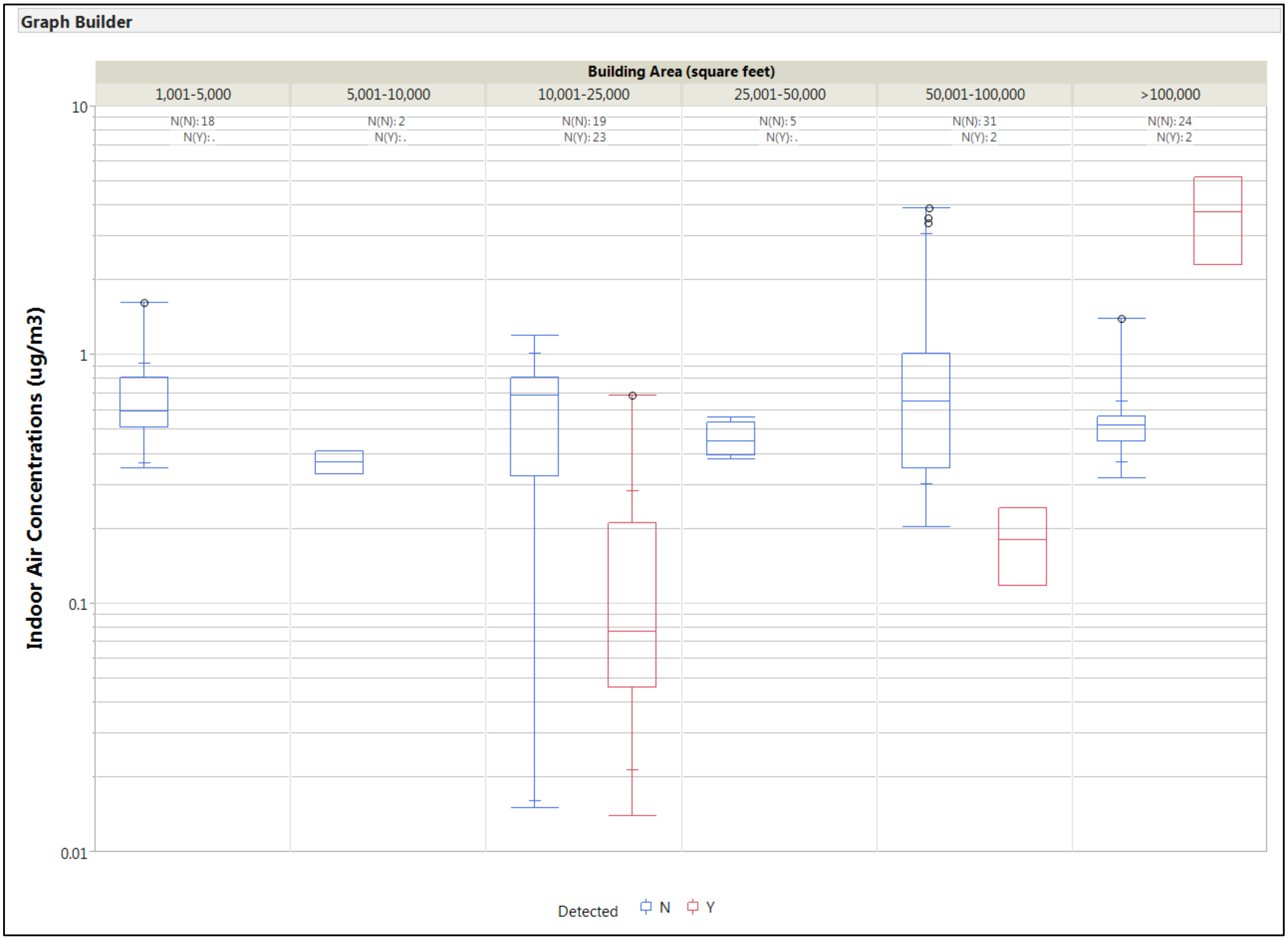


FIGURE E36

1,1-DCA Indoor Air Concentration by Building Area

NESDI Project #476

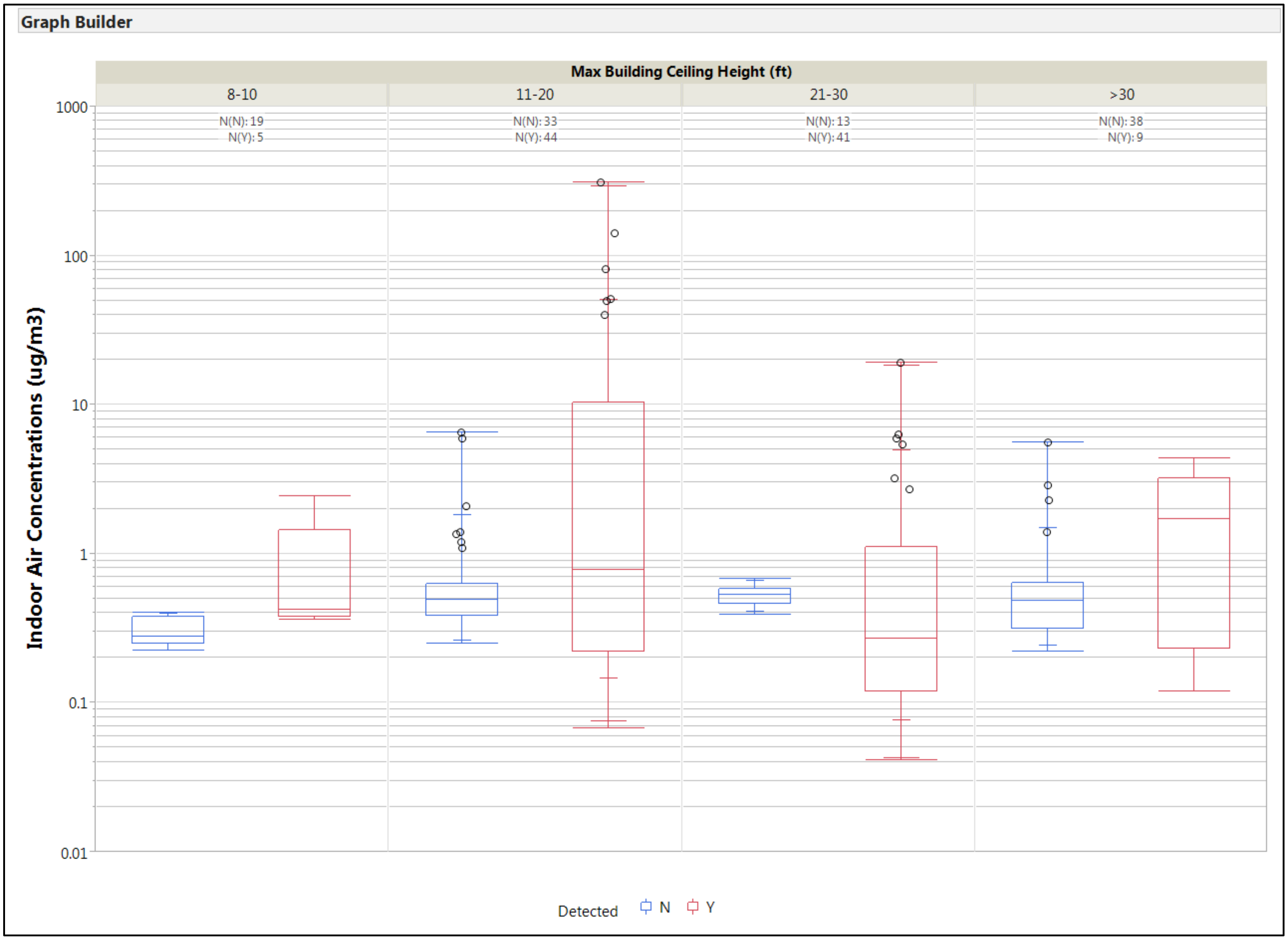
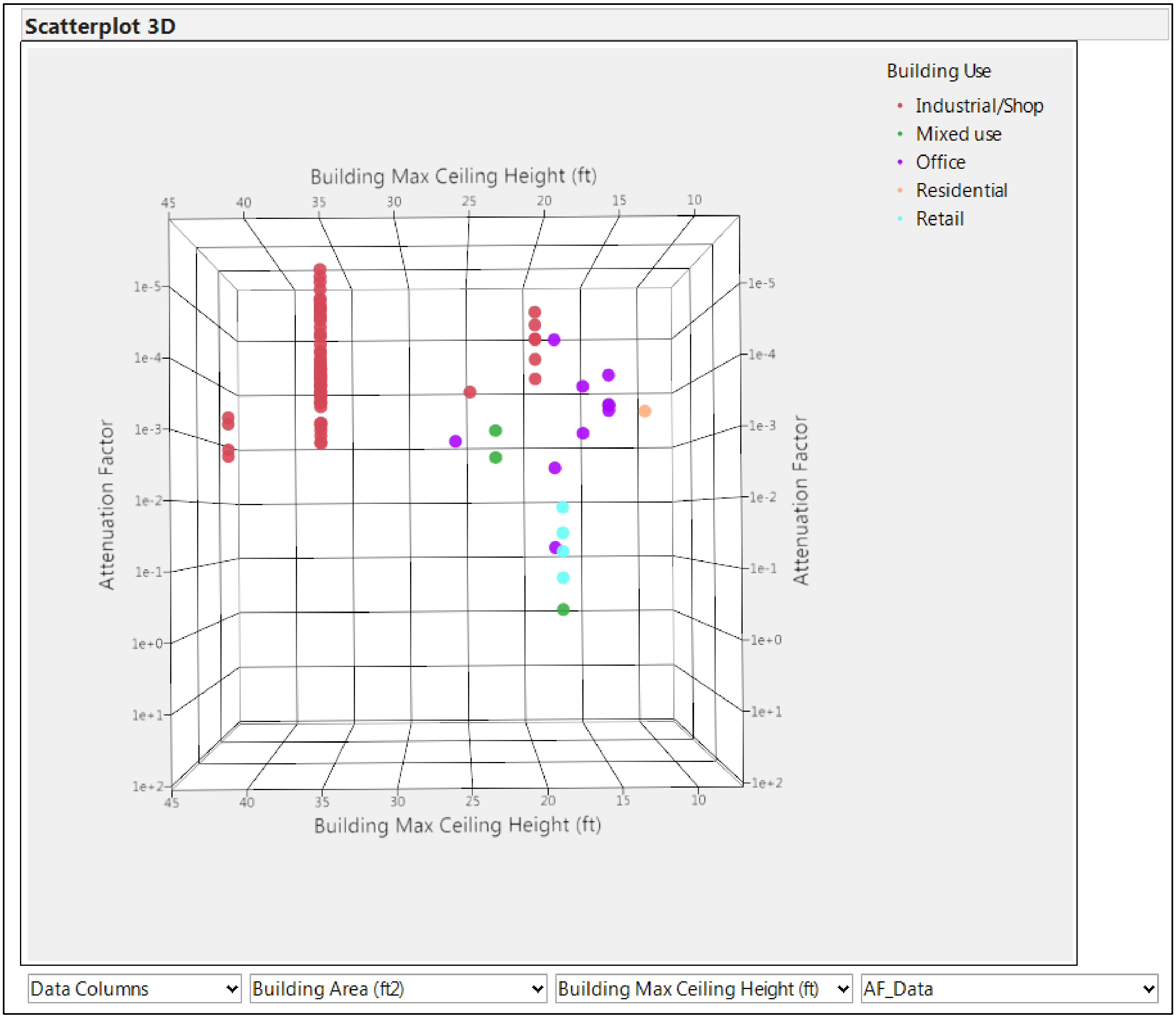


FIGURE E37
PCE Indoor Air Concentration by Maximum Building Ceiling Height
No Screens Applied
NESDI Project #476



Data Columns | Building Area (ft2) | Building Max Ceiling Height (ft) | AF_Data

FIGURE E38
Normalized PCE Indoor Air Concentration vs Building Ceiling Height
Baseline and Source Strength Screens Applied
NESDI Project #476

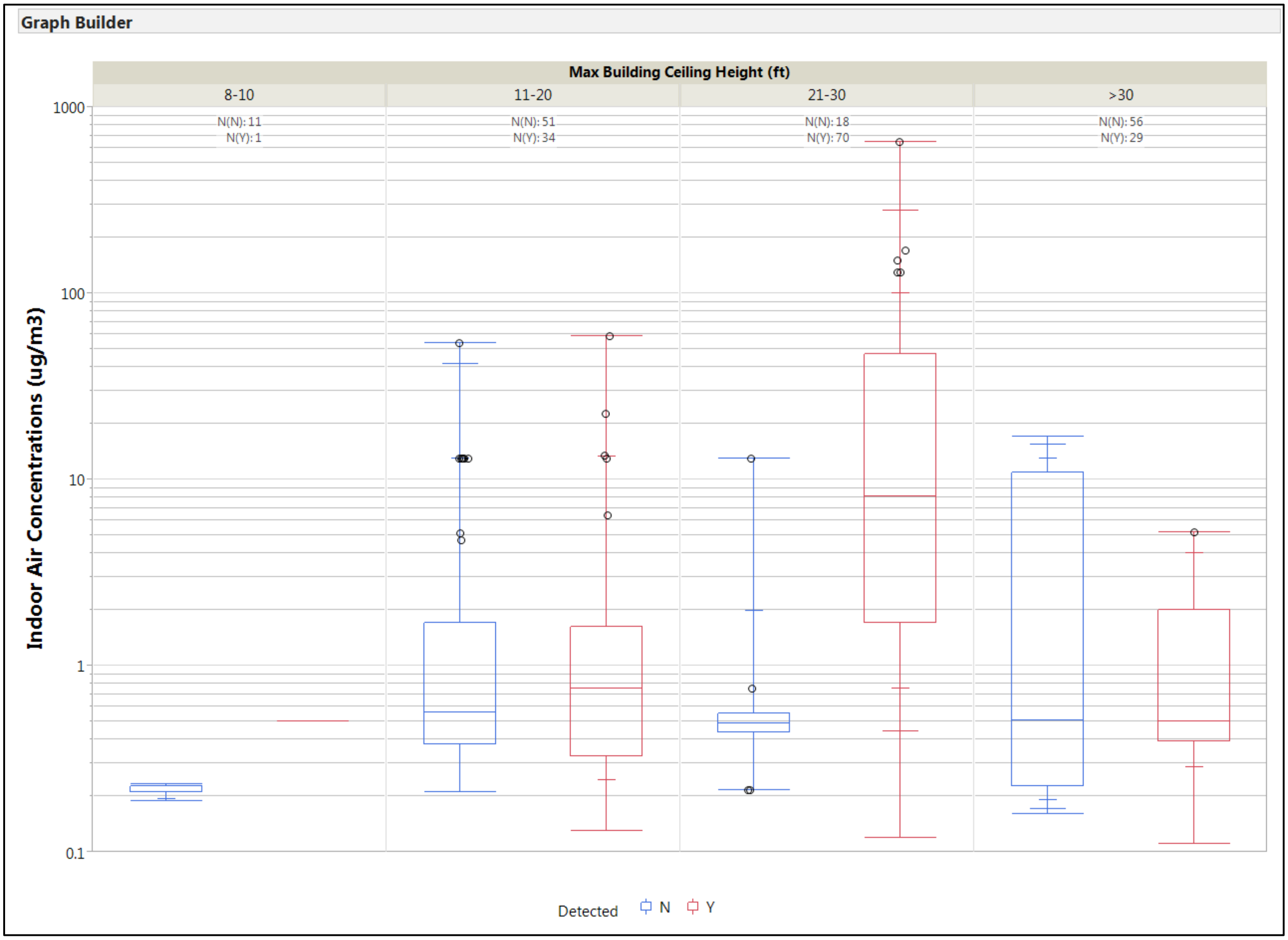


FIGURE E39
TCE Indoor Air Concentration by Maximum Building Ceiling Height; All Data
NESDI Project #476

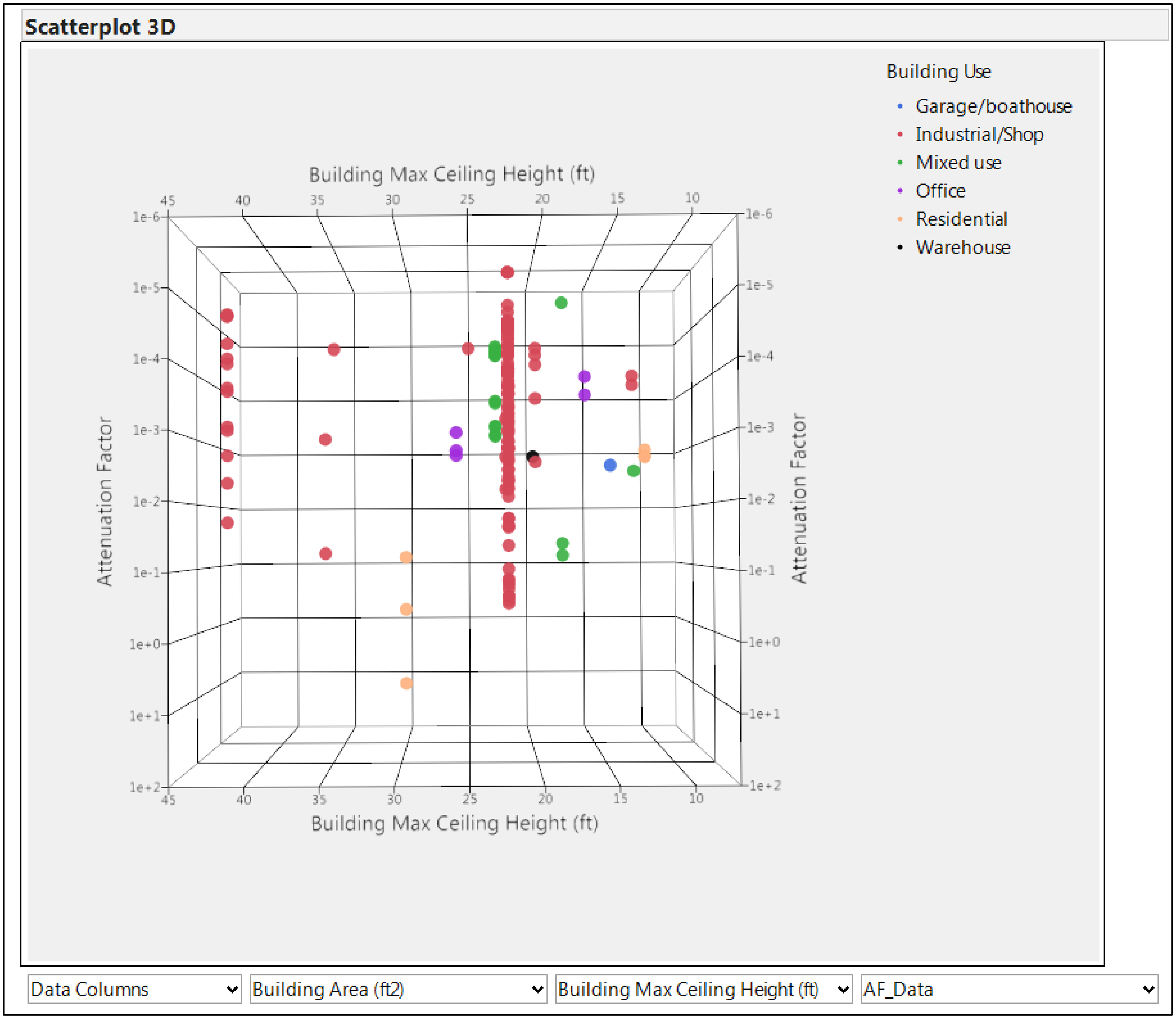


FIGURE E40
Normalized TCE Indoor Air Concentration vs Building Height
Baseline and Source Strength Screens Applied
NESDI Project #476

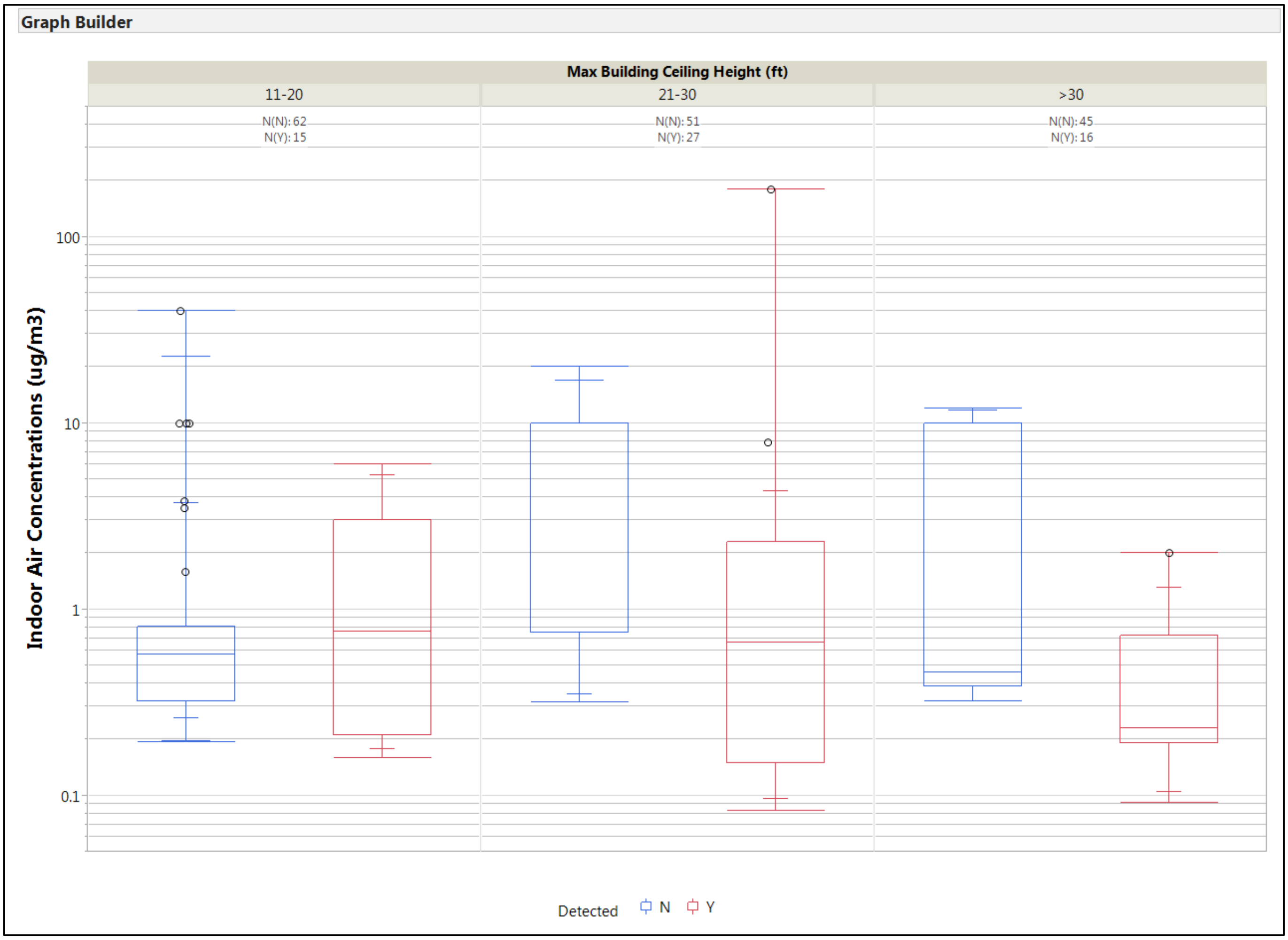


FIGURE E41
Cis-1,2-DCE Indoor Air Concentration by Maximum Building Ceiling Height; All Data
NESDI Project #476

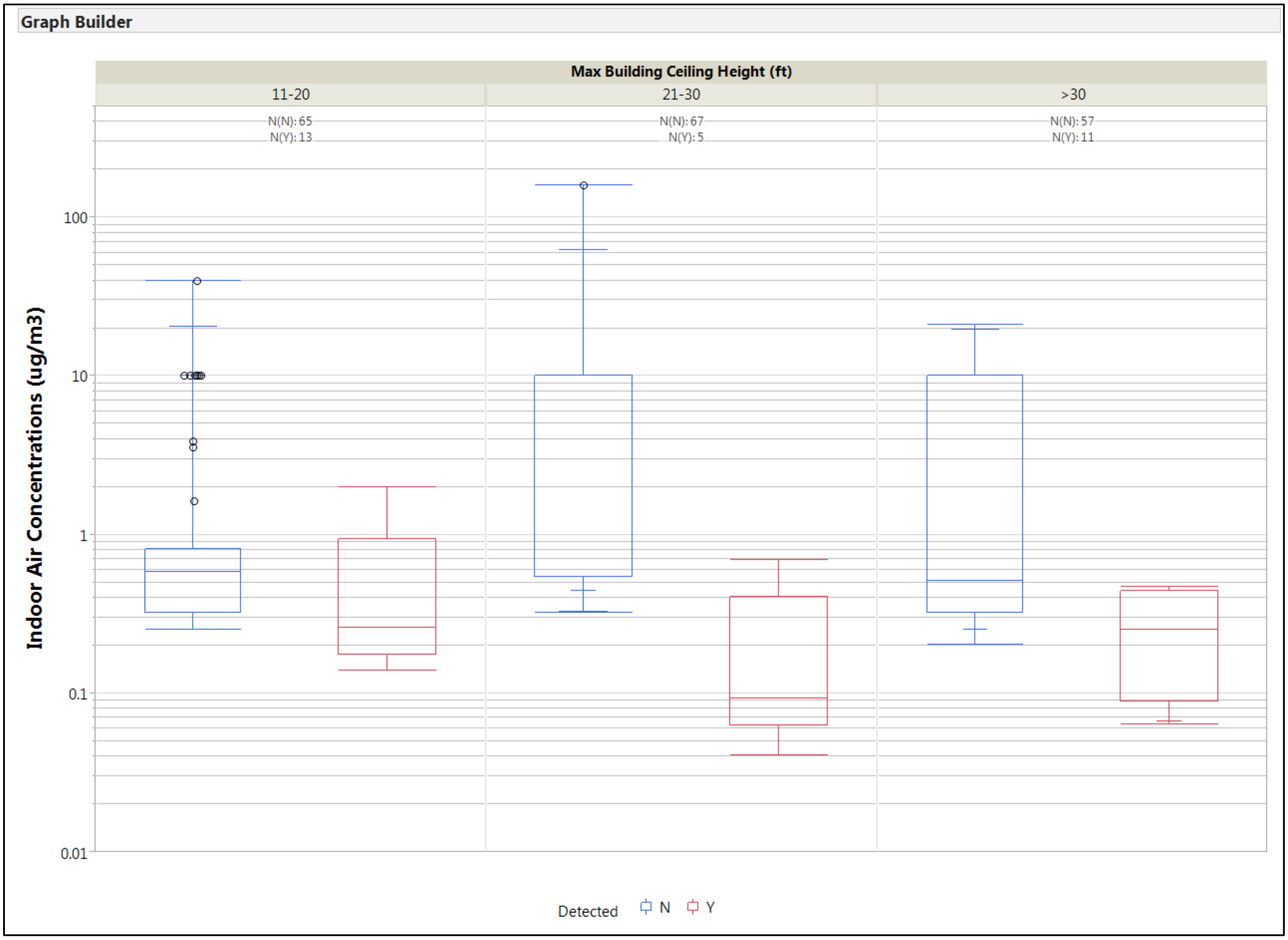


FIGURE E42

1,2-DCA Indoor Air Concentration by Maximum Building Ceiling Height; All Data

NESDI Project #476

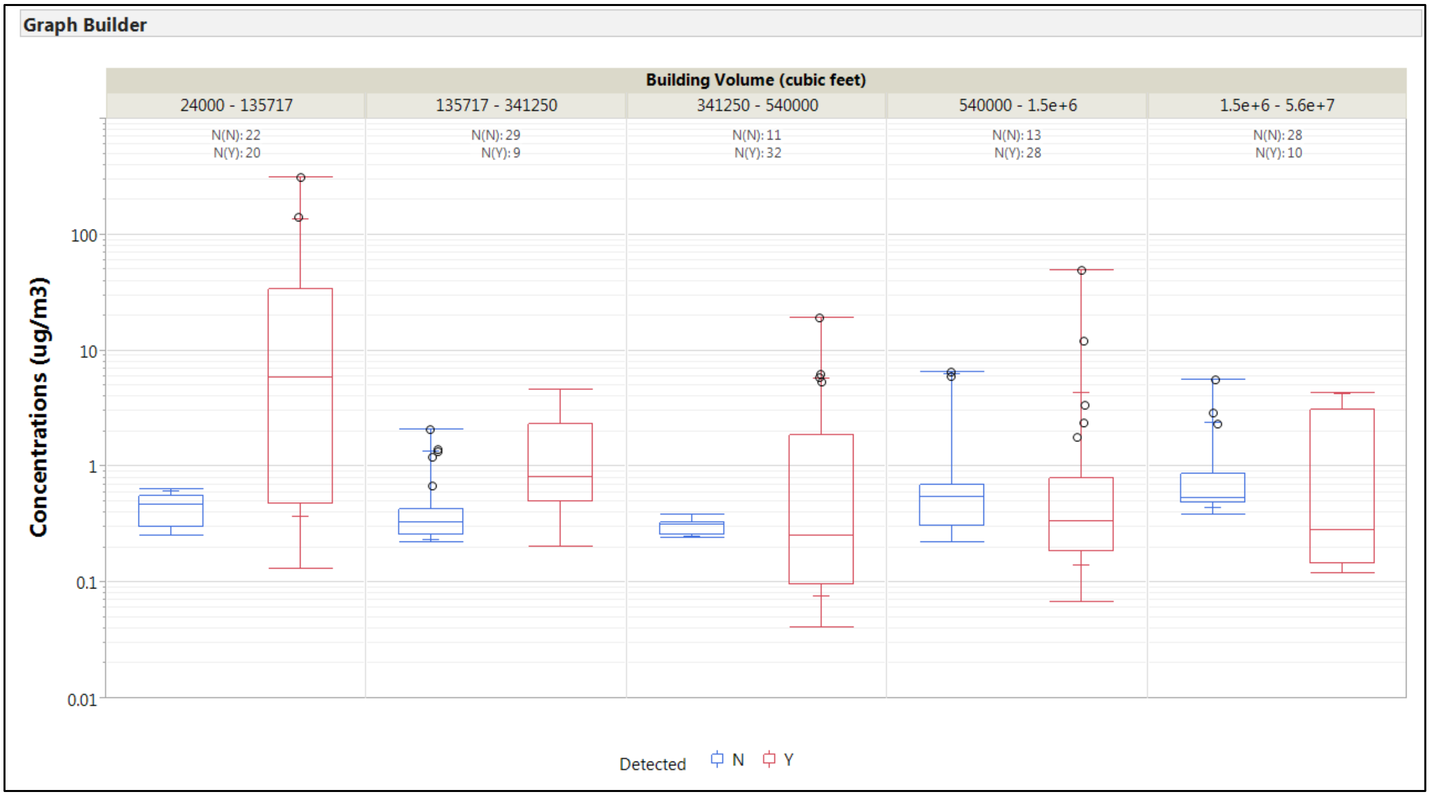


FIGURE E43
PCE Indoor Air Concentration by Building Volume
No Screens Applied
NESDI Project #476

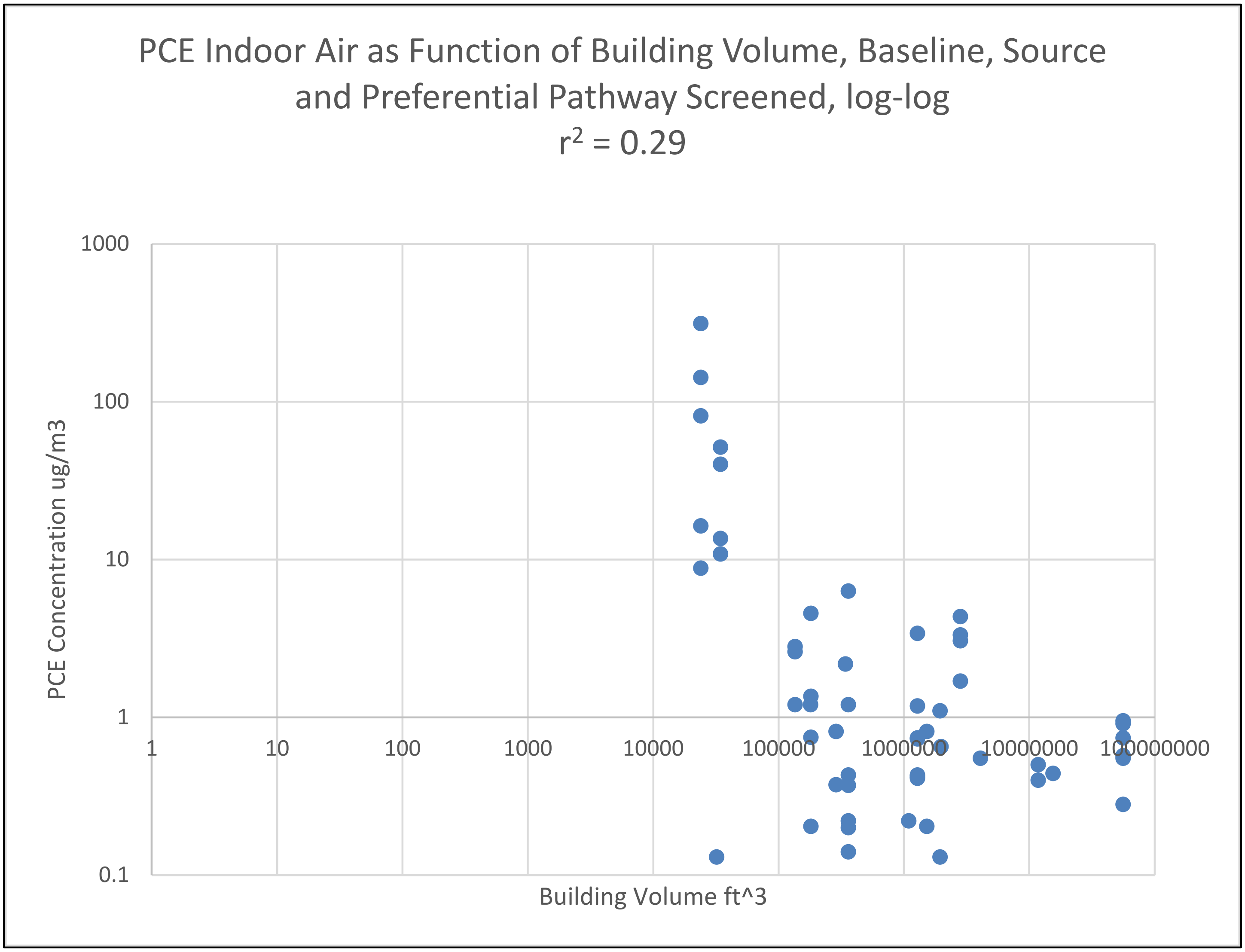


FIGURE E44
PCE Indoor Air Concentration vs Building Volume
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

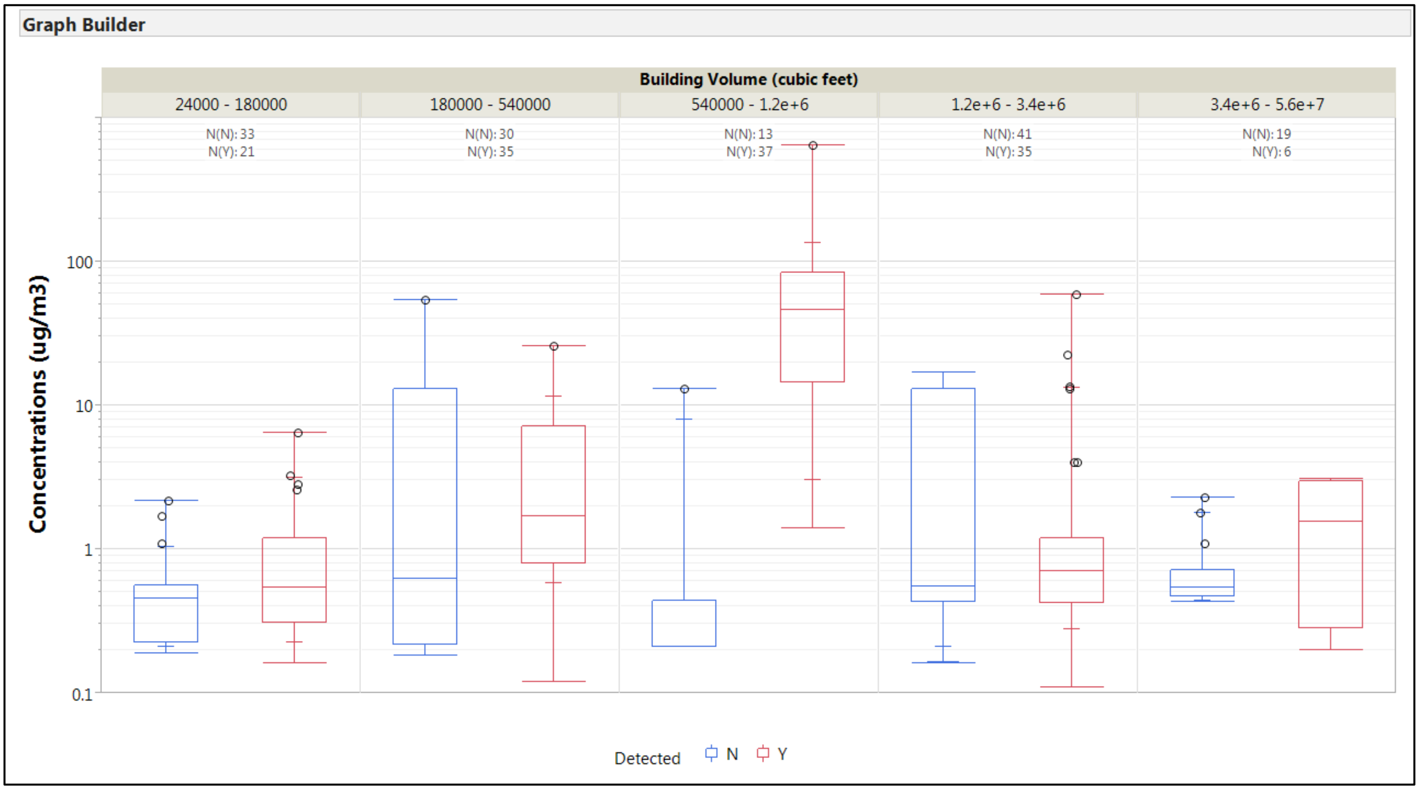


FIGURE E45
TCE Indoor Air Concentration by Building Volume
No Screens Applied
NESDI Project #476

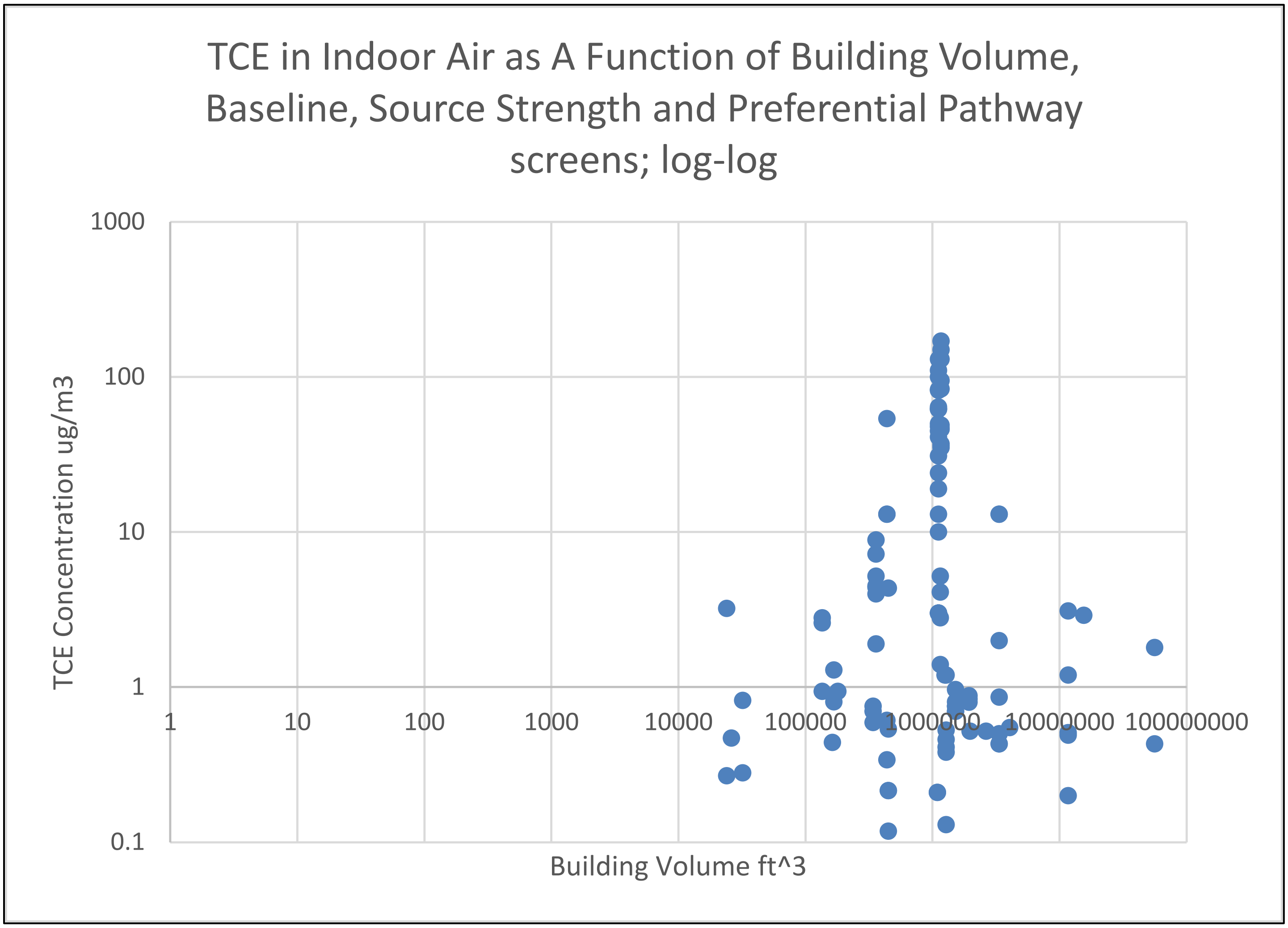


FIGURE E46

TCE Indoor Air Concentration vs Building Volume

Baseline, Source Strength and Preferential Pathway Screens Applied

NESDI Project #476

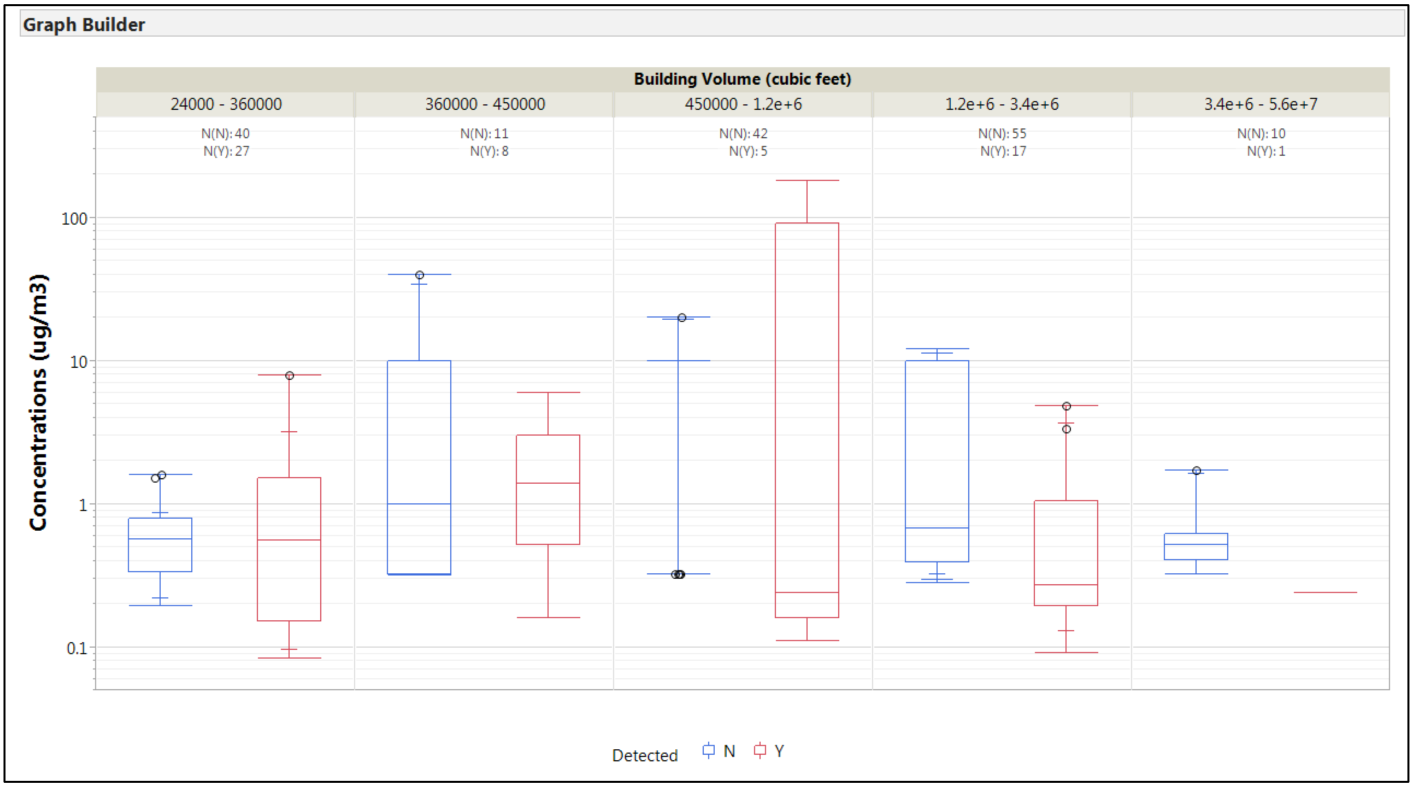


FIGURE E47
Cis-1,2-DCE by Building Volume
NESDI Project #476

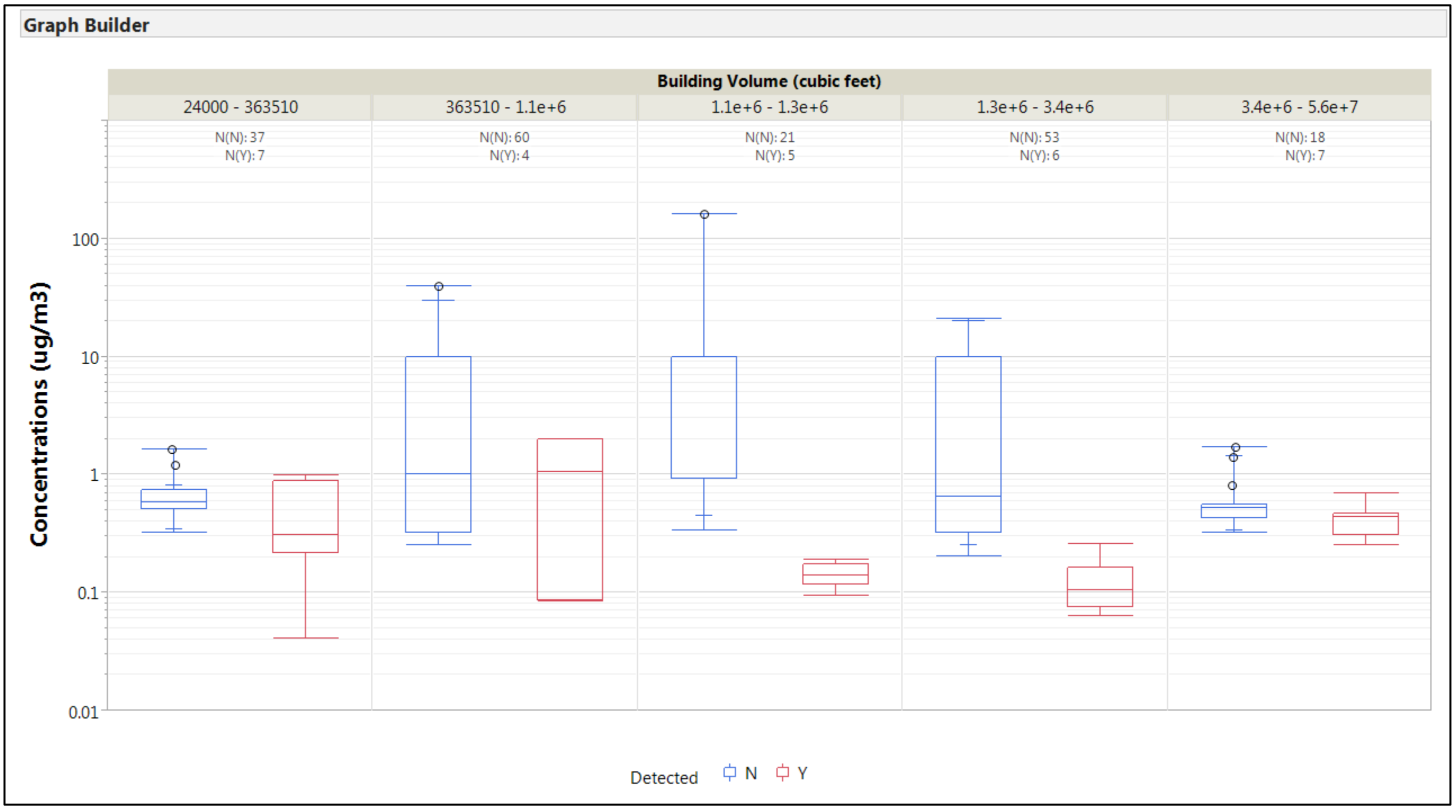


FIGURE E48

1,2-DCA Indoor Air Concentration by Building Volume

NESDI Project #476

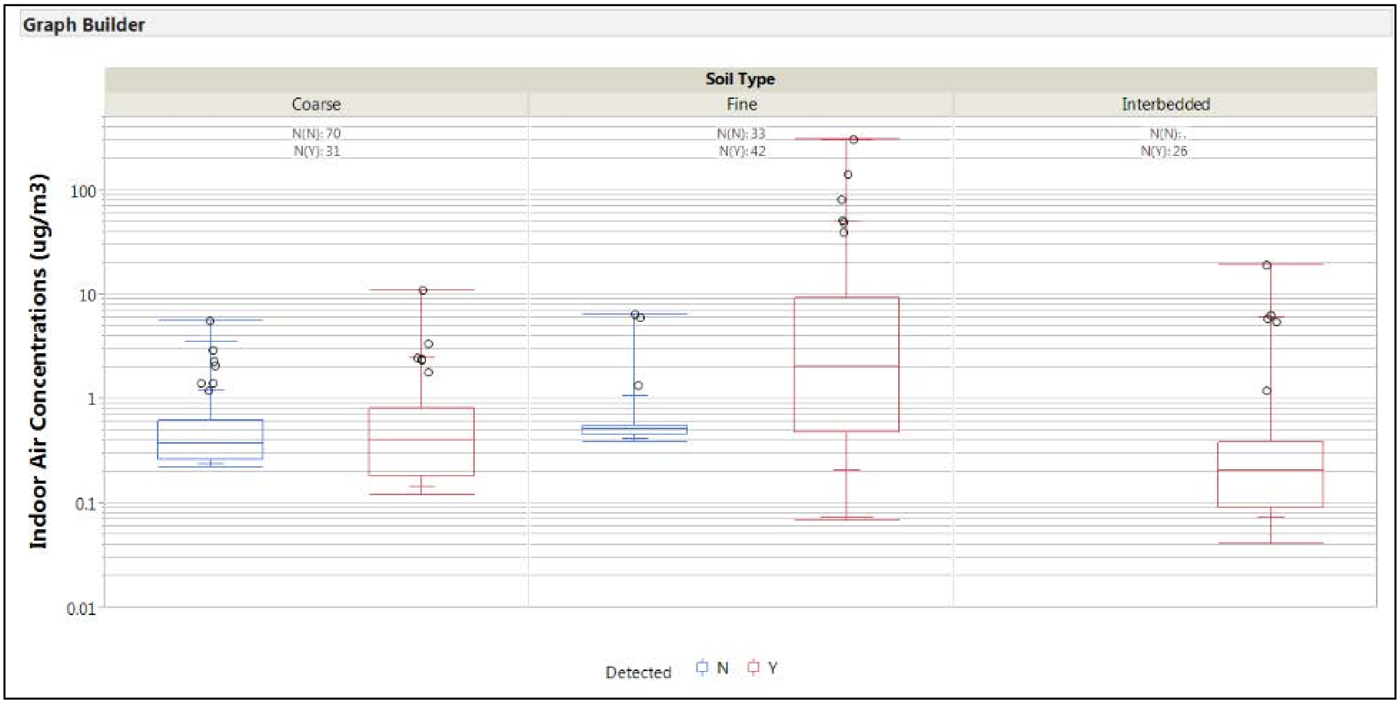


FIGURE E49

PCE Indoor Air Concentration by Soil Type

NESDI Project #476

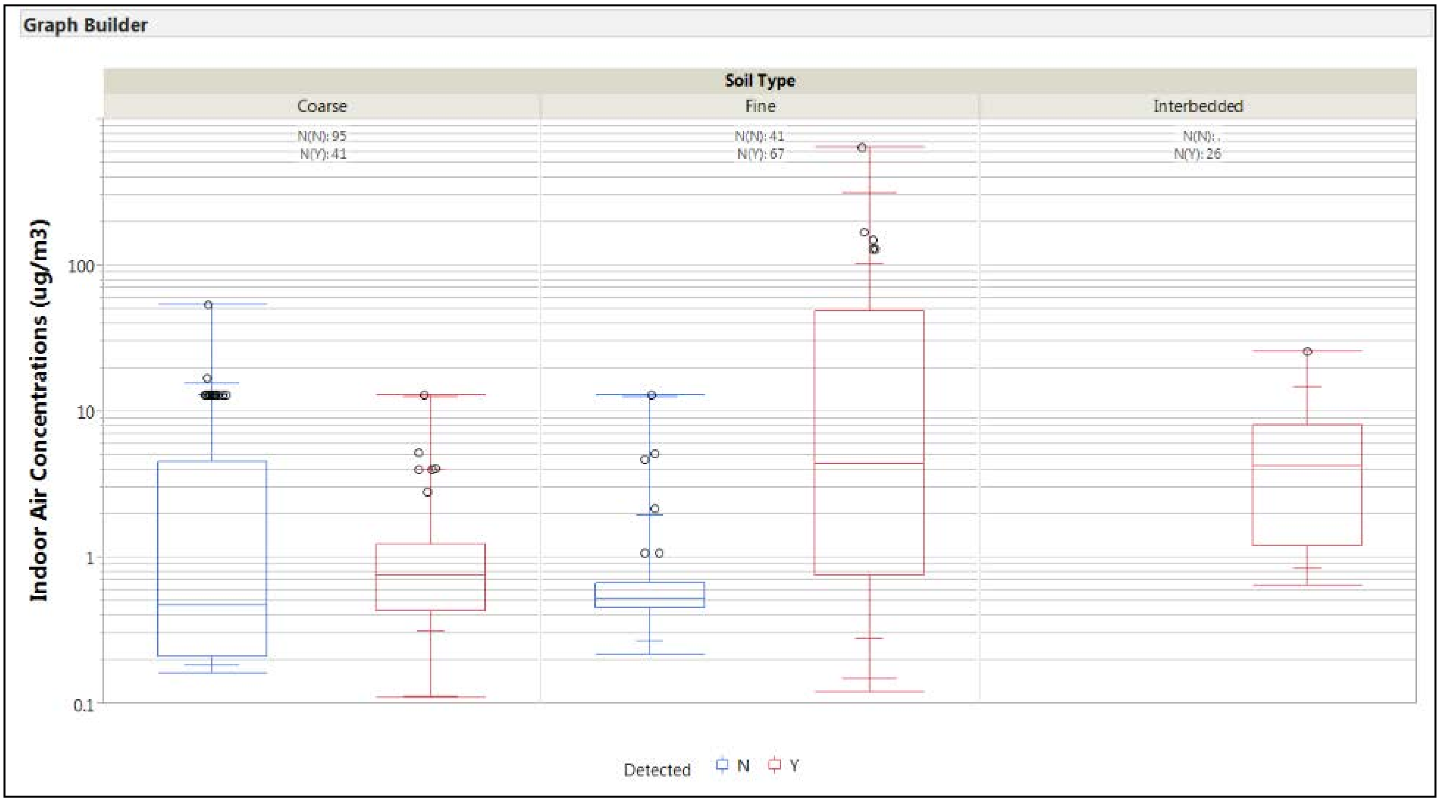


FIGURE E50

TCE Indoor Air Concentration by Soil Type

NESDI Project #476

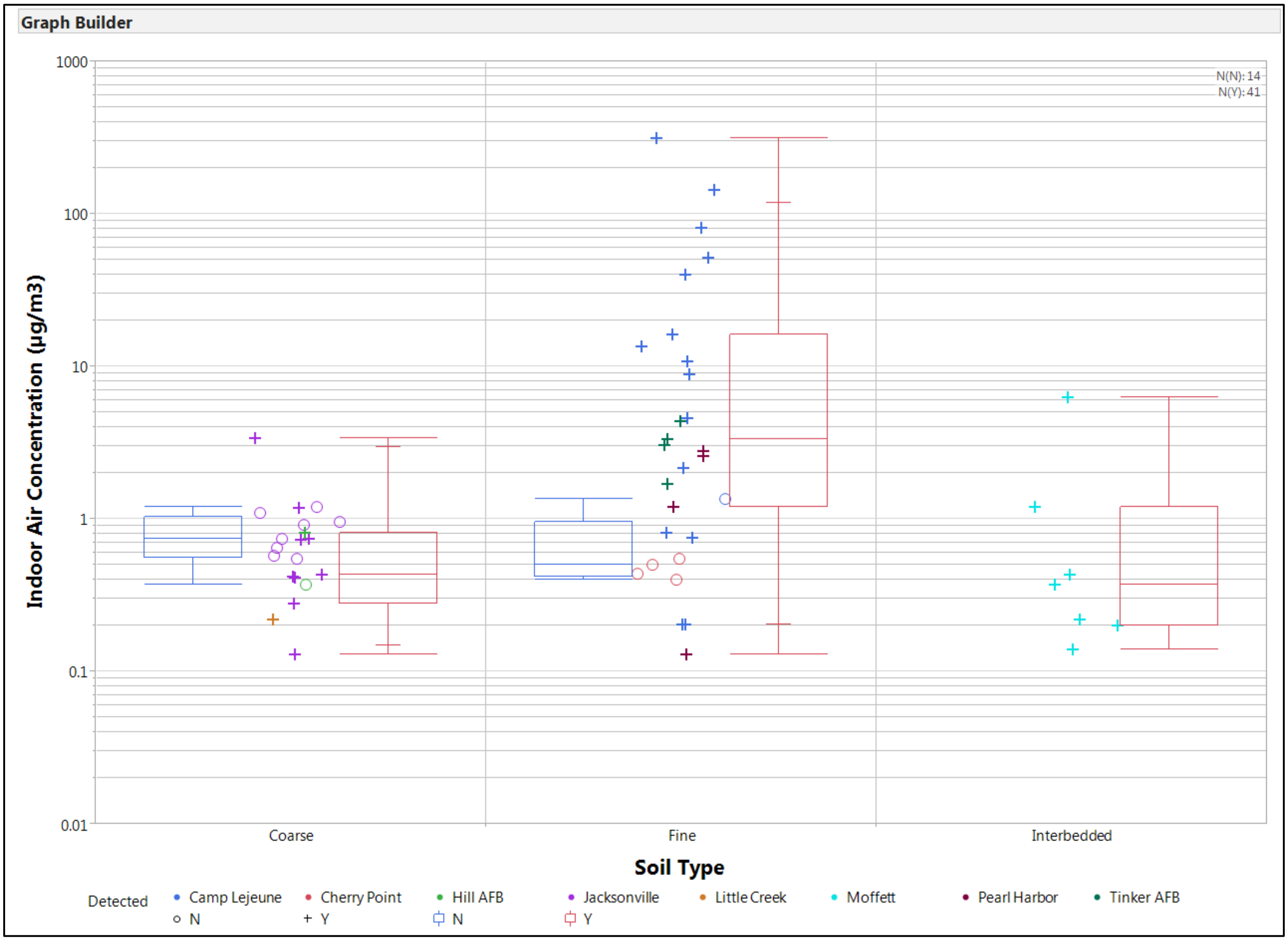


FIGURE E51
PCE Indoor Air Concentration by Soil Type
Data Plotted by Base
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

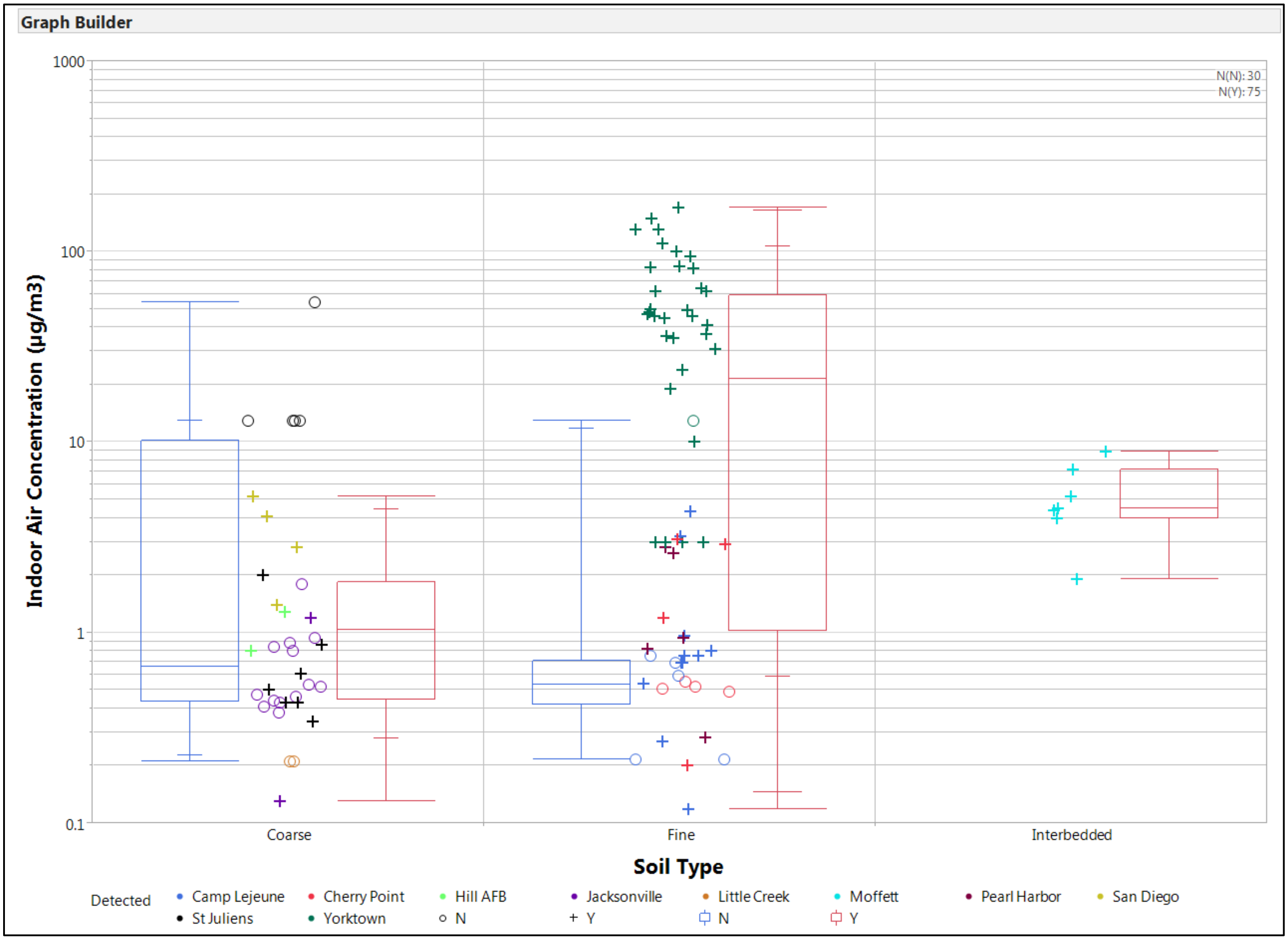


FIGURE E52
TCE Indoor Air Concentration by Soil Type
Data Plotted By Base
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

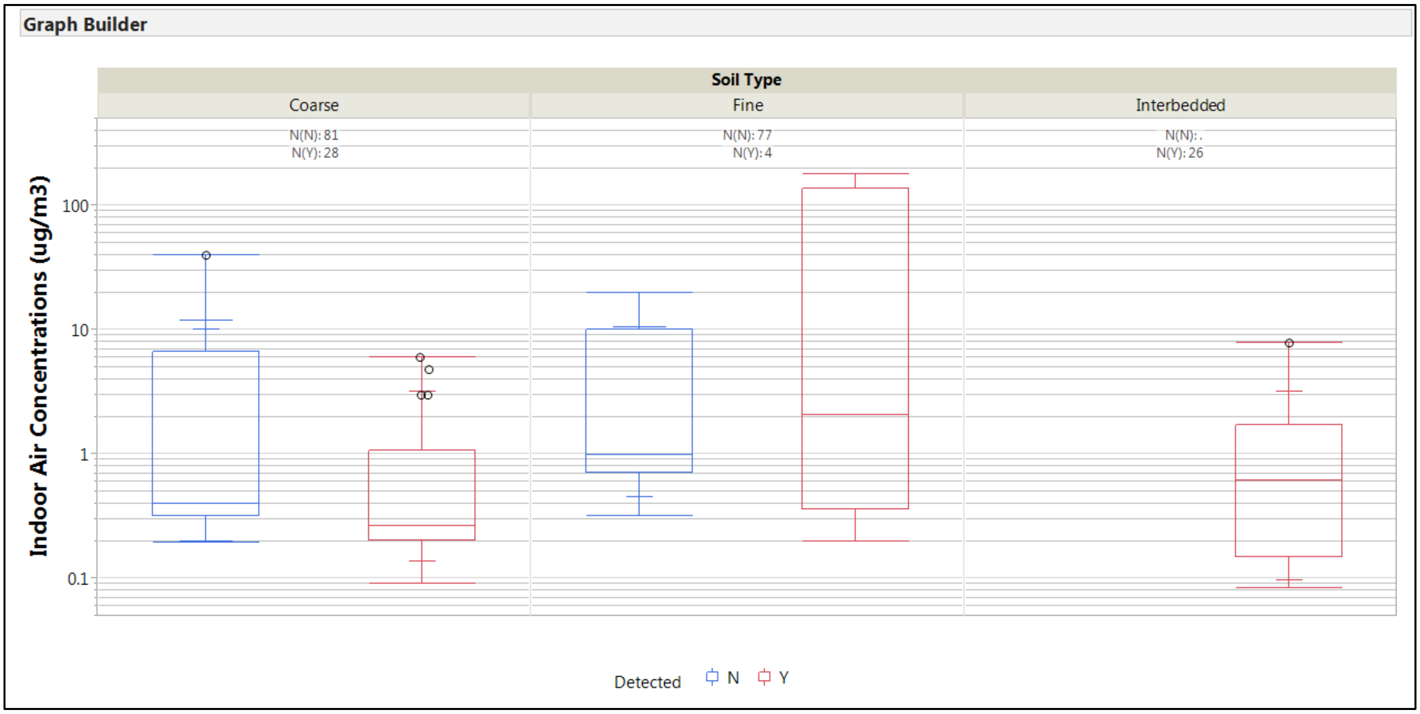


FIGURE E53
Cis-1,2-DCE Indoor Air Concentration by Soil Type
NESDI Project #476

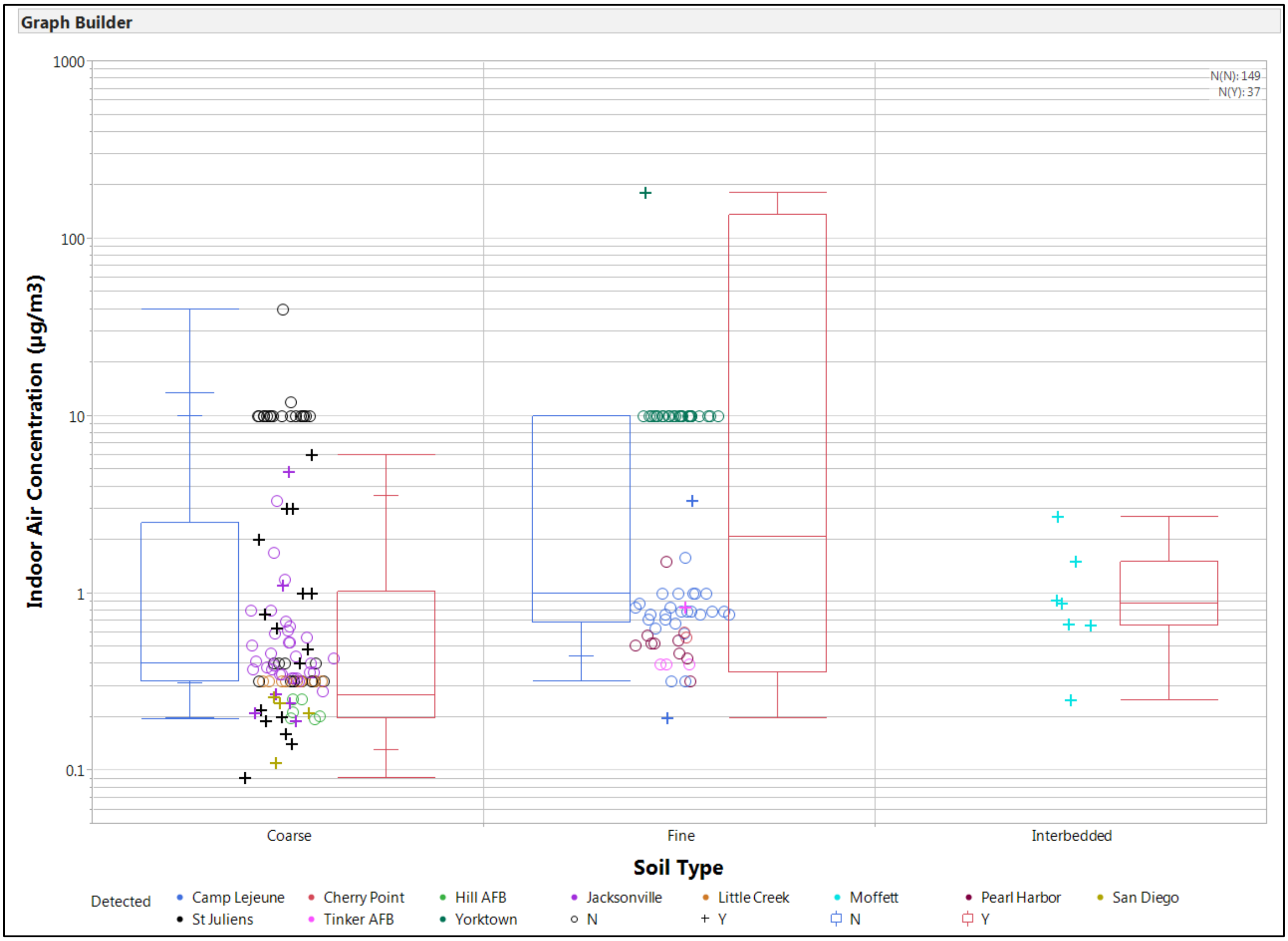


FIGURE E54
Cis-DCE Indoor Air Concentration by Soil Type
Baseline, Source Strength and Preferential Pathway Screens Applied
NESDI Project #476

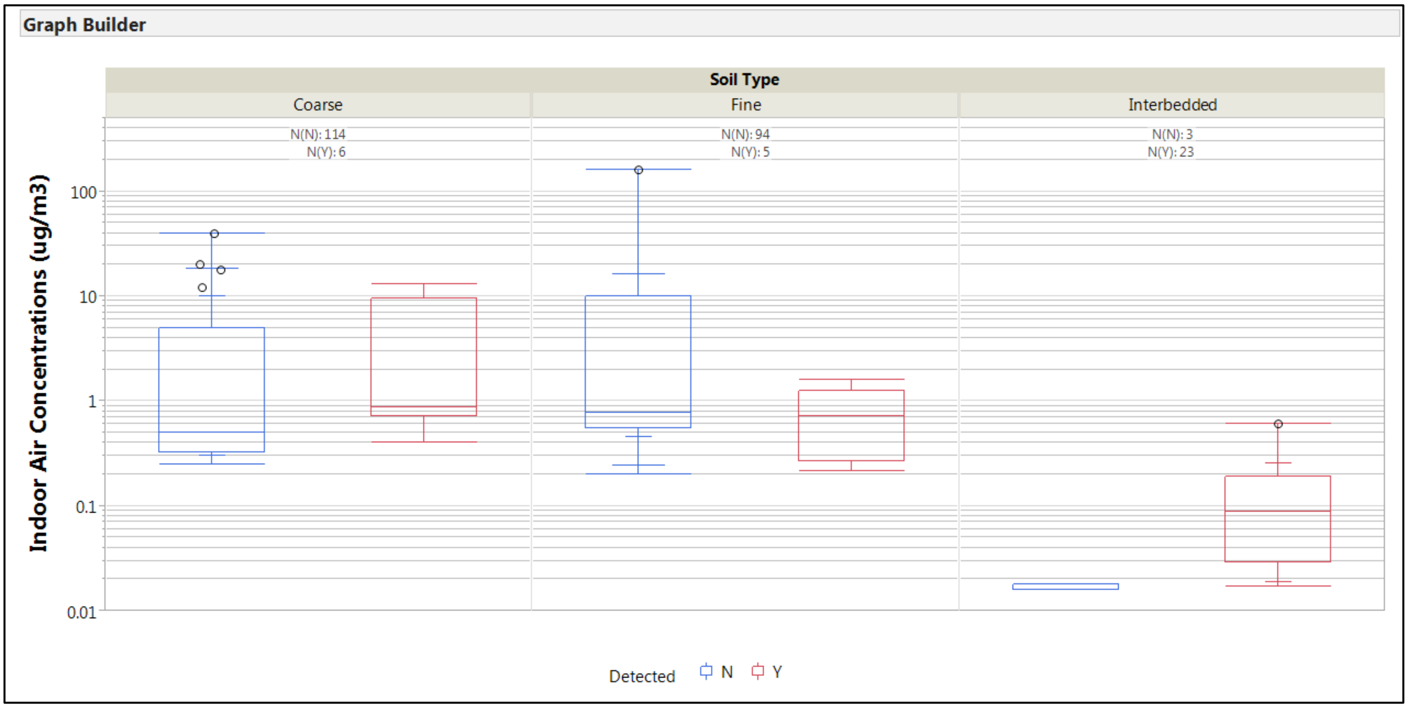


FIGURE E55

1,1-DCE Indoor Air Concentration by Soil Type

NESDI Project #476

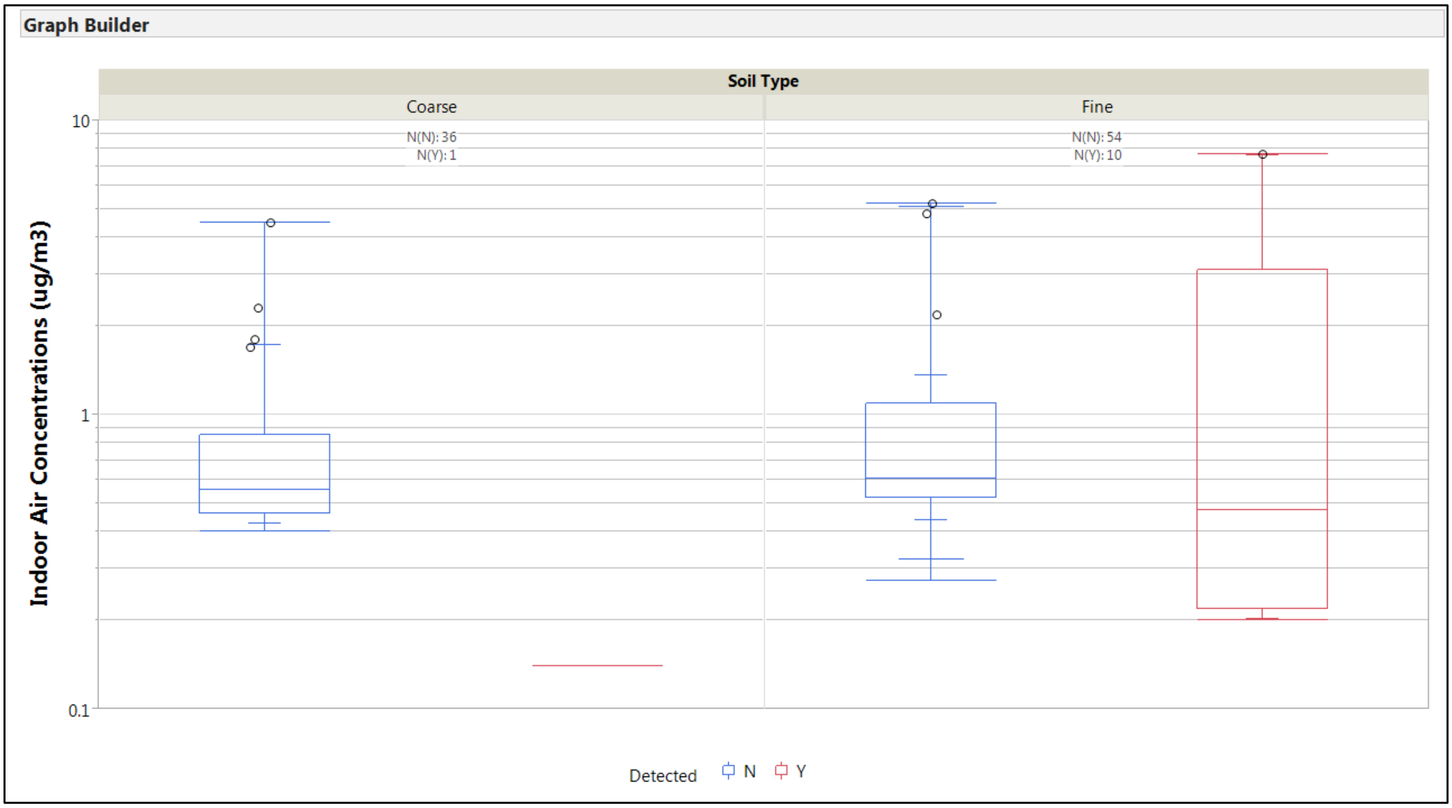


FIGURE E56

1,1,1-TCA Indoor Air Concentration by Soil Type

NESDI Project #476

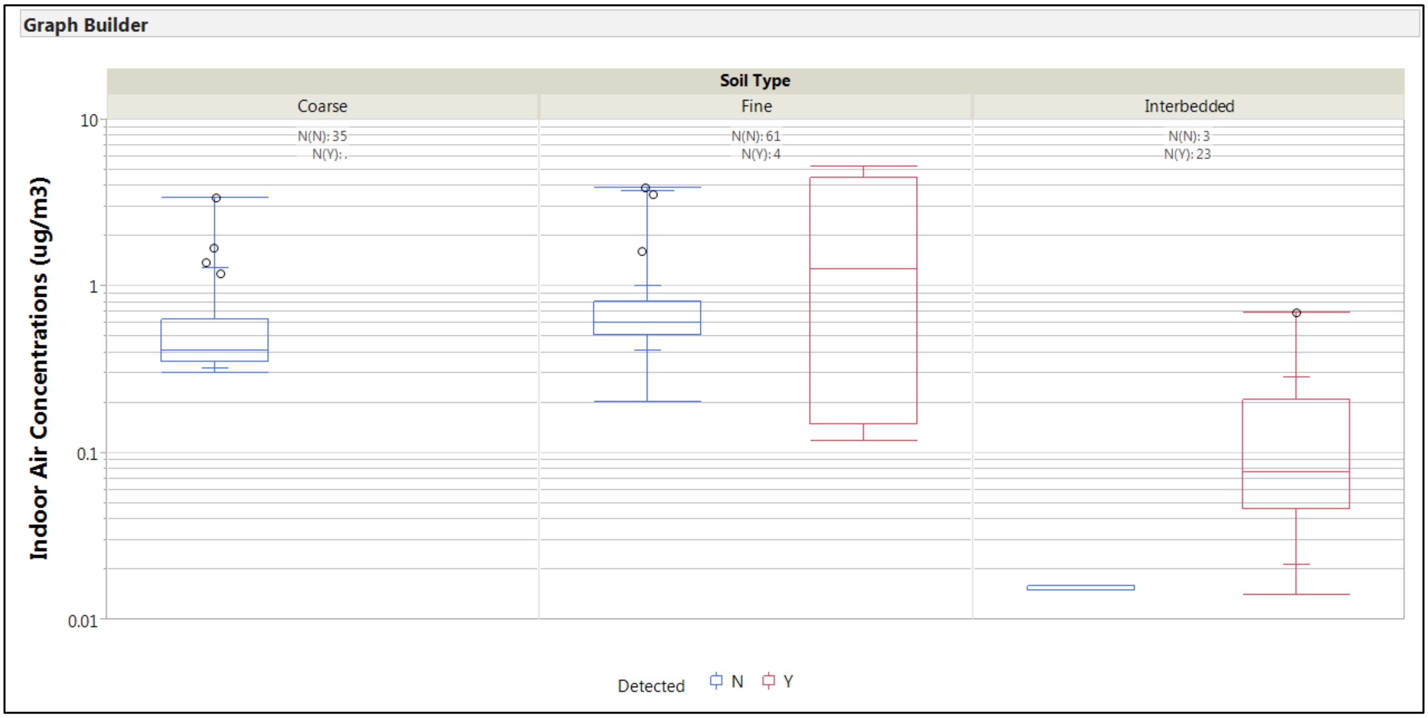


FIGURE E57

1,1-DCA Indoor Air Concentration by Soil Type

NESDI Project #476

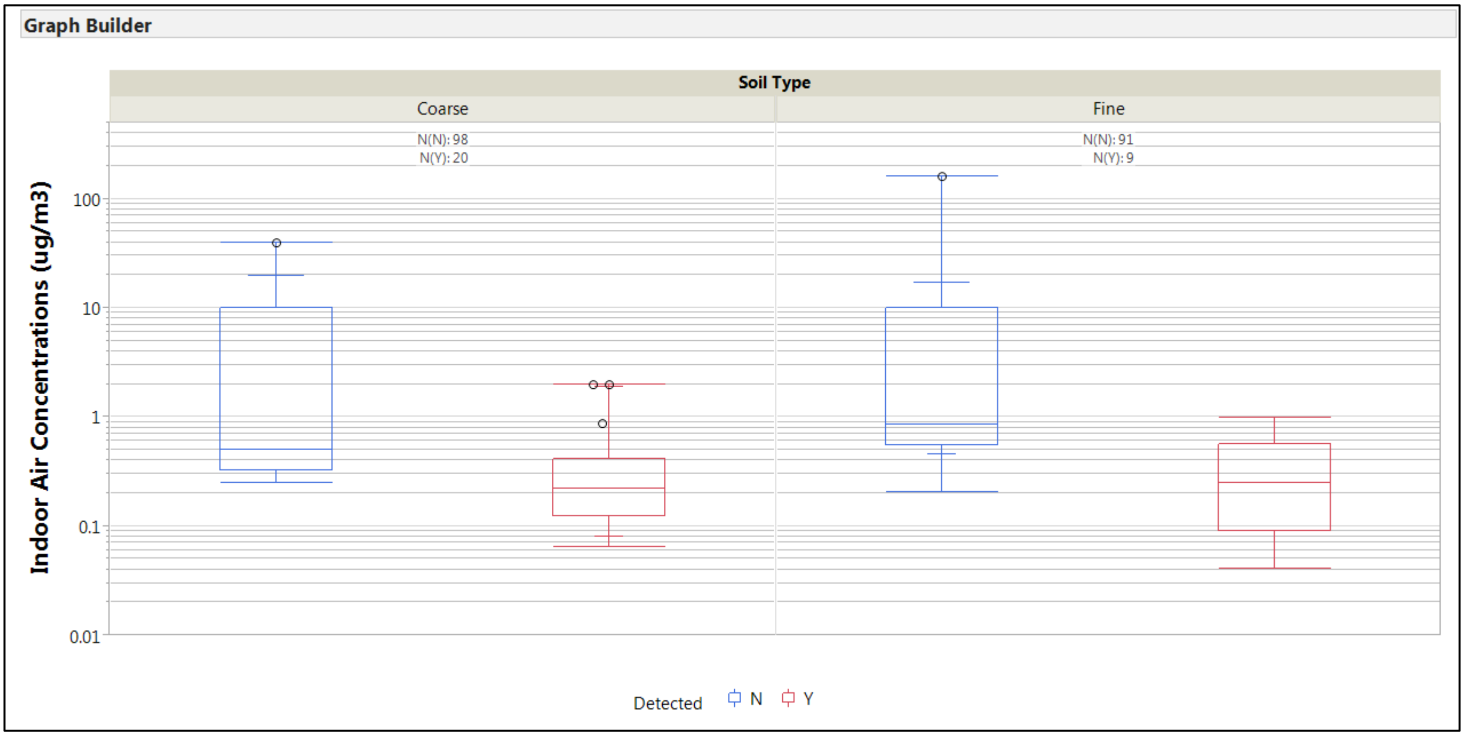


FIGURE E58

1,2-DCA Indoor Air Concentration by Soil Type

NESDI Project #476

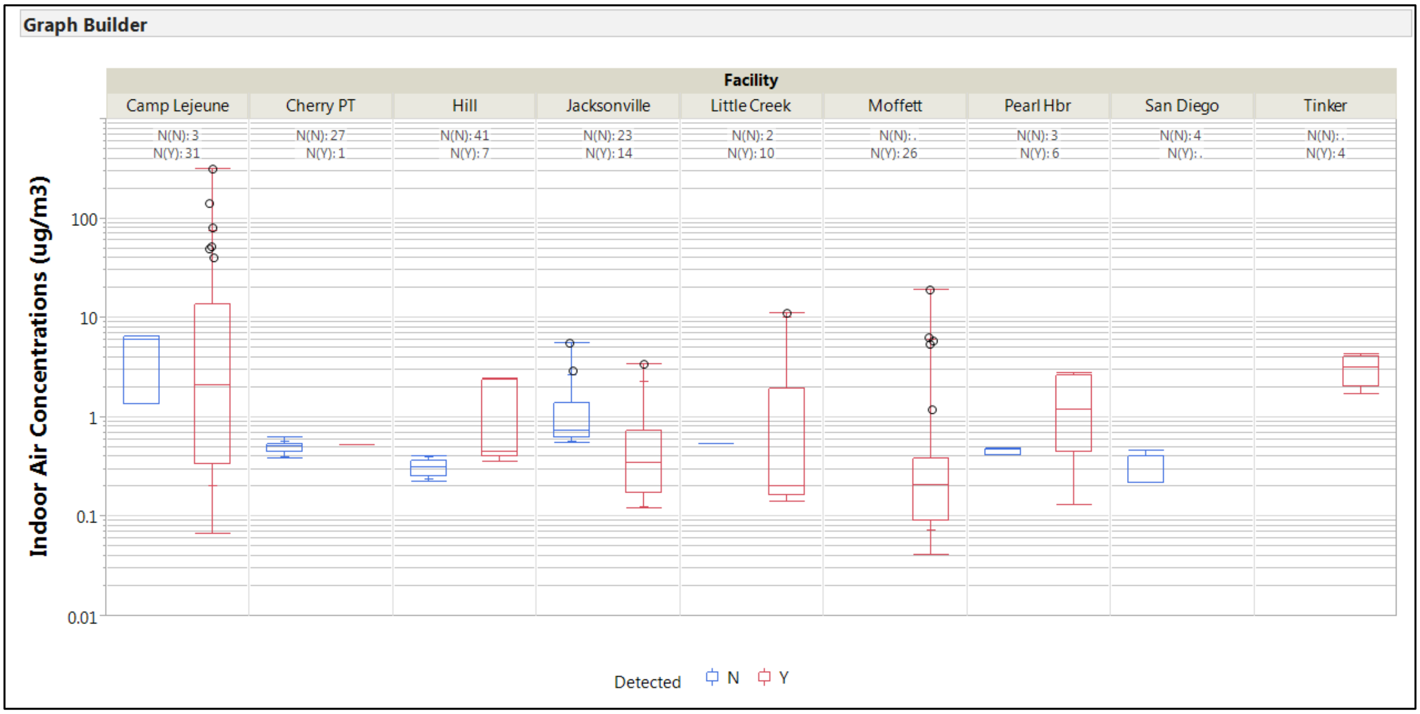


FIGURE E59

PCE Indoor Air Concentration by Facility

NESDI Project #476

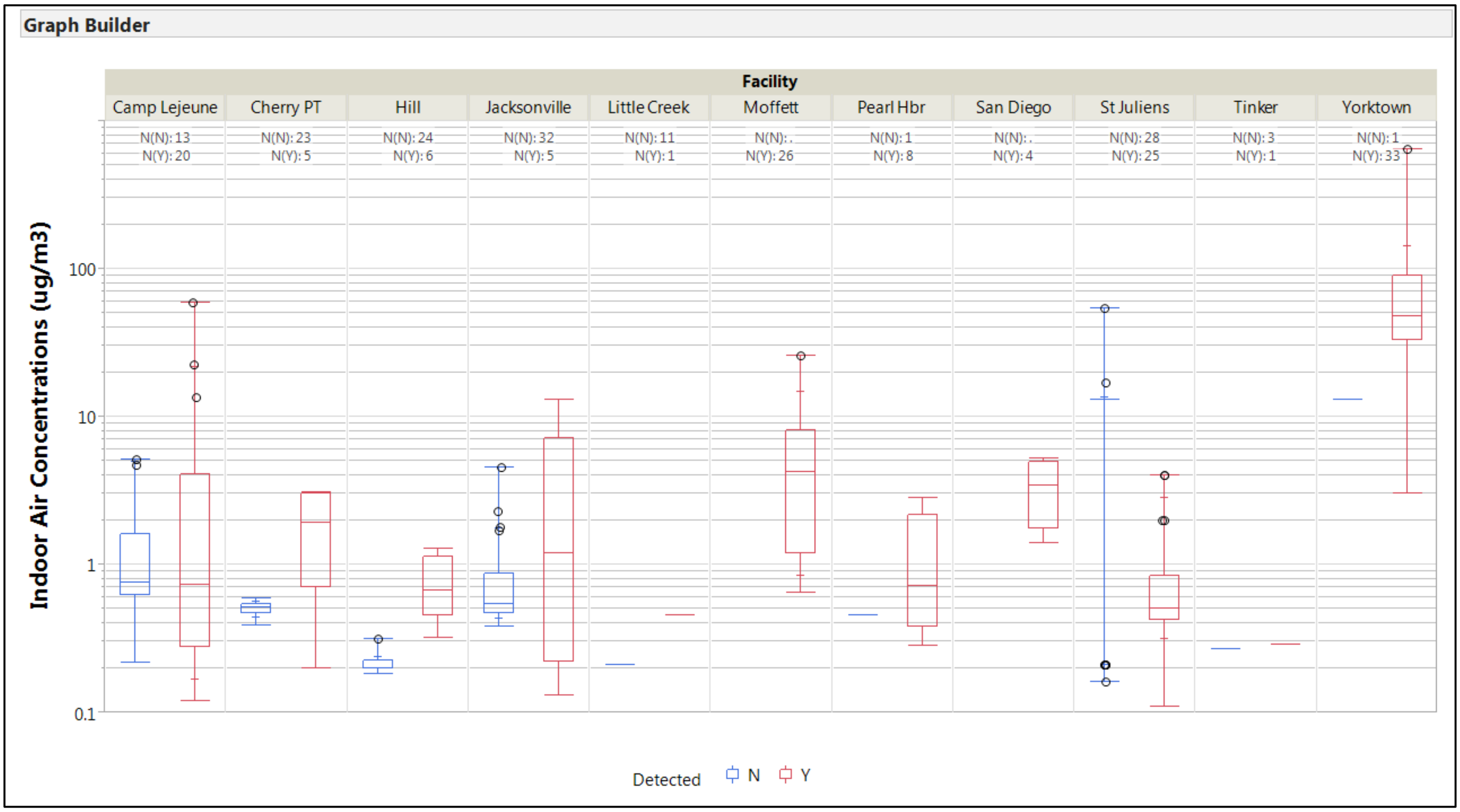


FIGURE E60
TCE Indoor Air Concentration by Facility
NESDI Project #476

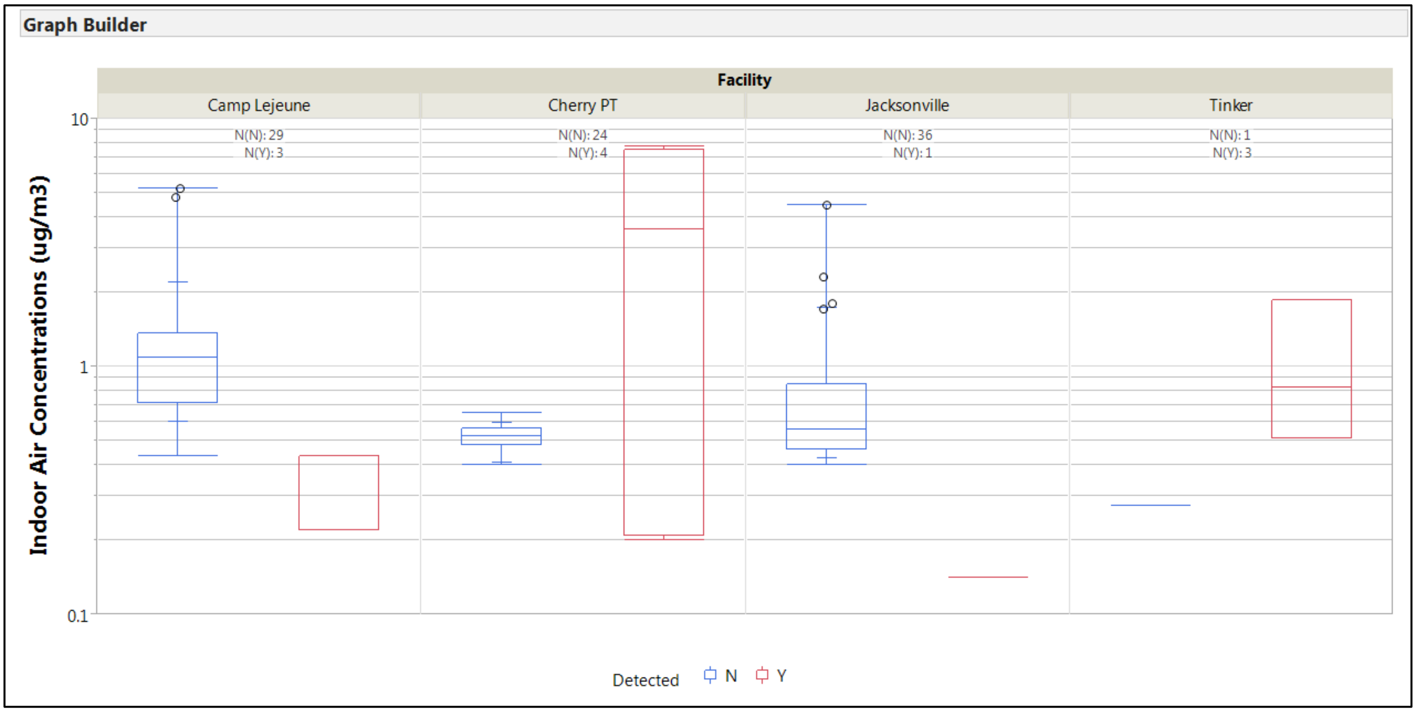


FIGURE E61
1,1,1-TCA Indoor Air Concentration by Facility
NESDI Project #476

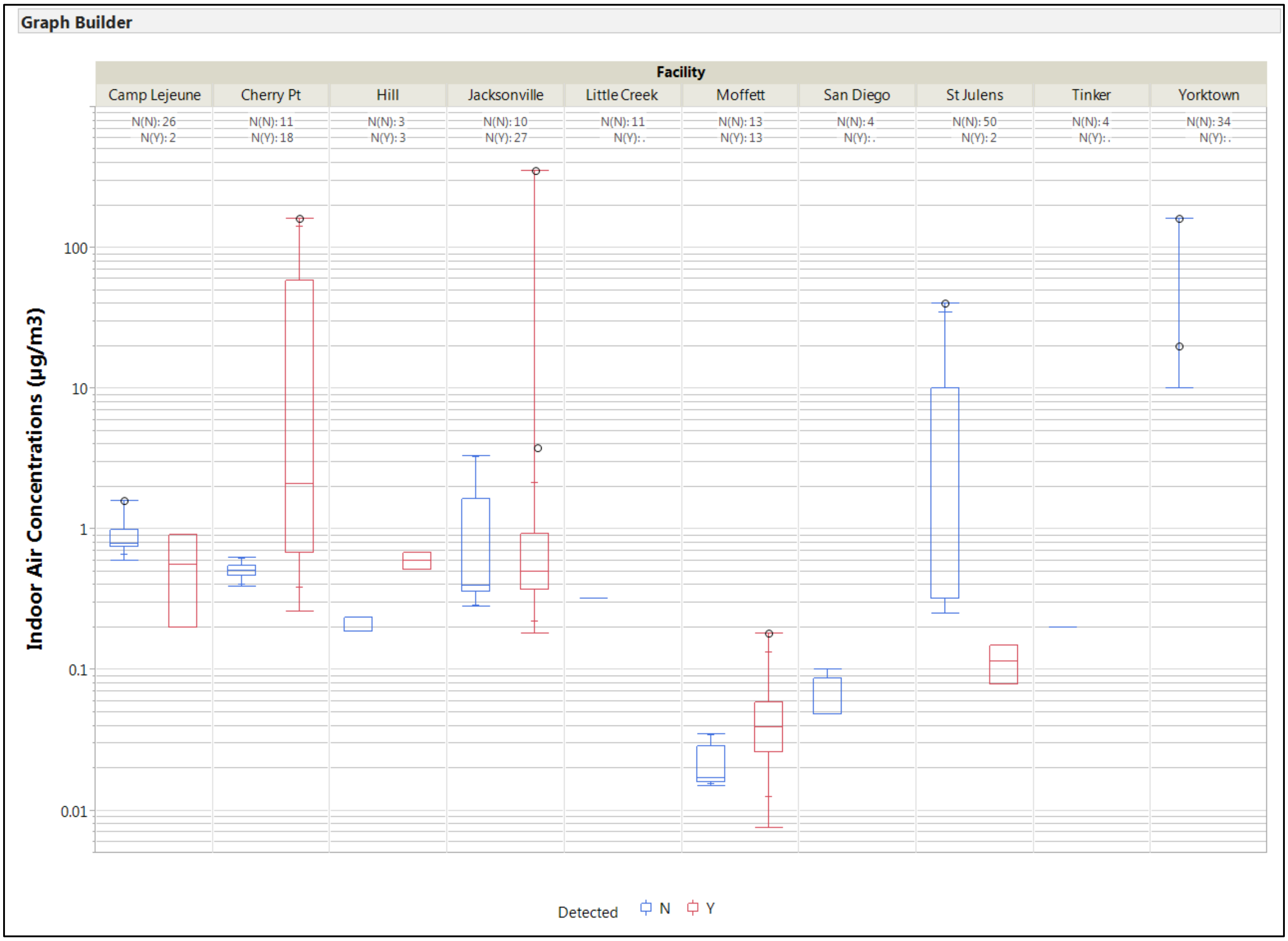


FIGURE E62

Trans-1,2-DCE Indoor Air Concentration by Facility

NESDI Project #476

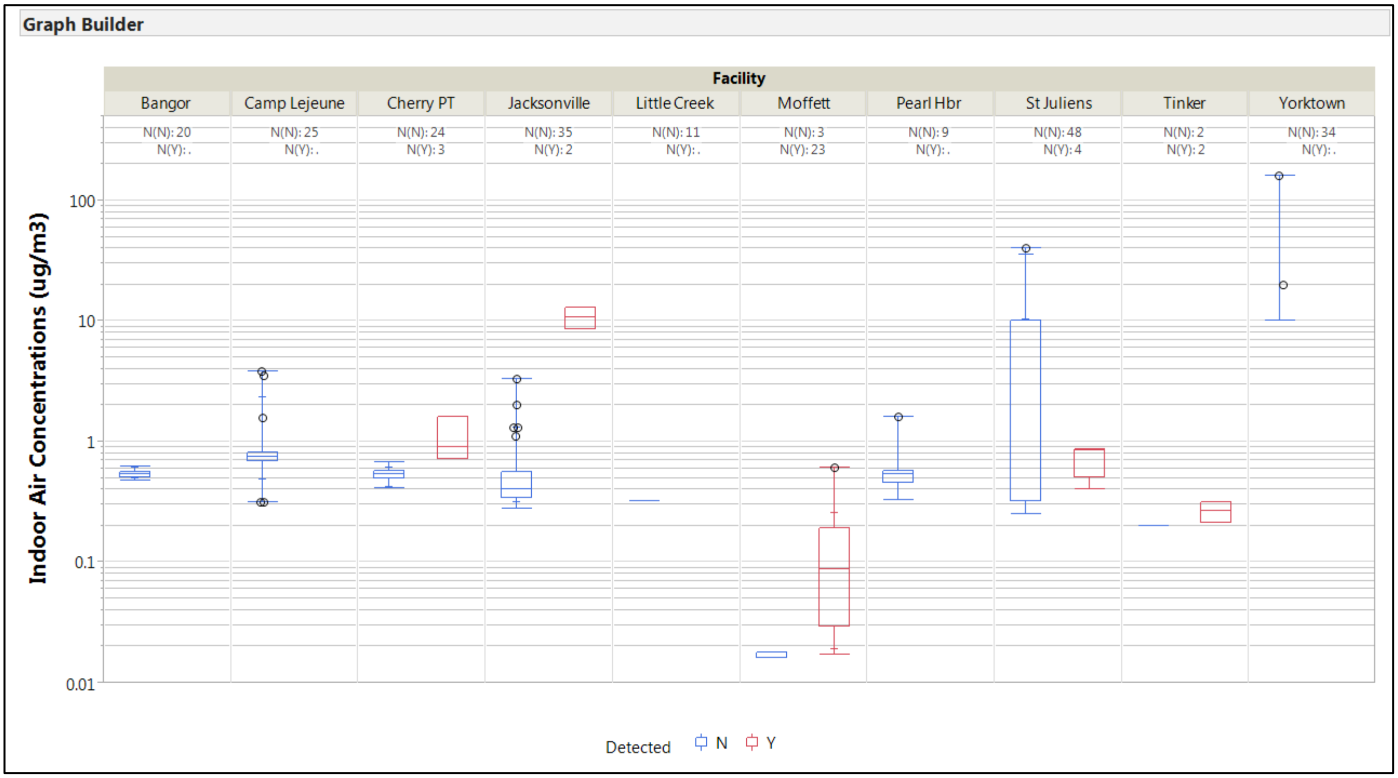


FIGURE E63
1,1-DCE Indoor Air Concentration by Facility
NESDI Project #476

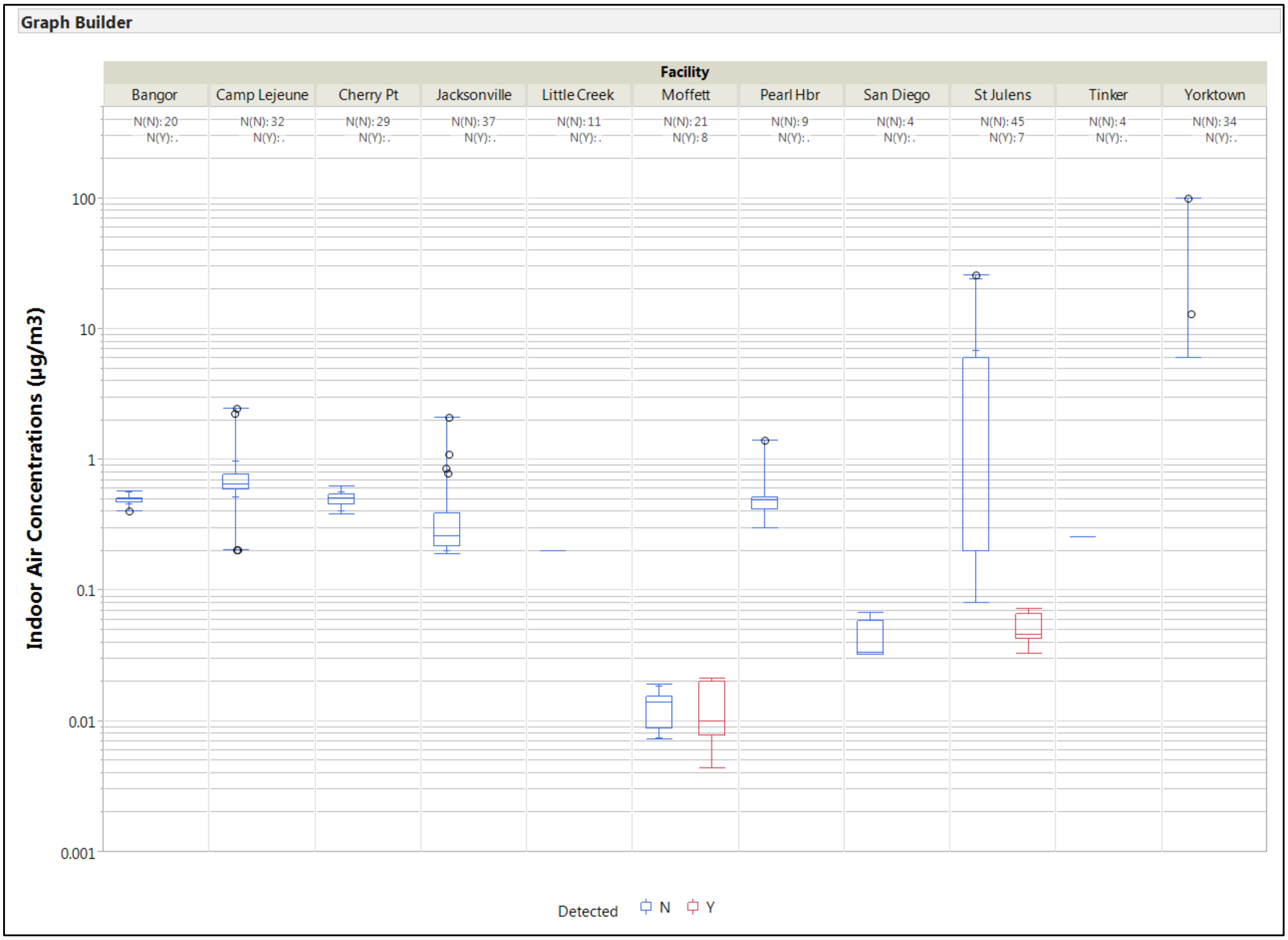


FIGURE E64

Vinyl Chloride Indoor Air Concentration by Facility

NESDI Project #476

Figure E-65 is available to RPMs upon request.

Figure E-66 is available to RPMs upon request.

Figure E-67 is available to RPMs upon request.

Figure E-68 is available to RPMs upon request.

Figure E-69 is available to RPMs upon request.

Figure E-70 is available to RPMs upon request.

Figure E-71 is available to RPMs upon request.

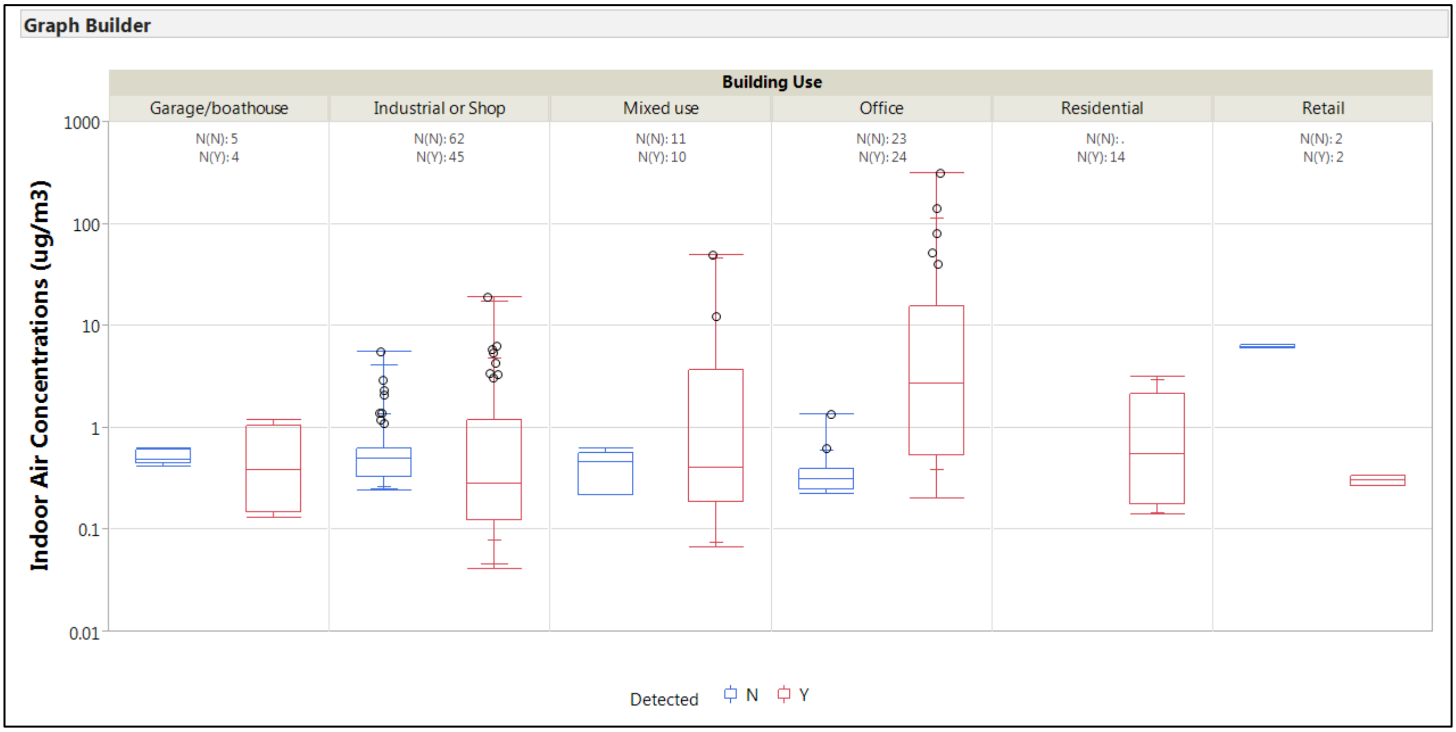


FIGURE E72
PCE Indoor Air Concentration by Building Use
NESDI Project #476

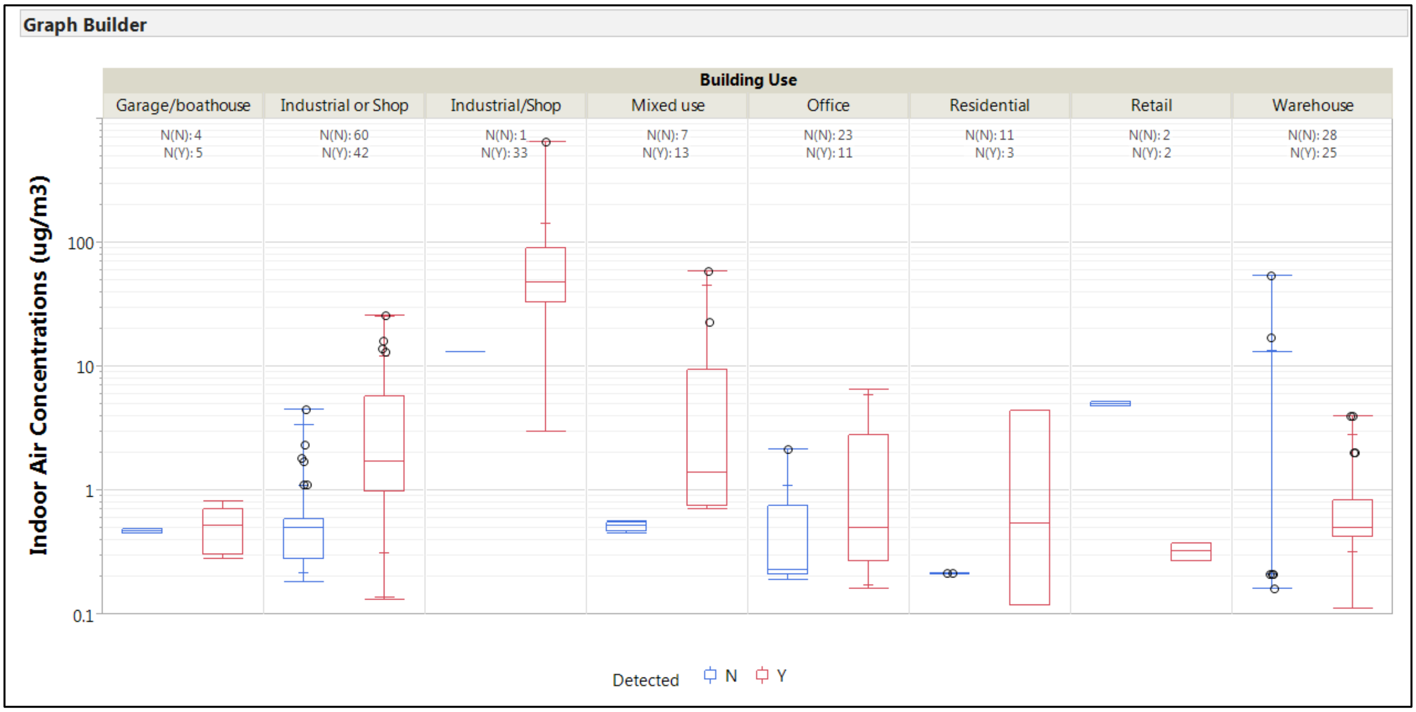


FIGURE E73

TCE Indoor Air Concentration by Building Use

NESDI Project #476

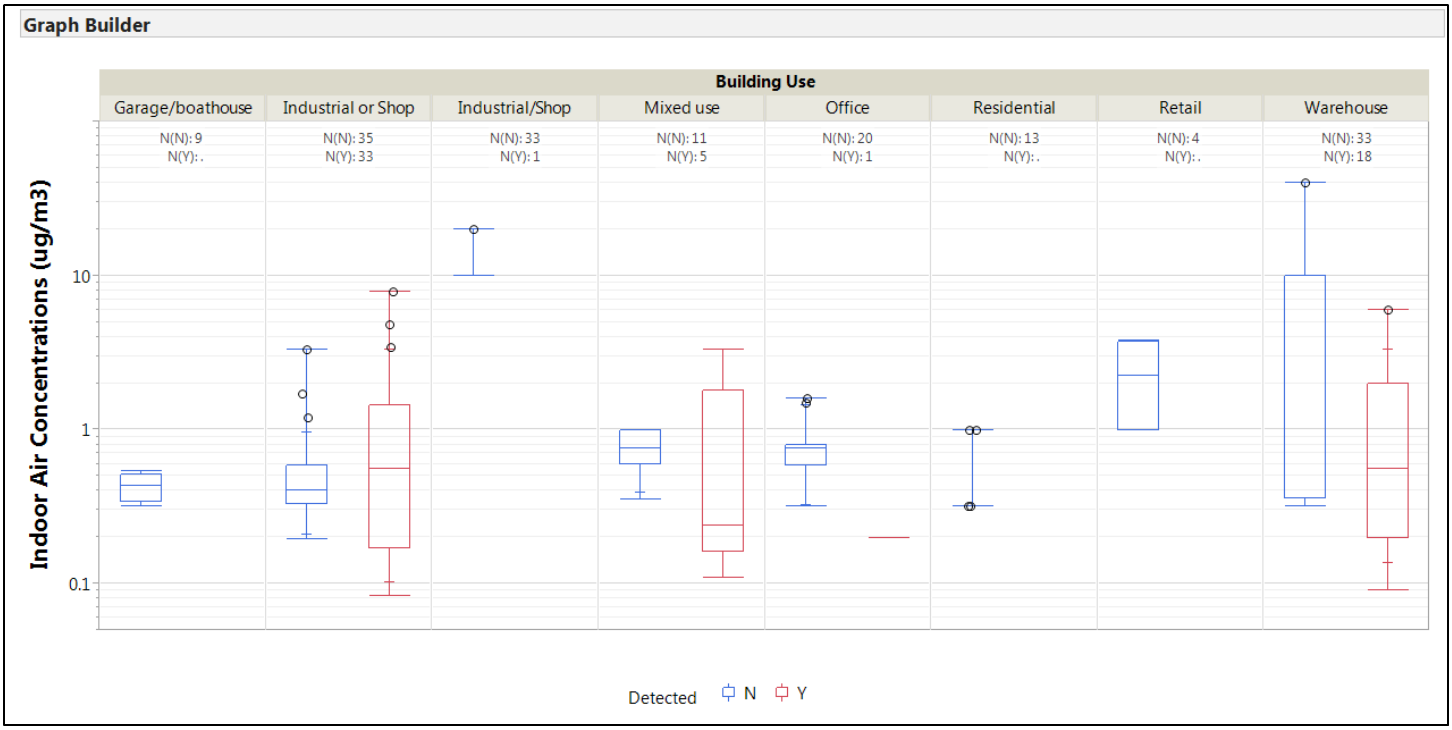


FIGURE E74
Cis-1,2-DCE Indoor Air Concentration by Building Use
NESDI Project #476

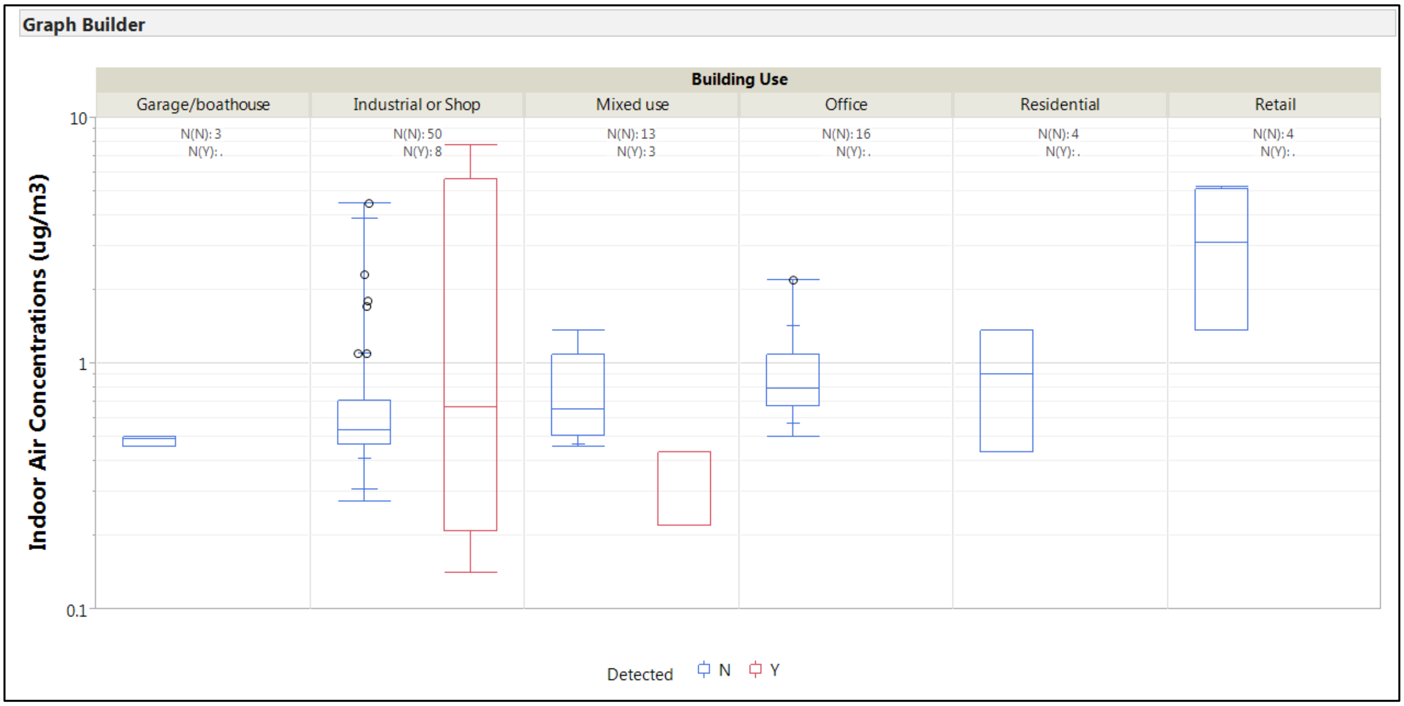


FIGURE E75
1,1,1-TCA Indoor Air Concentration by Building Use
NESDI Project #476

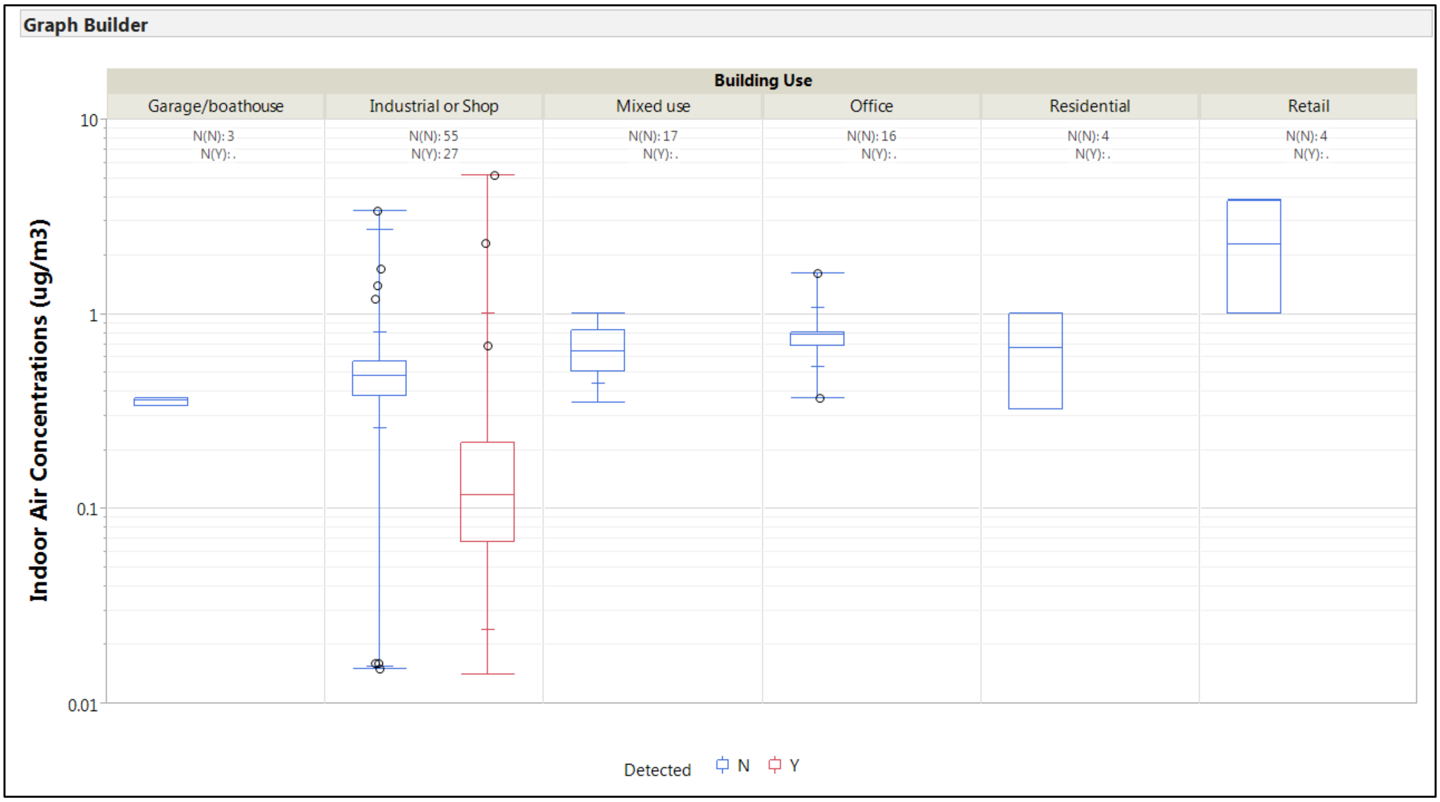


FIGURE E76
1,1-DCA Indoor Air Concentration by Building Use
NESDI Project #476

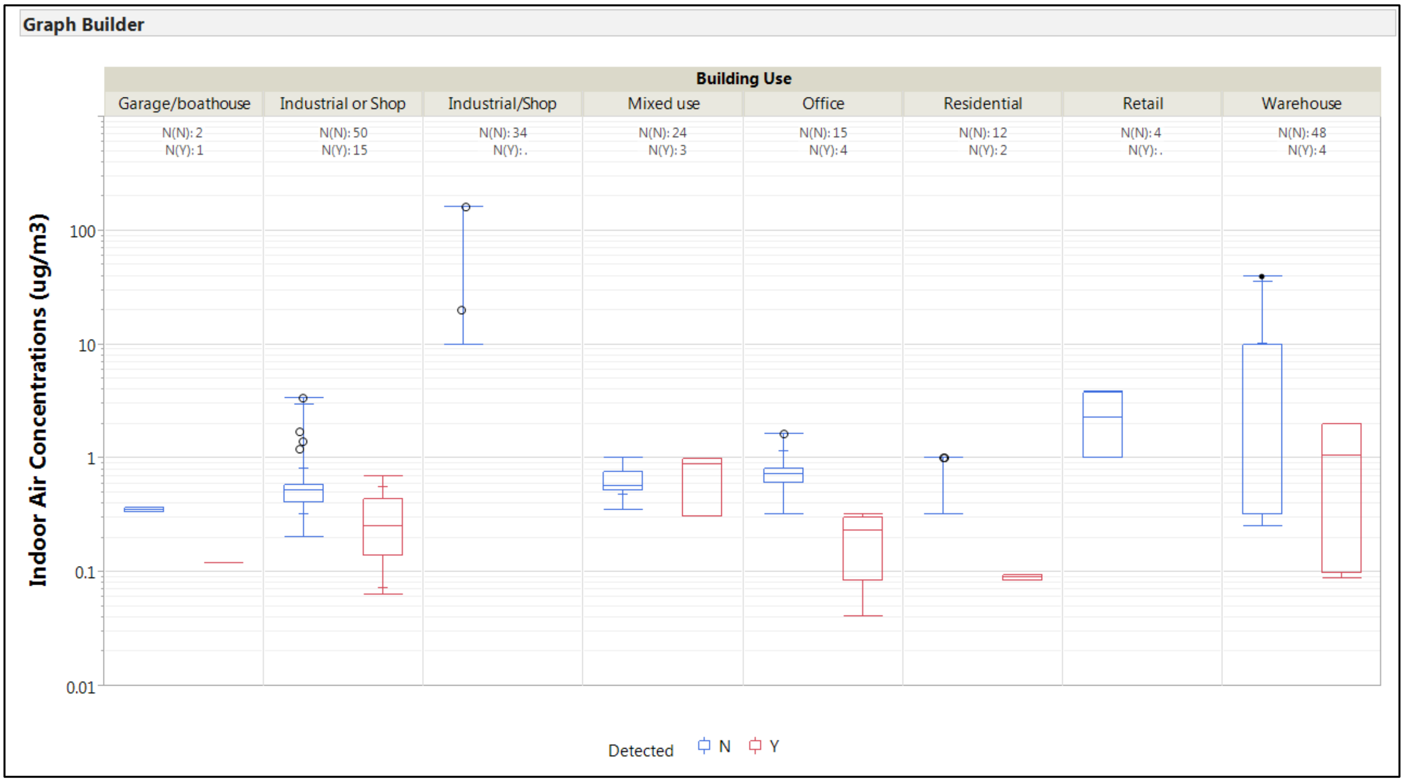


FIGURE E77

1,2-DCA Indoor Air Concentration by Building Use

NESDI Project #476

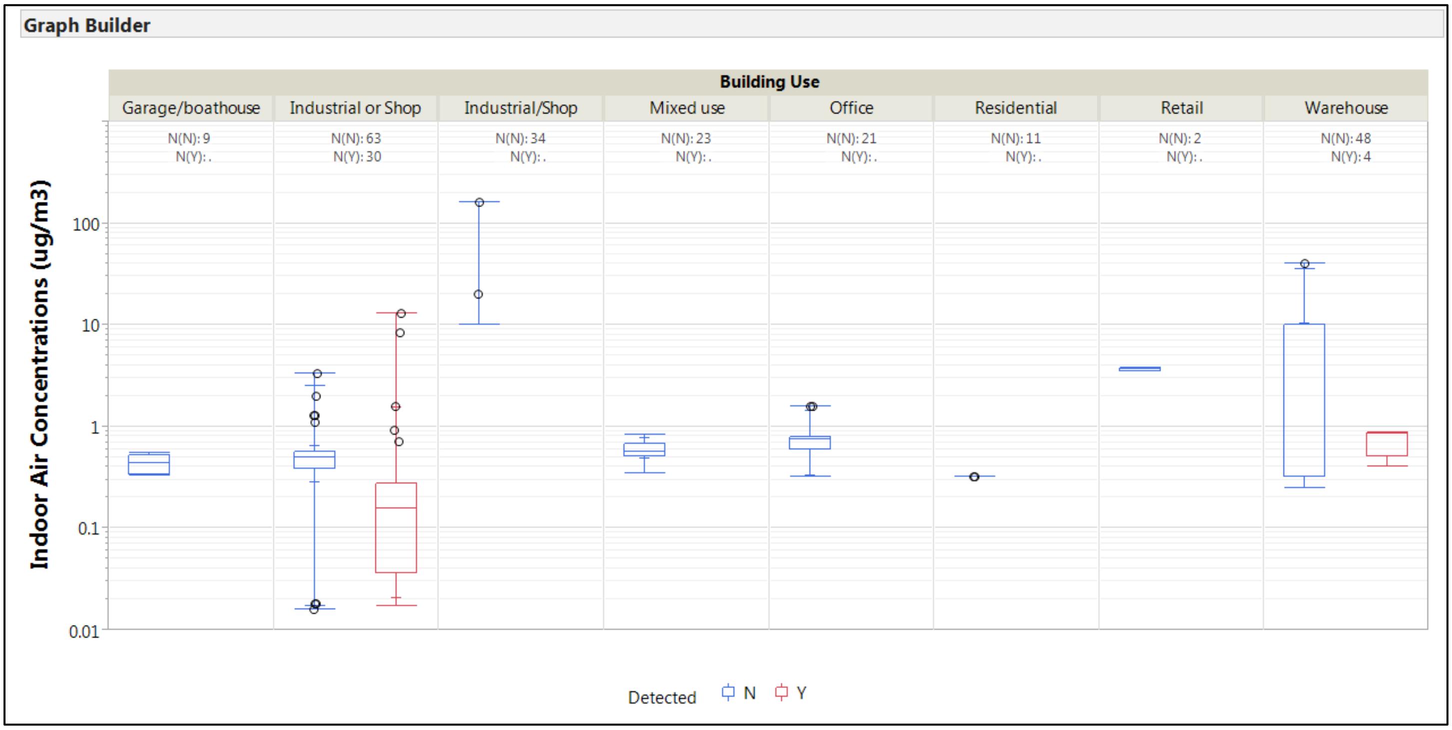


FIGURE E78
1,1-DCE Indoor Air Concentration by Building Use
NESDI Project #476

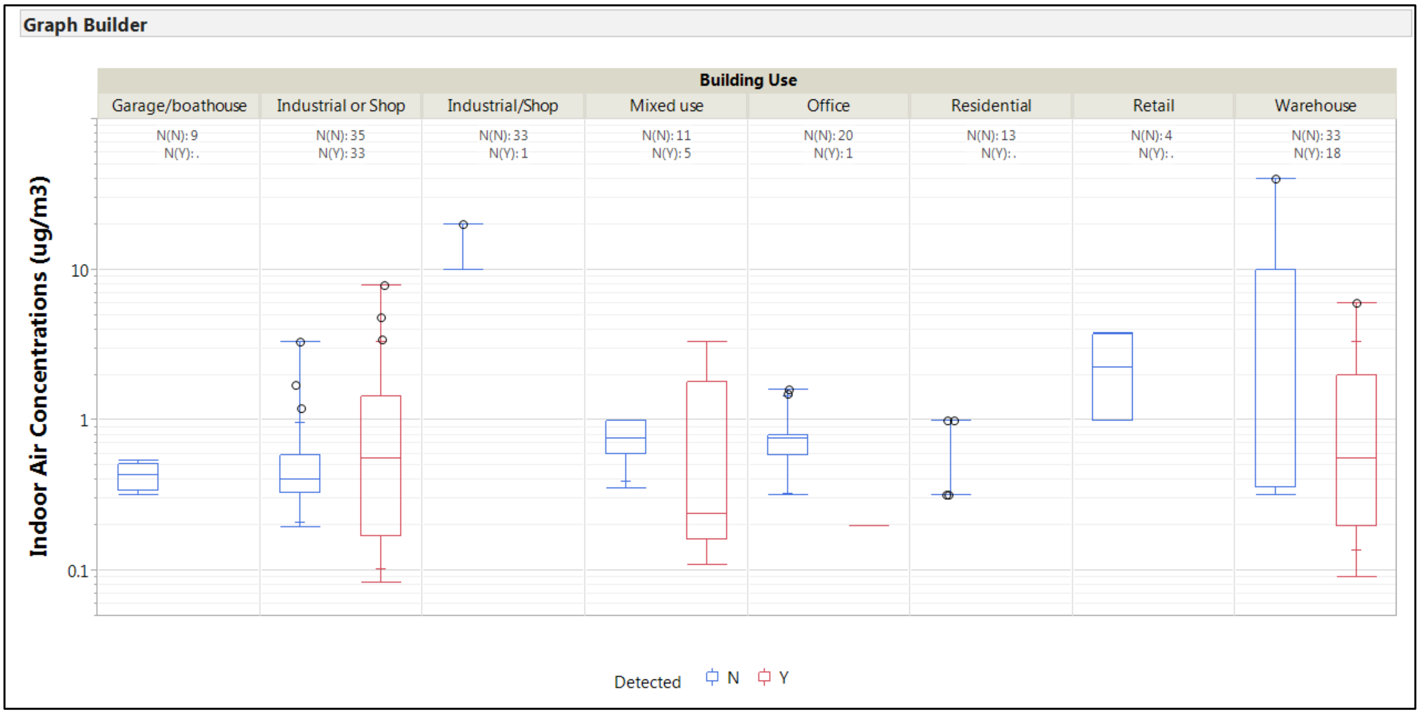


FIGURE E79
1,2-DCE Indoor Air Concentration by Building Use
NESDI Project #476

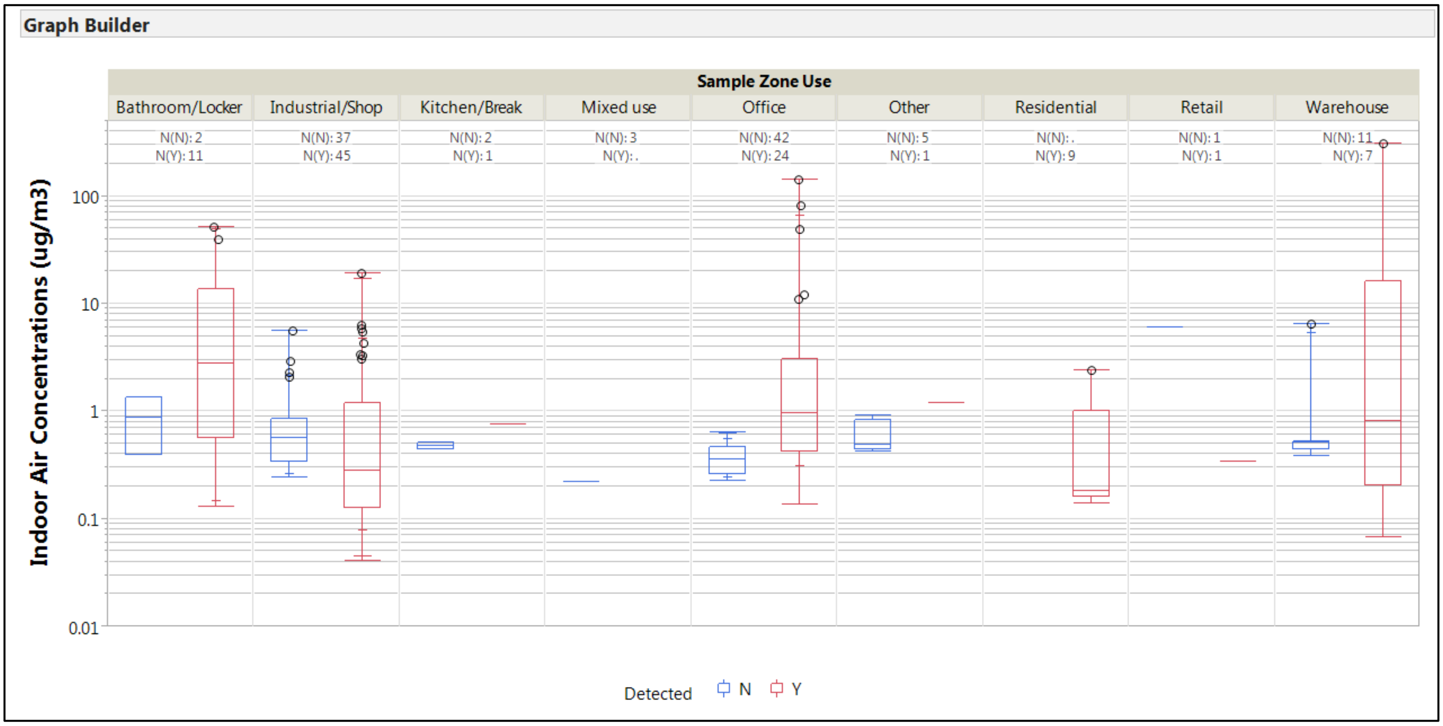


FIGURE E80

PCE Indoor Air Concentration by Sample Zone Use

NESDI Project #476

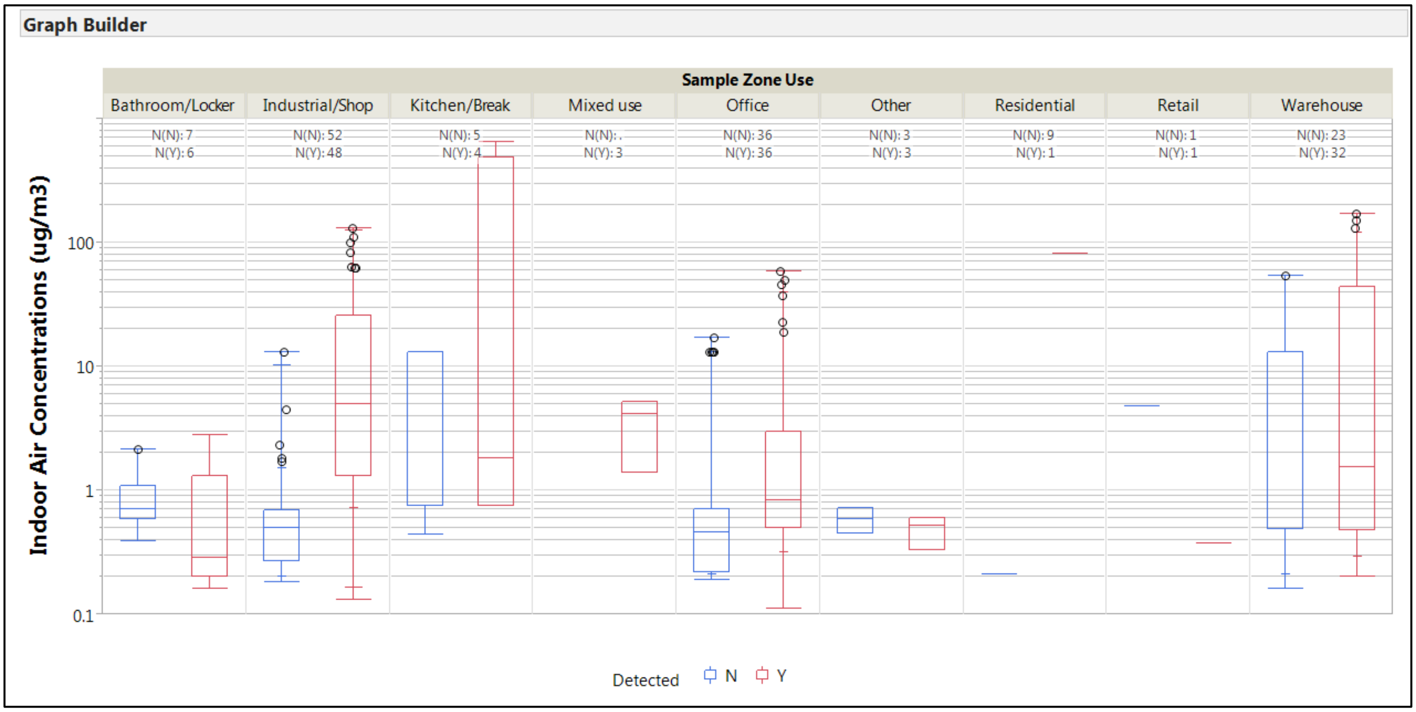


FIGURE E81

TCE Indoor Air Concentration by Sample Zone Use

NESDI Project #476

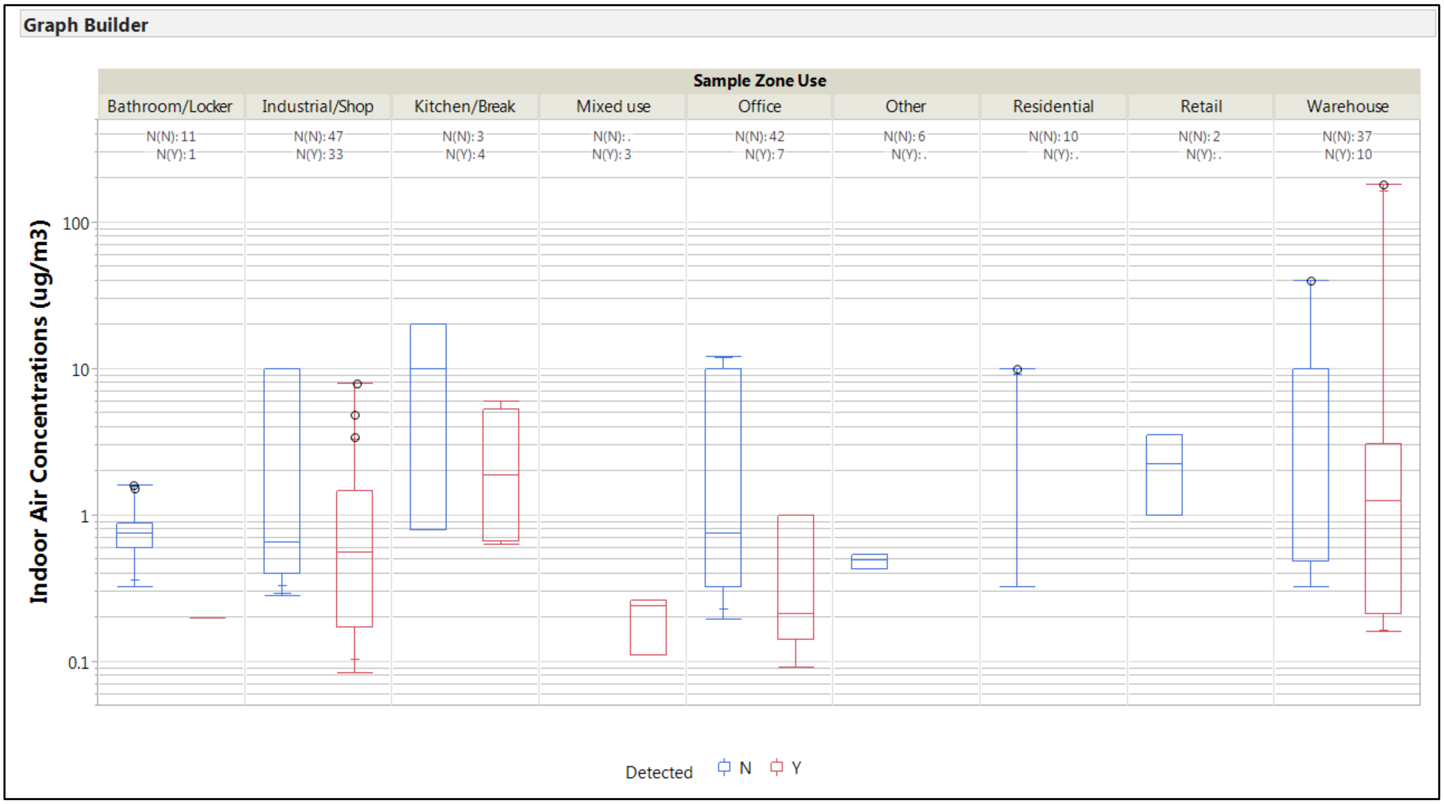


FIGURE E82

Cis-1,2-DCE Indoor Air Concentration by Sample Zone Use

NESDI Project #476

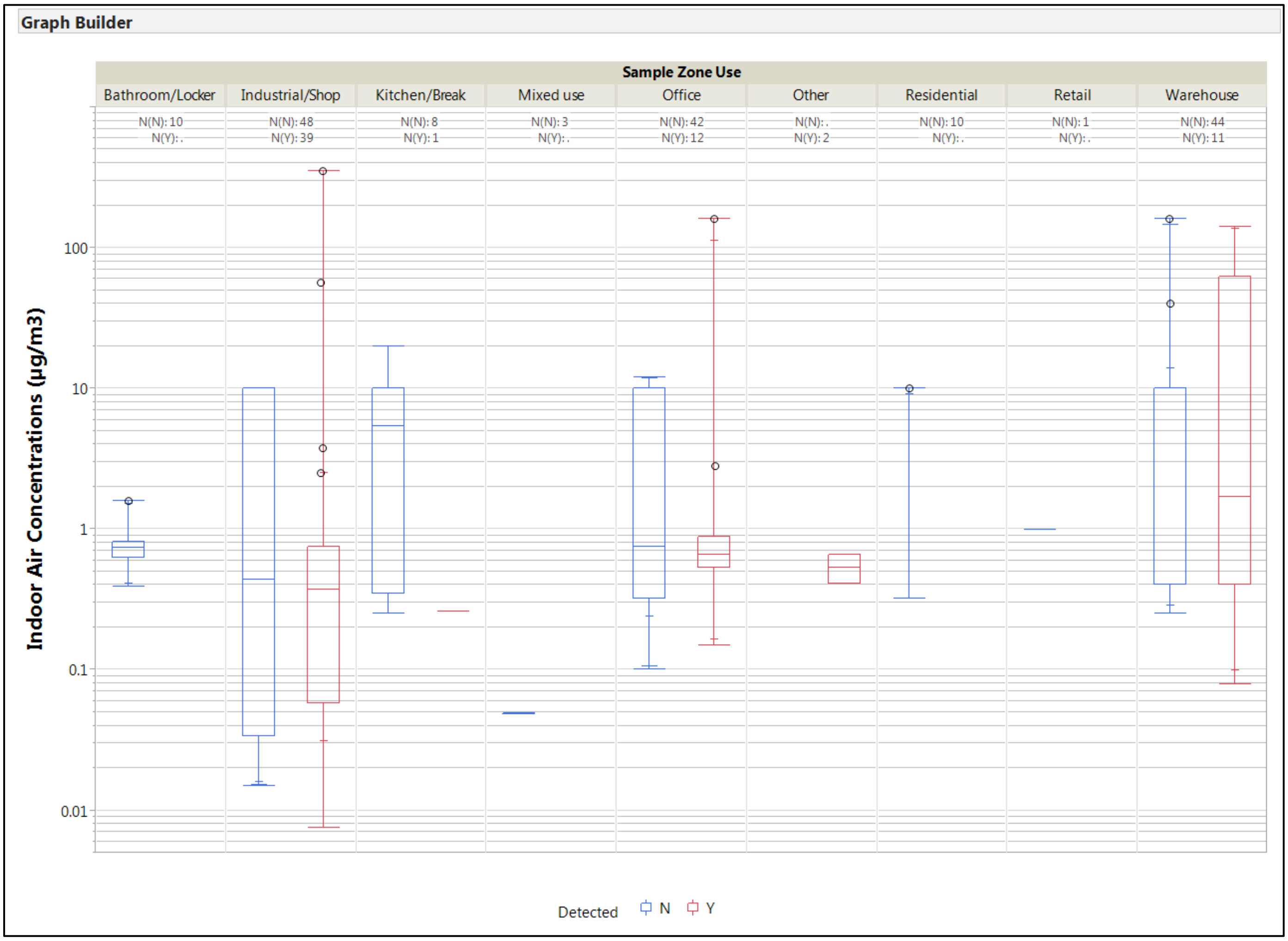


FIGURE E83

Trans-1,2-DCE Indoor Air Concentration by Sample Zone Use

NESDI Project #476

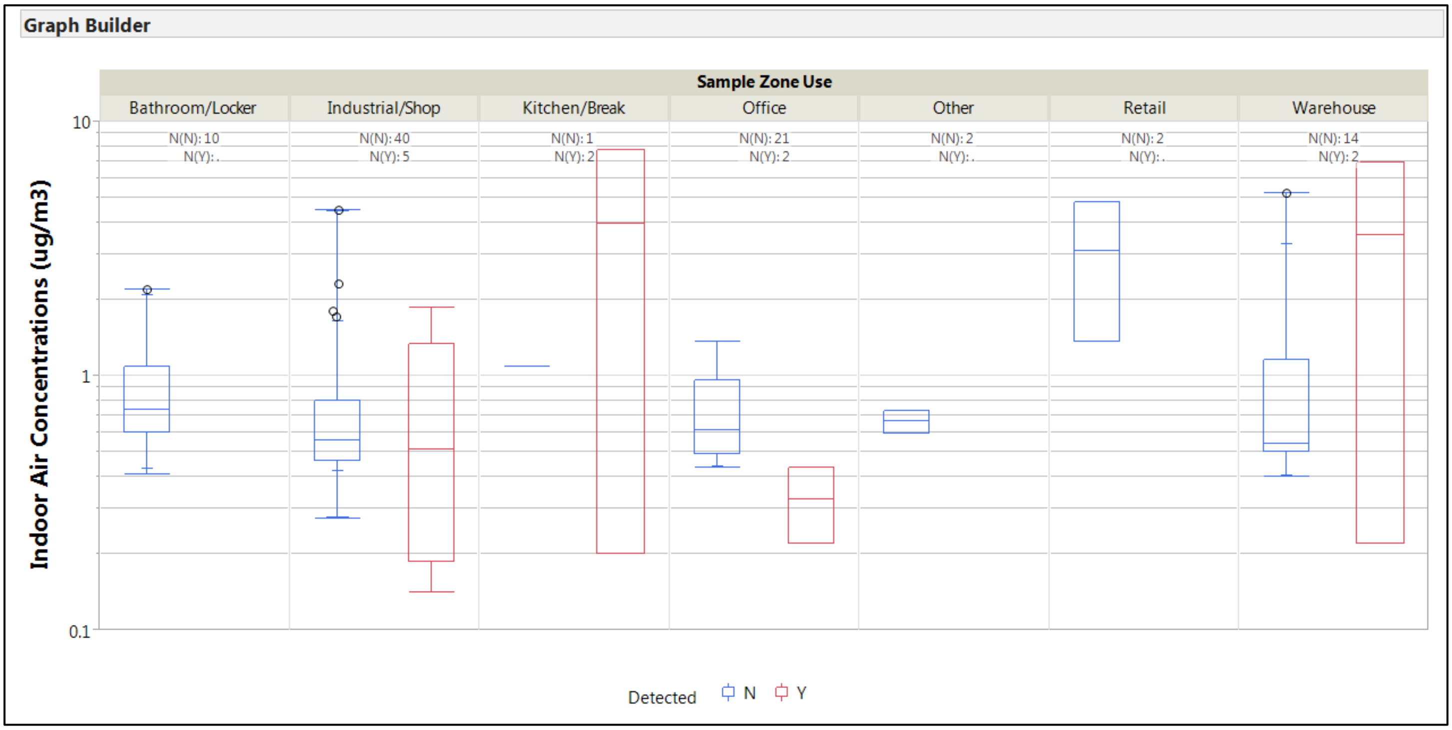


FIGURE E84

1,1,1-TCA Indoor Air Concentration by Sample Zone Use

NESDI Project #476

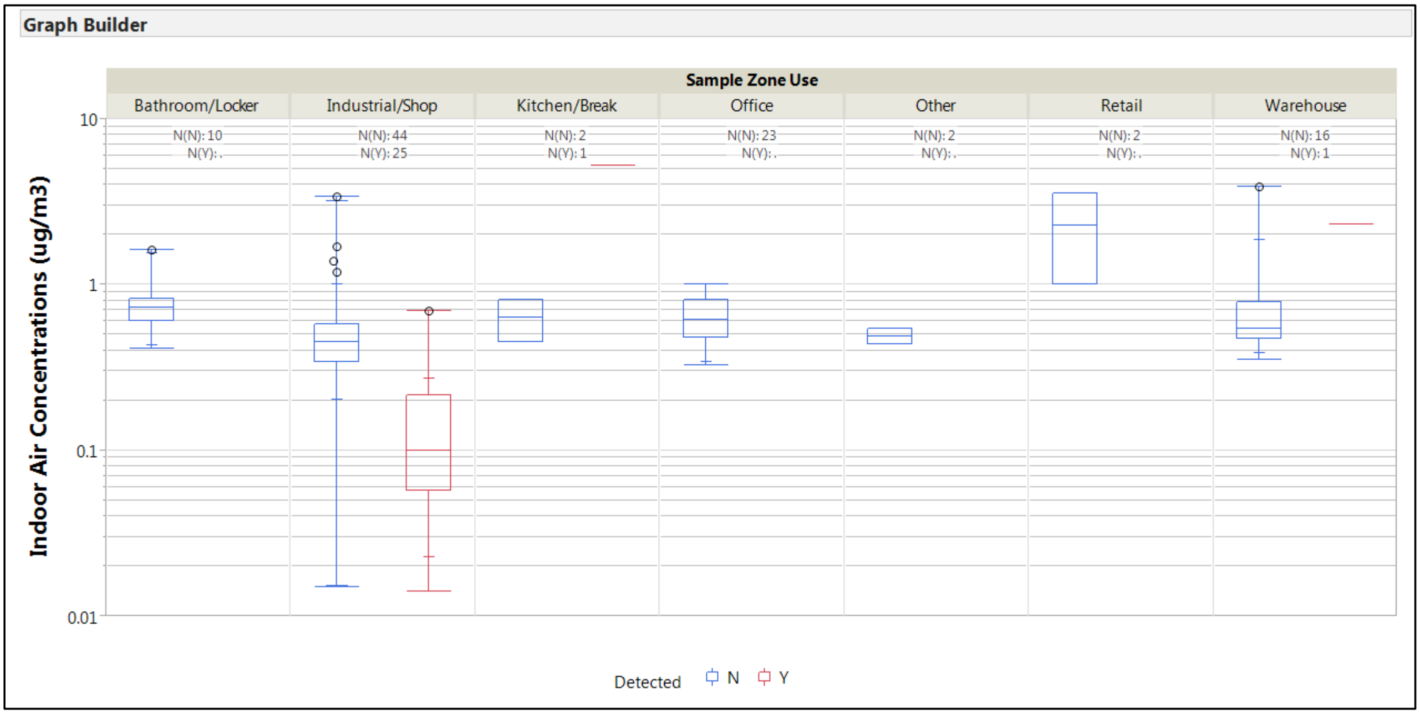


FIGURE E85
1,1-DCA Indoor Air Concentration by Sample Zone Use
NESDI Project #476

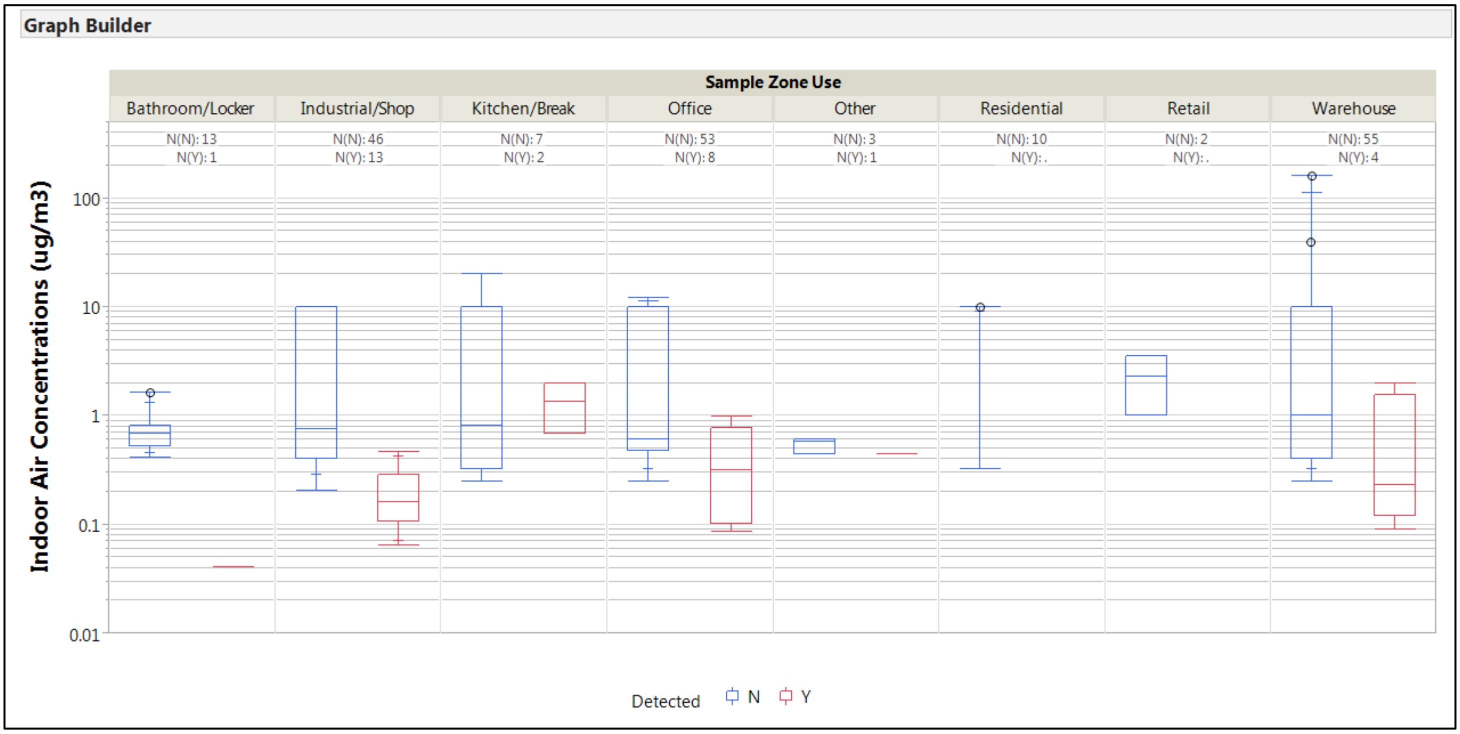


FIGURE E86
1,2-DCA Indoor Air Concentration by Sample Zone Use
NESDI Project #476

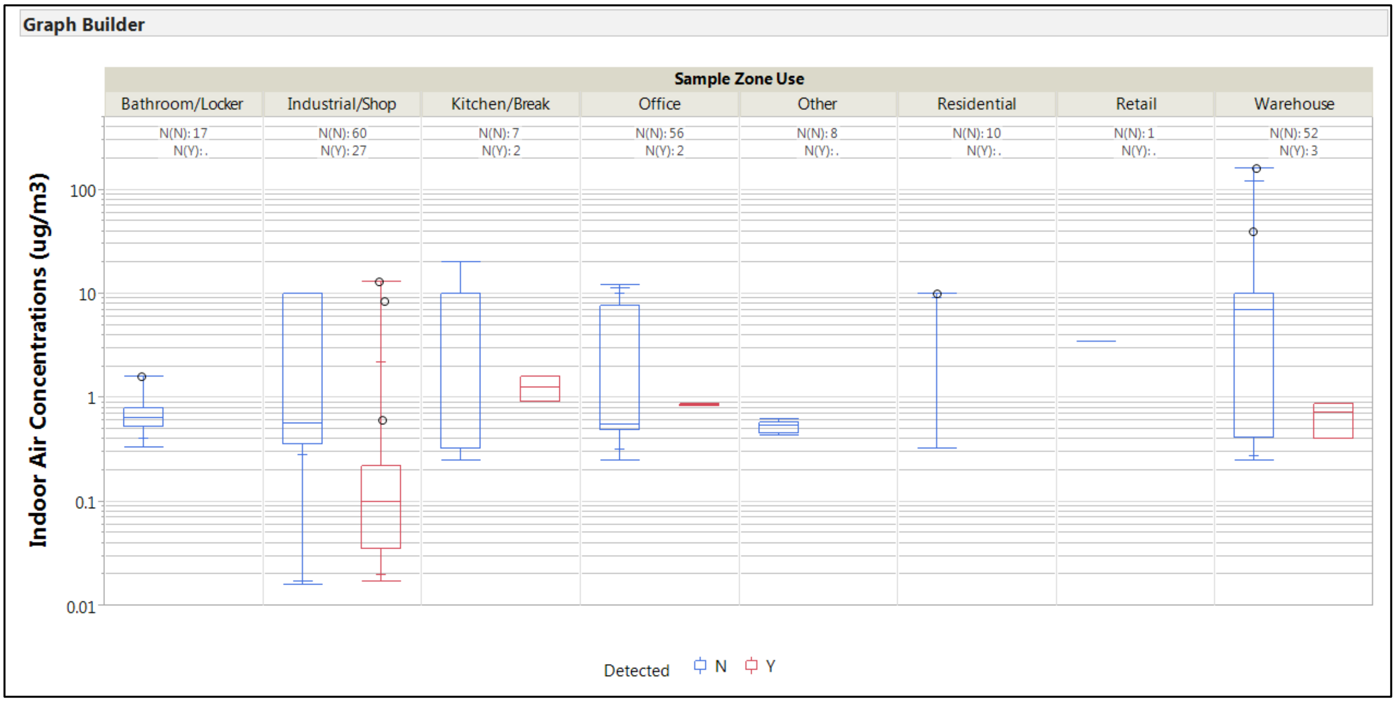


FIGURE E87

1,1,-DCE Indoor Air Concentration by Sample Zone Use

NESDI Project #476

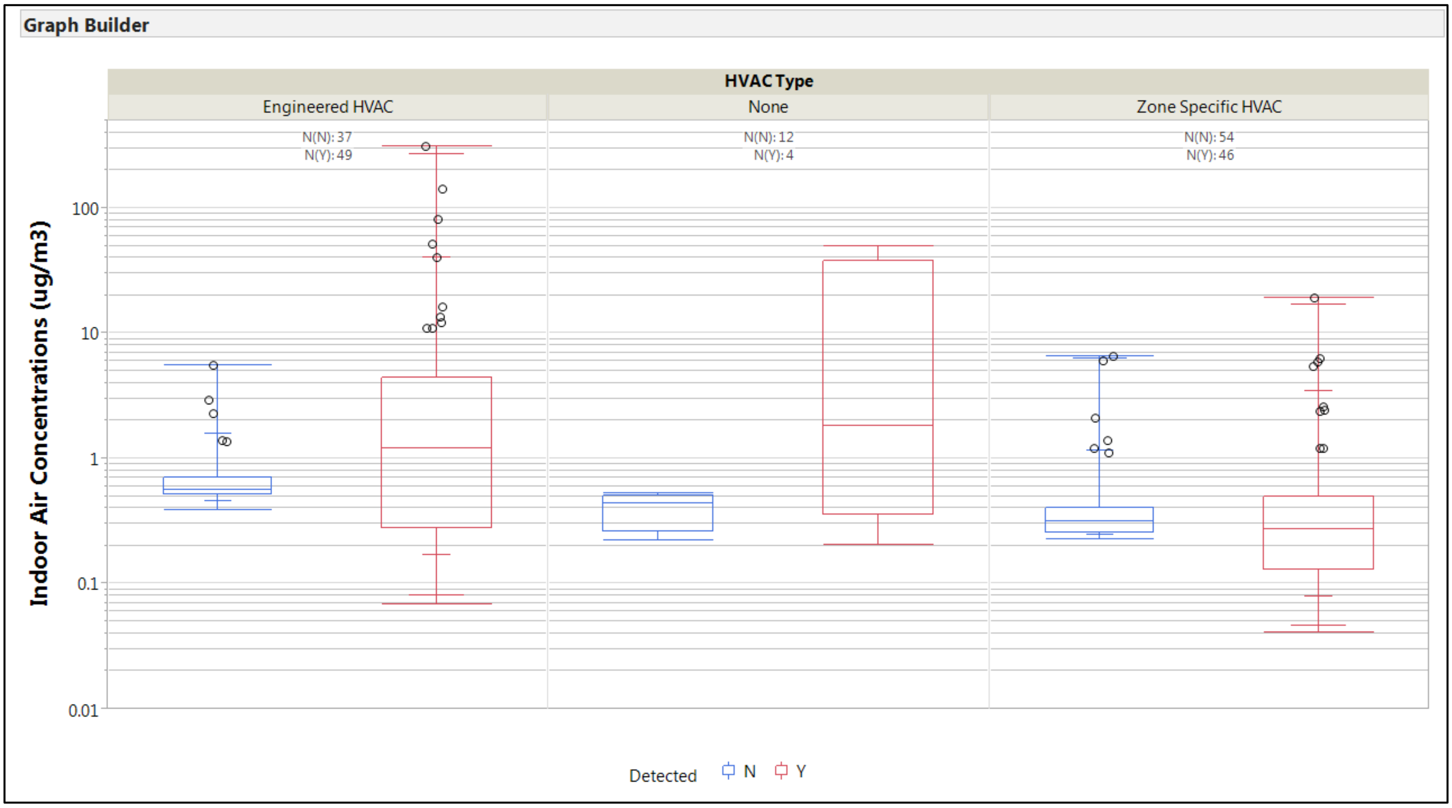


FIGURE E88
PCE Indoor Air Concentration by HVAC Type
NESDI Project #476

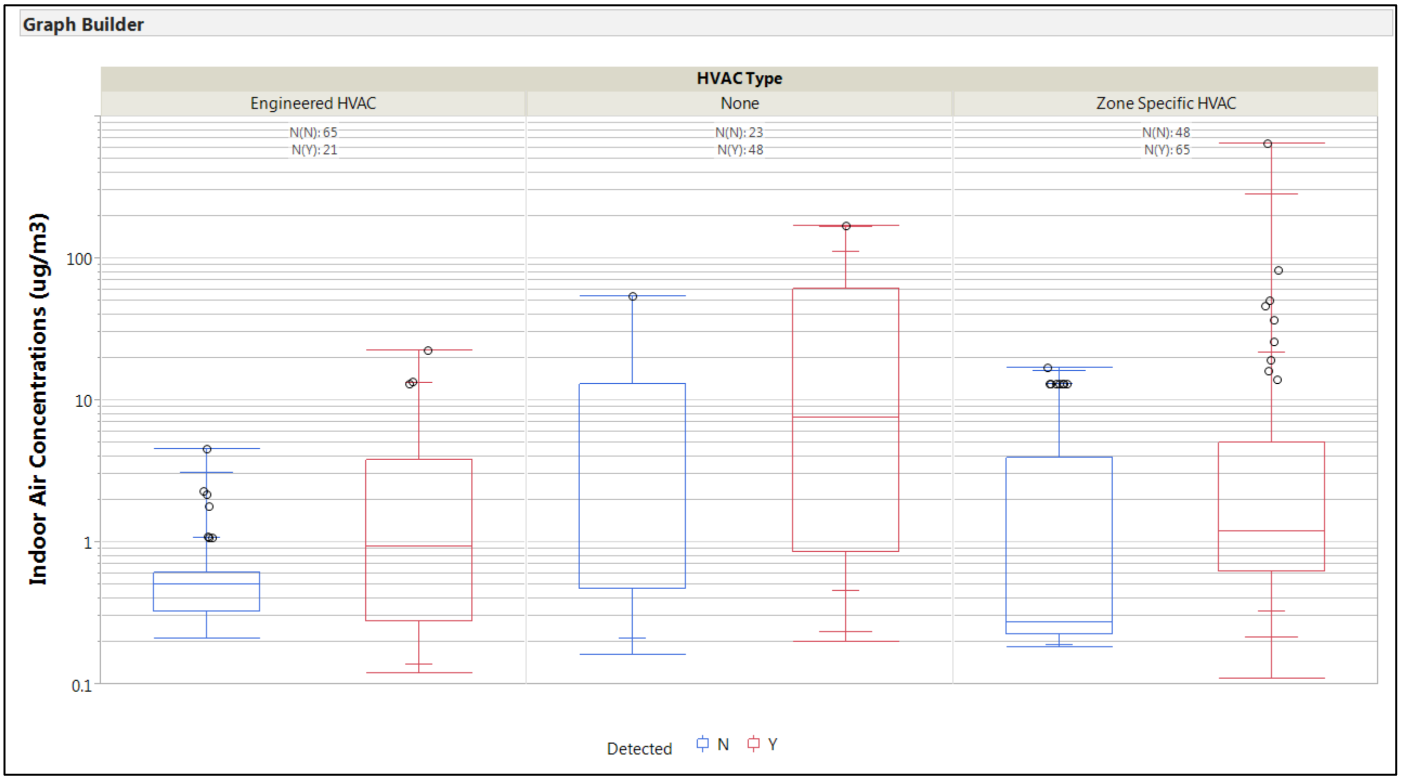


FIGURE E89
TCE Indoor Air Concentration by HVAC Type
NESDI Project #476

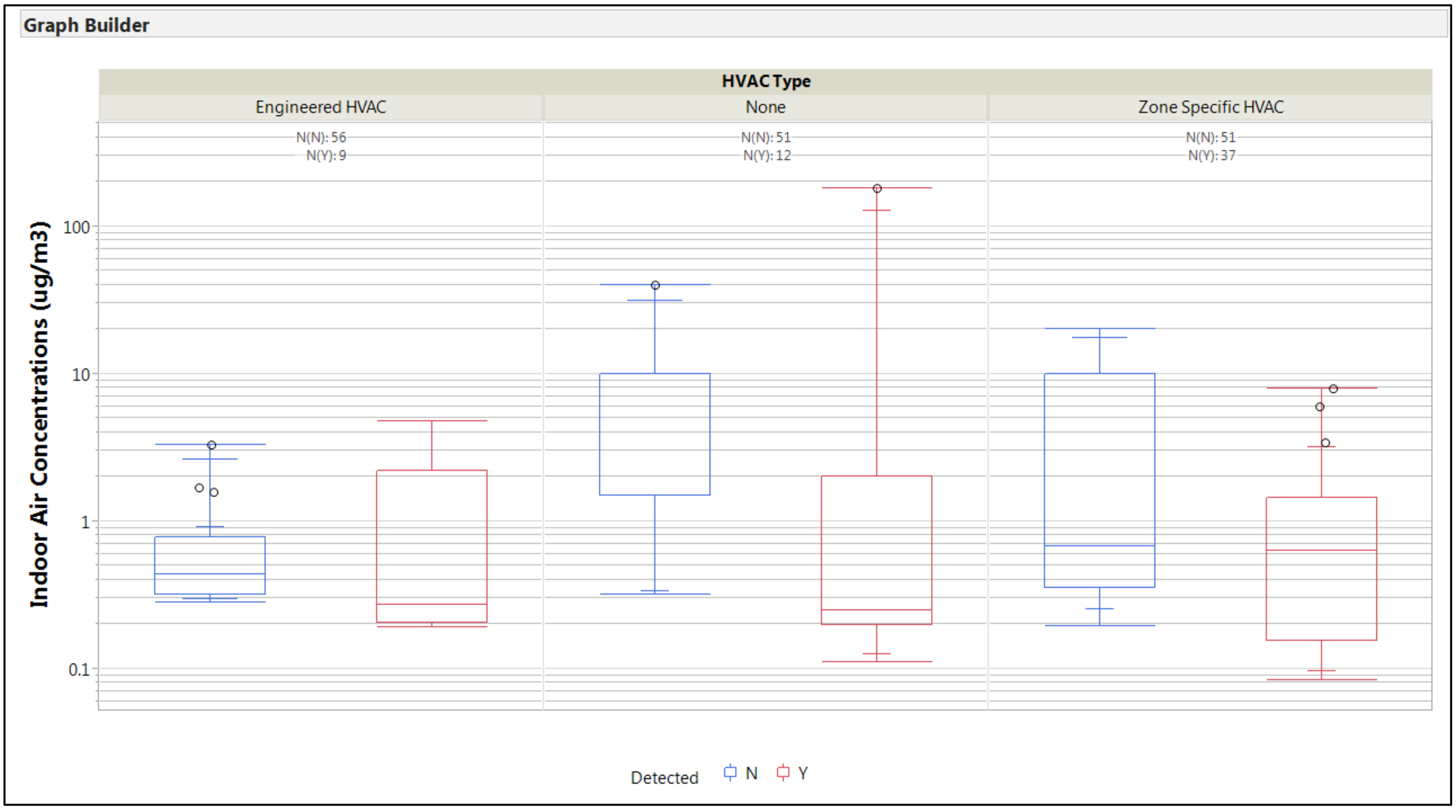


FIGURE E90

Cis-1,2-DCE Indoor Air Concentration by HVAC Type

NESDI Project #476

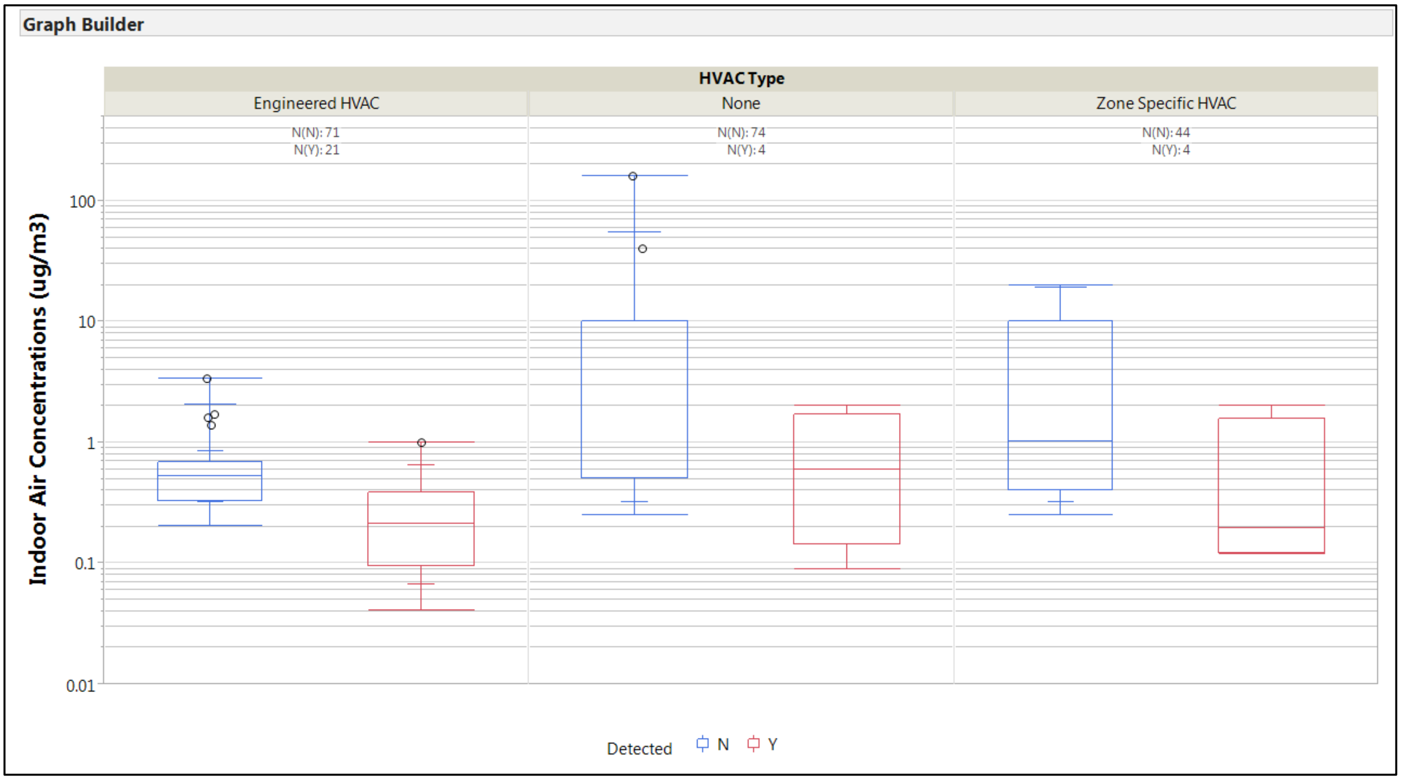


FIGURE E91
1,2-DCA Indoor Air Concentration by HVAC Type
NESDI Project #476

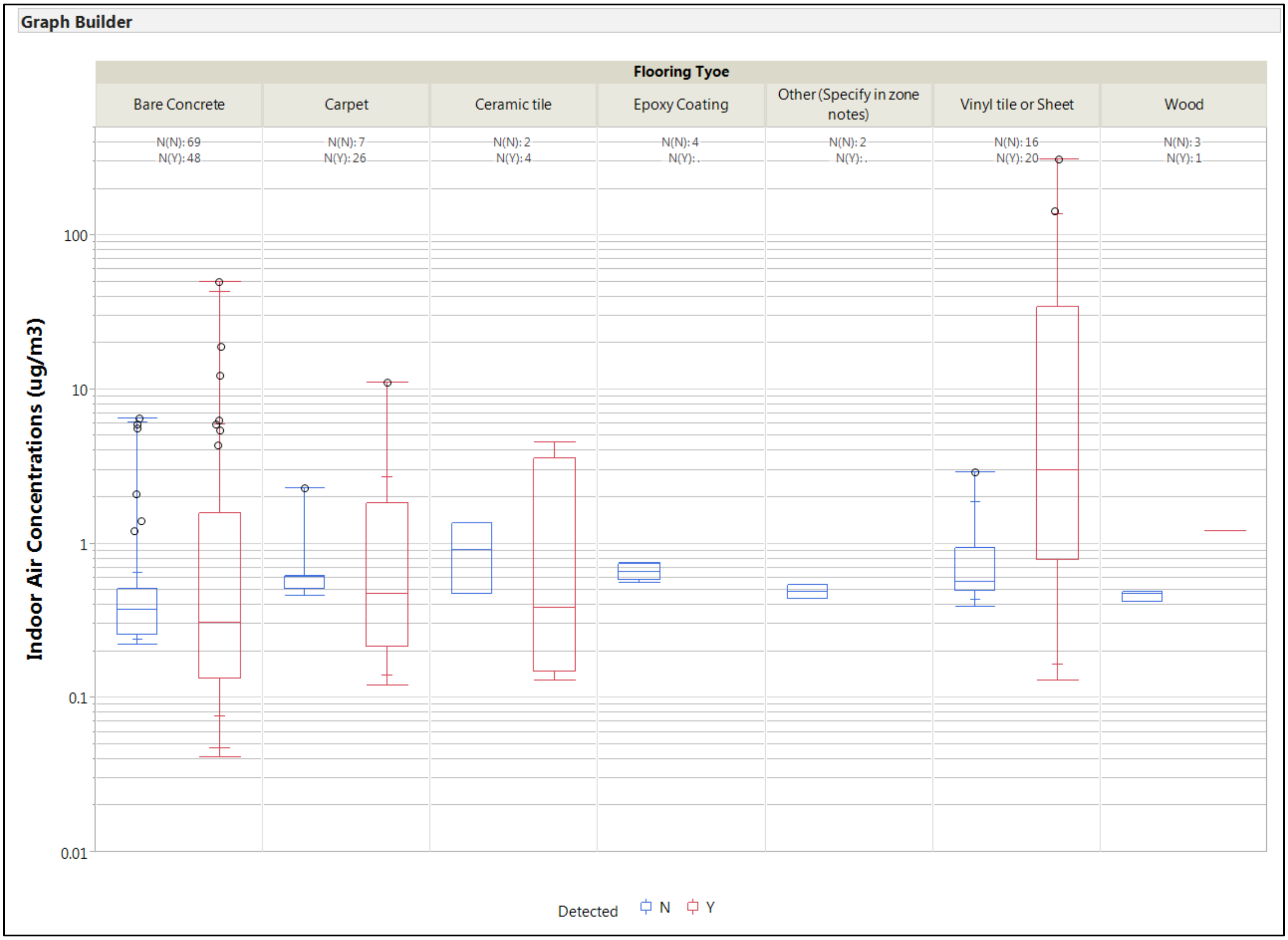


FIGURE E92
PCE Indoor Air Concentration by Flooring Type
NESDI Project #476

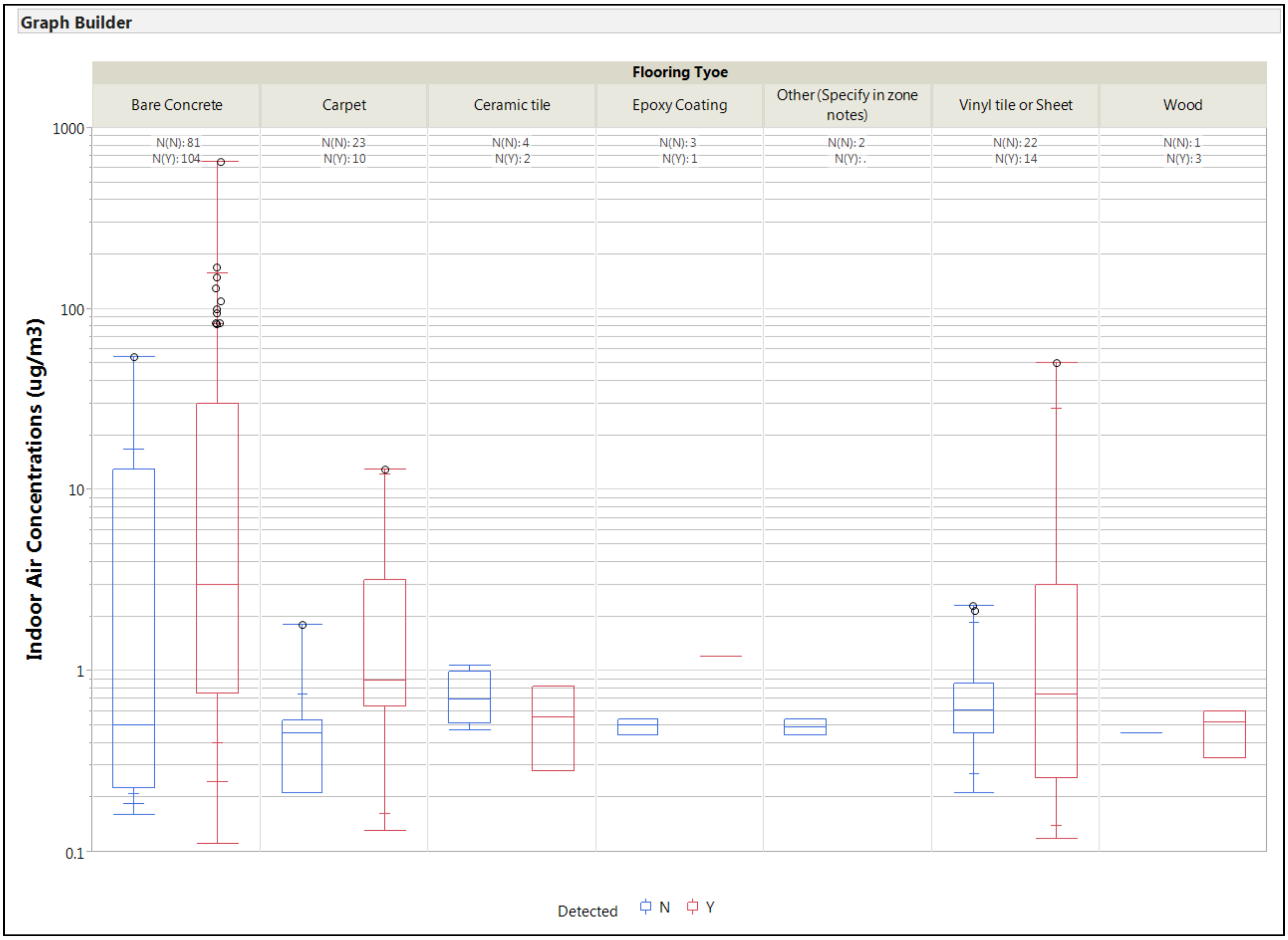


FIGURE E93
TCE Indoor Air Concentration by Flooring Type
NESDI Project #476

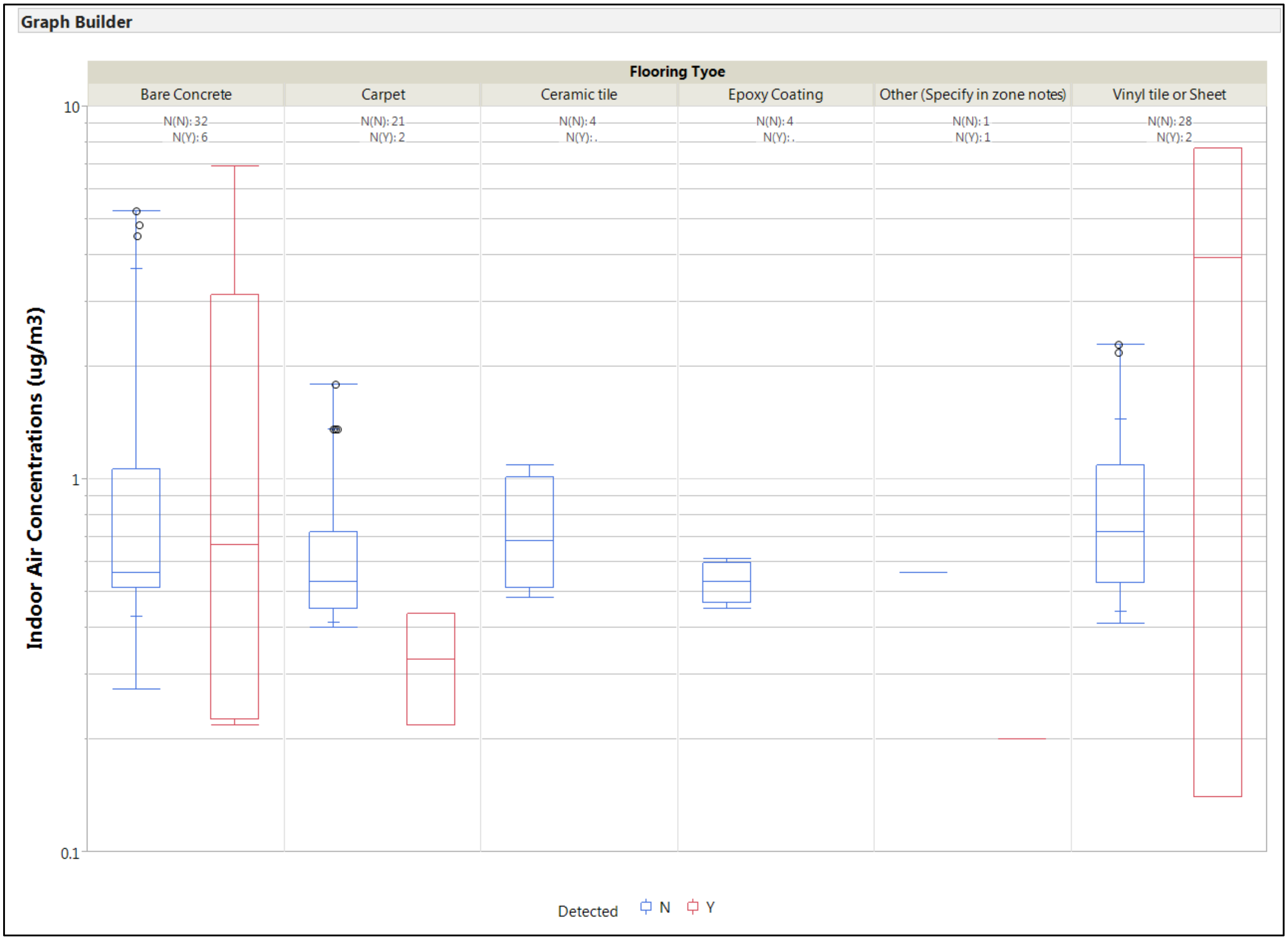


FIGURE E94

1,1,1-TCA Indoor Air Concentration by Flooring Type

NESDI Project #476

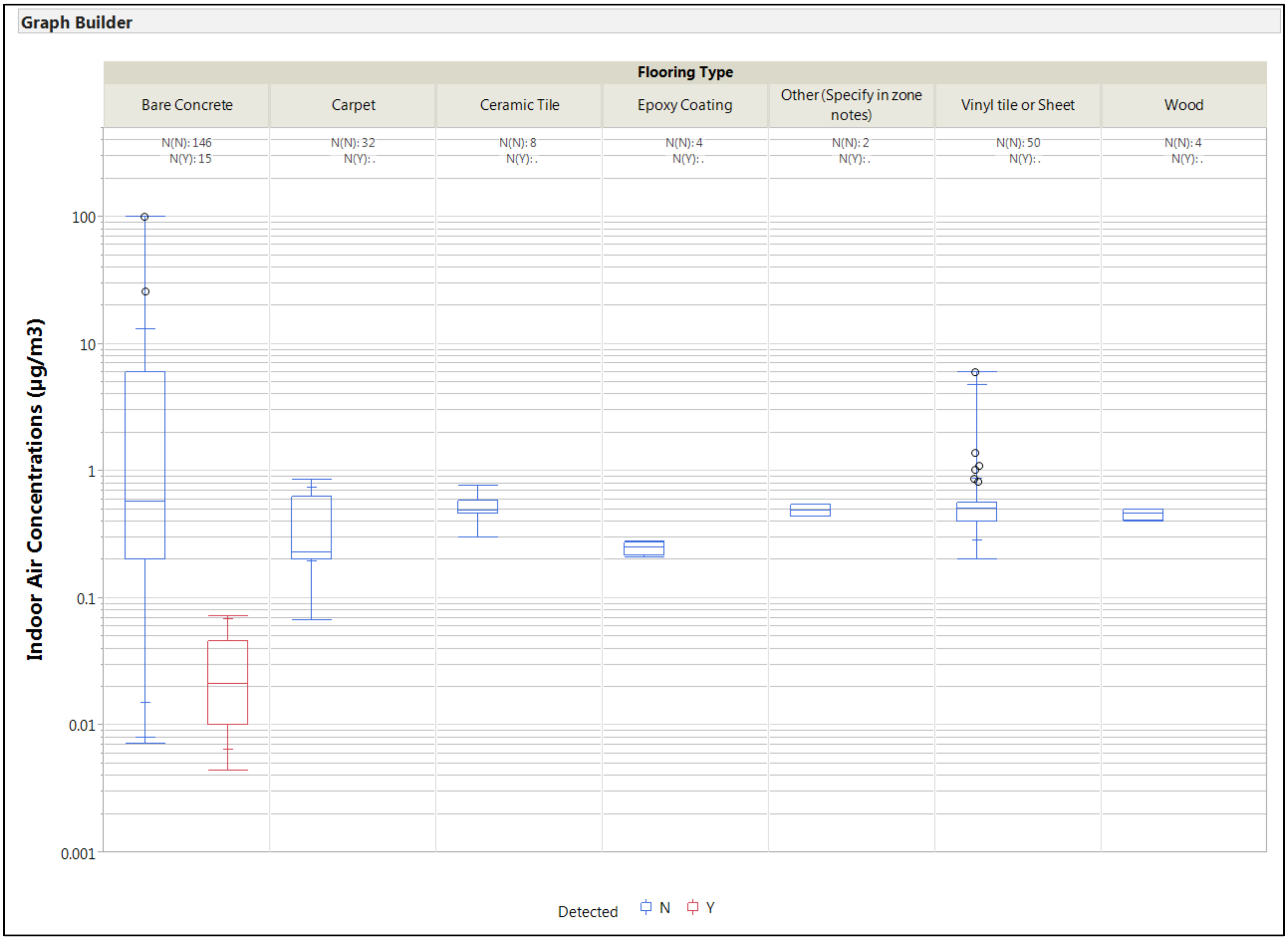


FIGURE E95
Vinyl Chloride Indoor Air Concentration by Flooring Type
NESDI Project #476

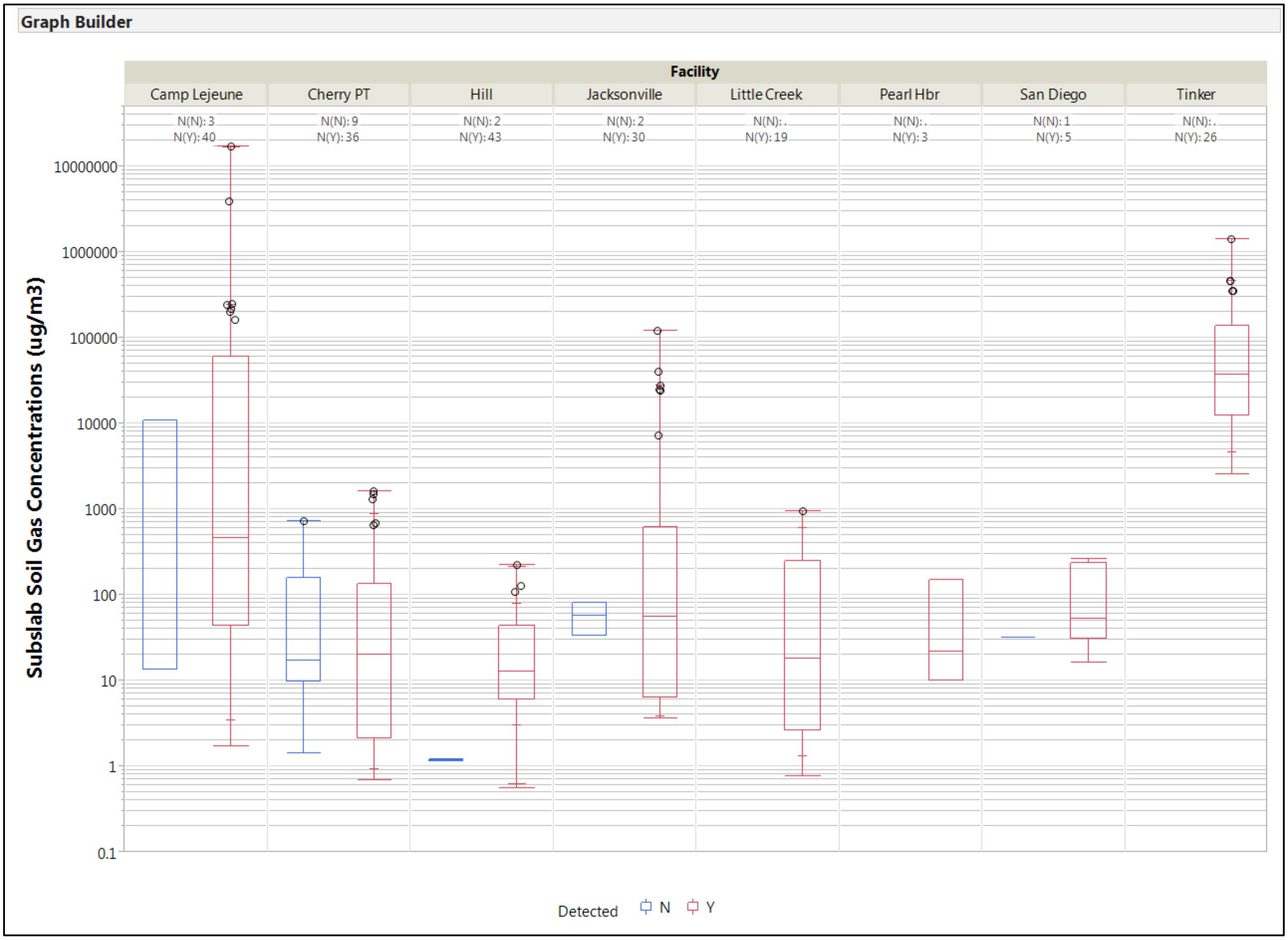


FIGURE E96
PCE Sub-slab Soil Gas Concentration by Facility
NESDI Project #476

Figure E-97 is available to RPMs upon request.

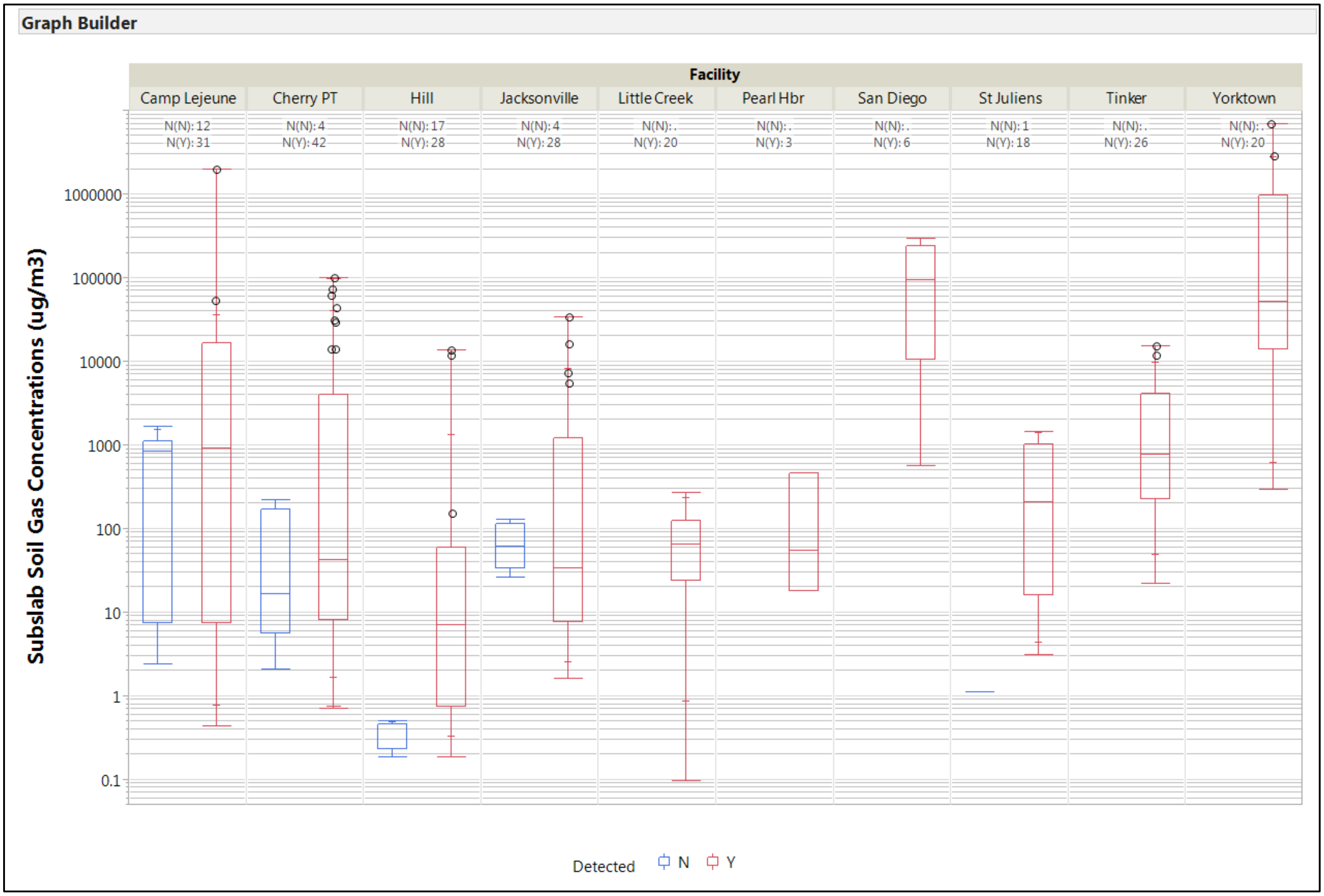


FIGURE E98
TCE Sub-slab Soil Gas Concentration by Facility
NESDI Project #476

Figure E-99 is available to RPMs upon request.

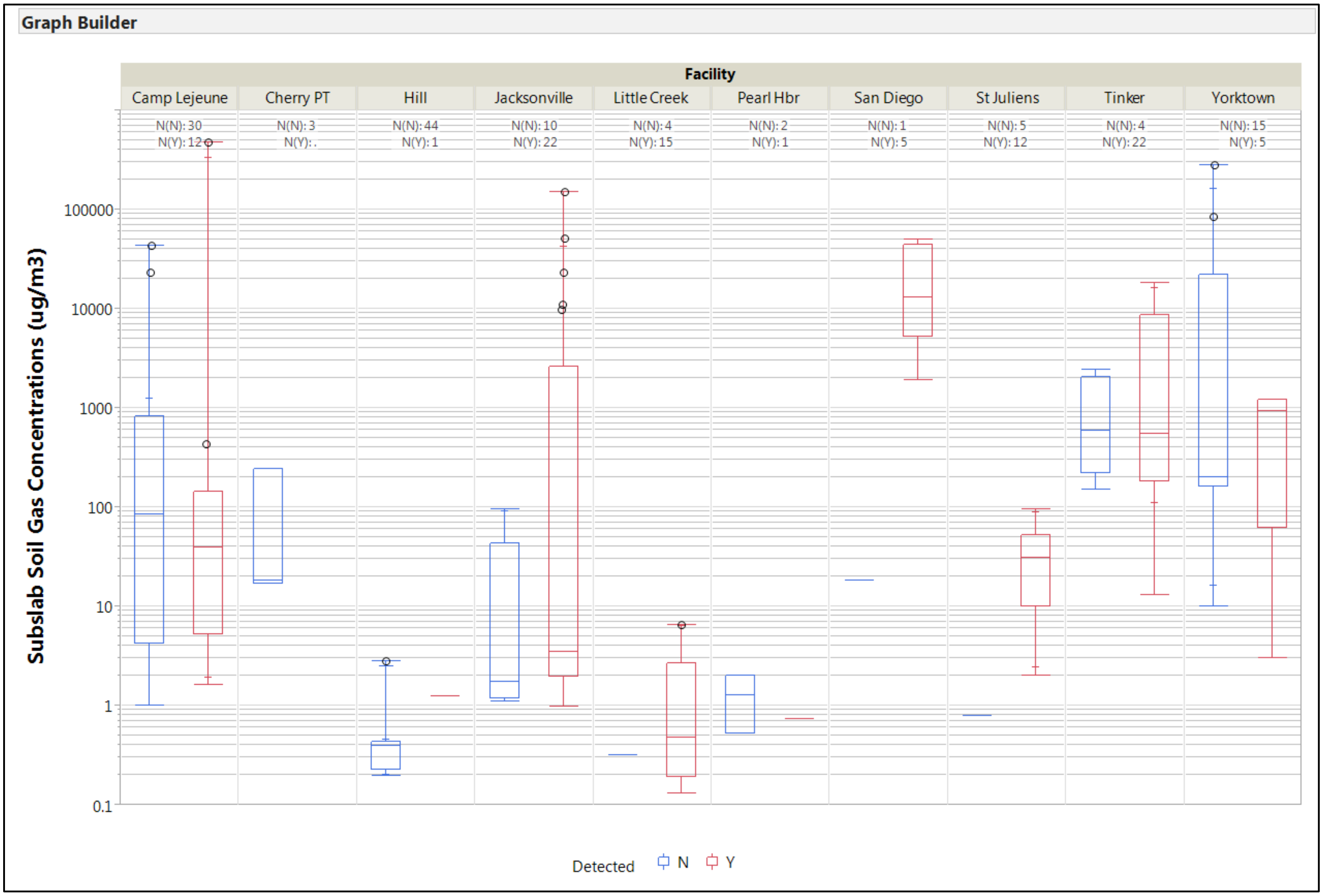


FIGURE E100
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Facility
NESDI Project #476

Figure E-101 is available to RPMs upon request.

Figure E-102 is available to RPMs upon request.

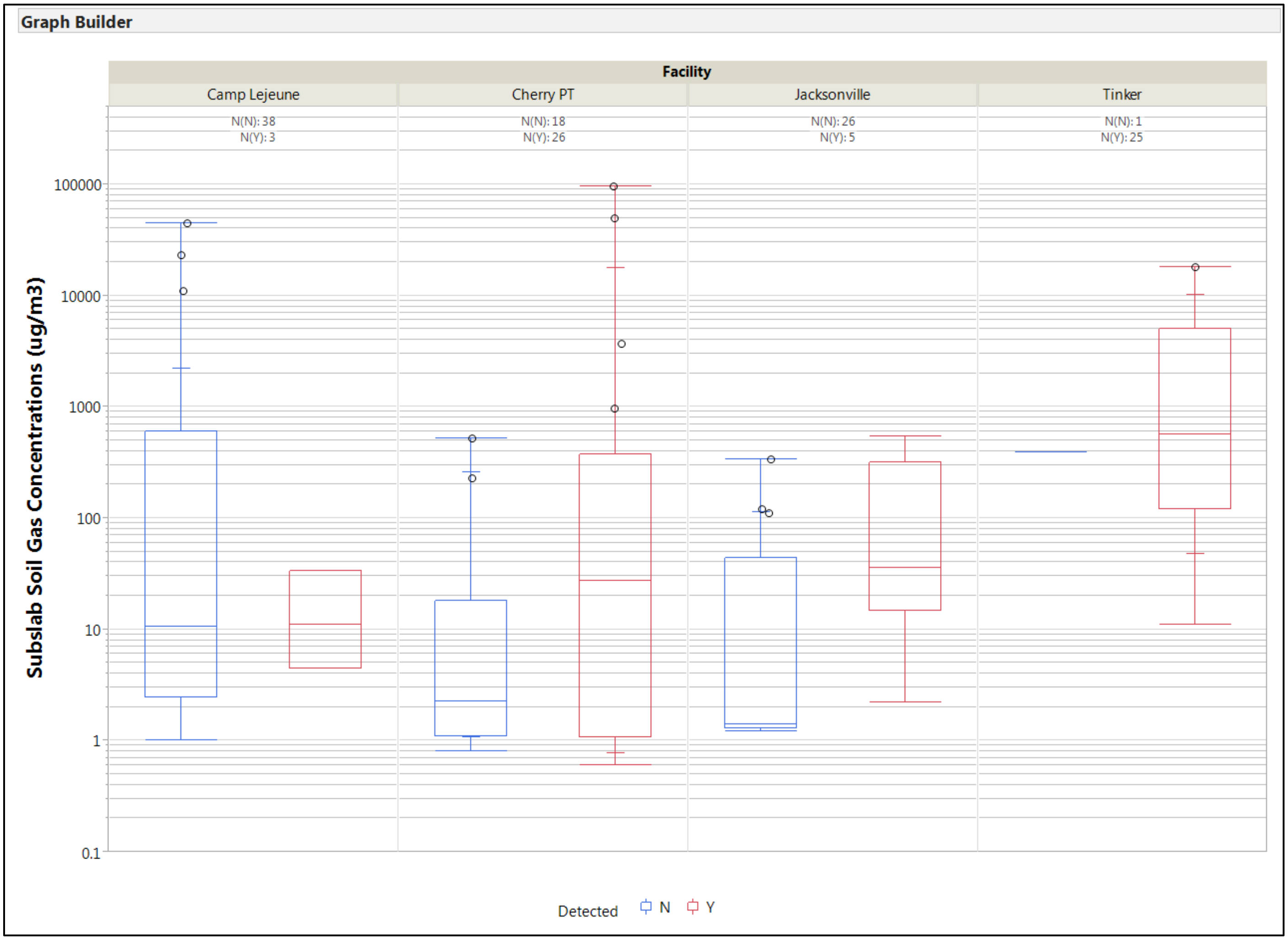


FIGURE E103

1,1-DCA Sub-slab Soil Gas Concentration by Facility

NESDI Project #476

Figure E-104 is available to RPMs upon request.

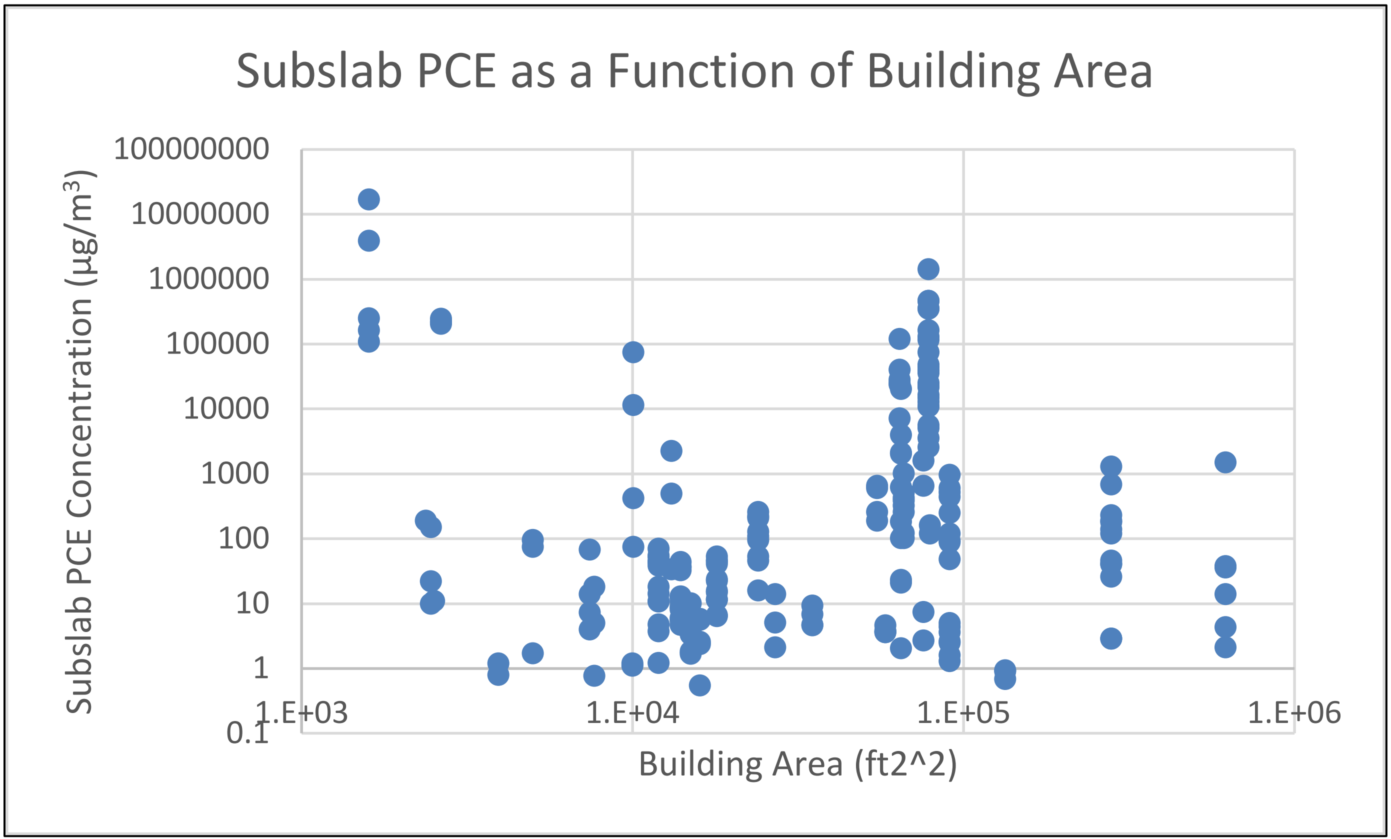


FIGURE E105
PCE Sub-slab Soil Gas Concentration vs Building Area
NESDI Project #476

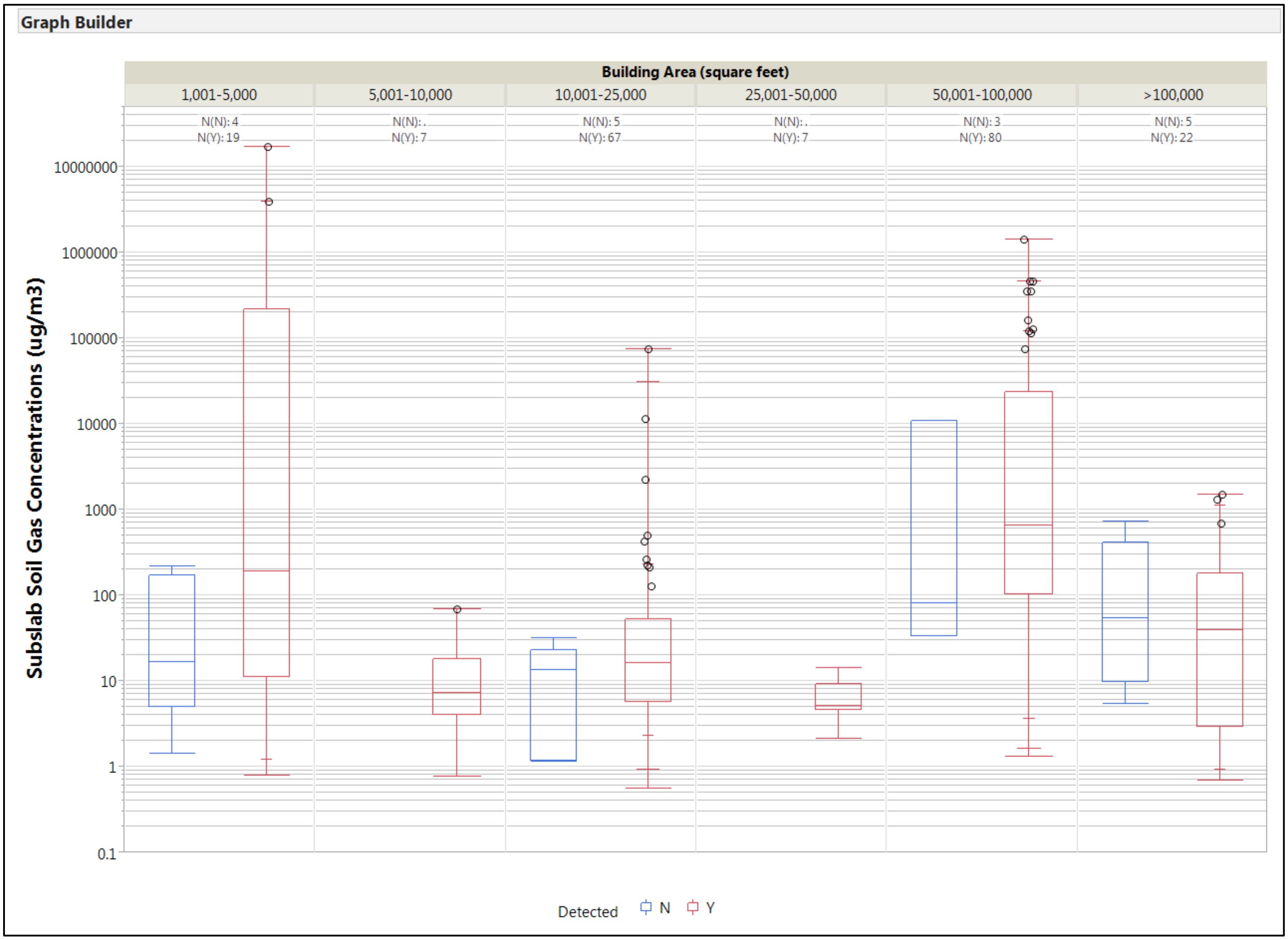


FIGURE E106

PCE Sub-slab Soil Gas Concentration by Building Area

NESDI Project #476

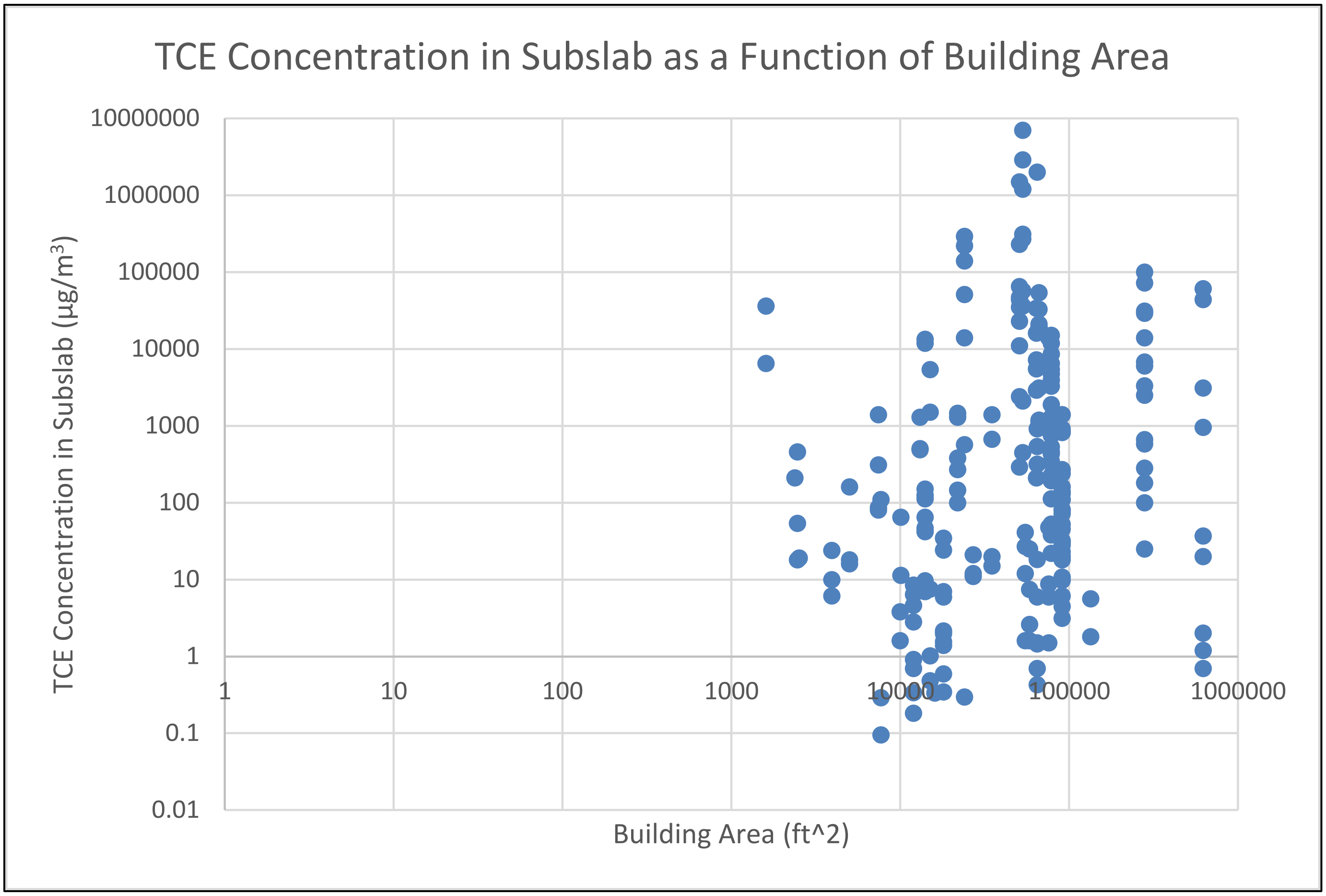


FIGURE E107

TCE Sub-slab Soil Gas Concentration vs Building Area

NESDI Project #476

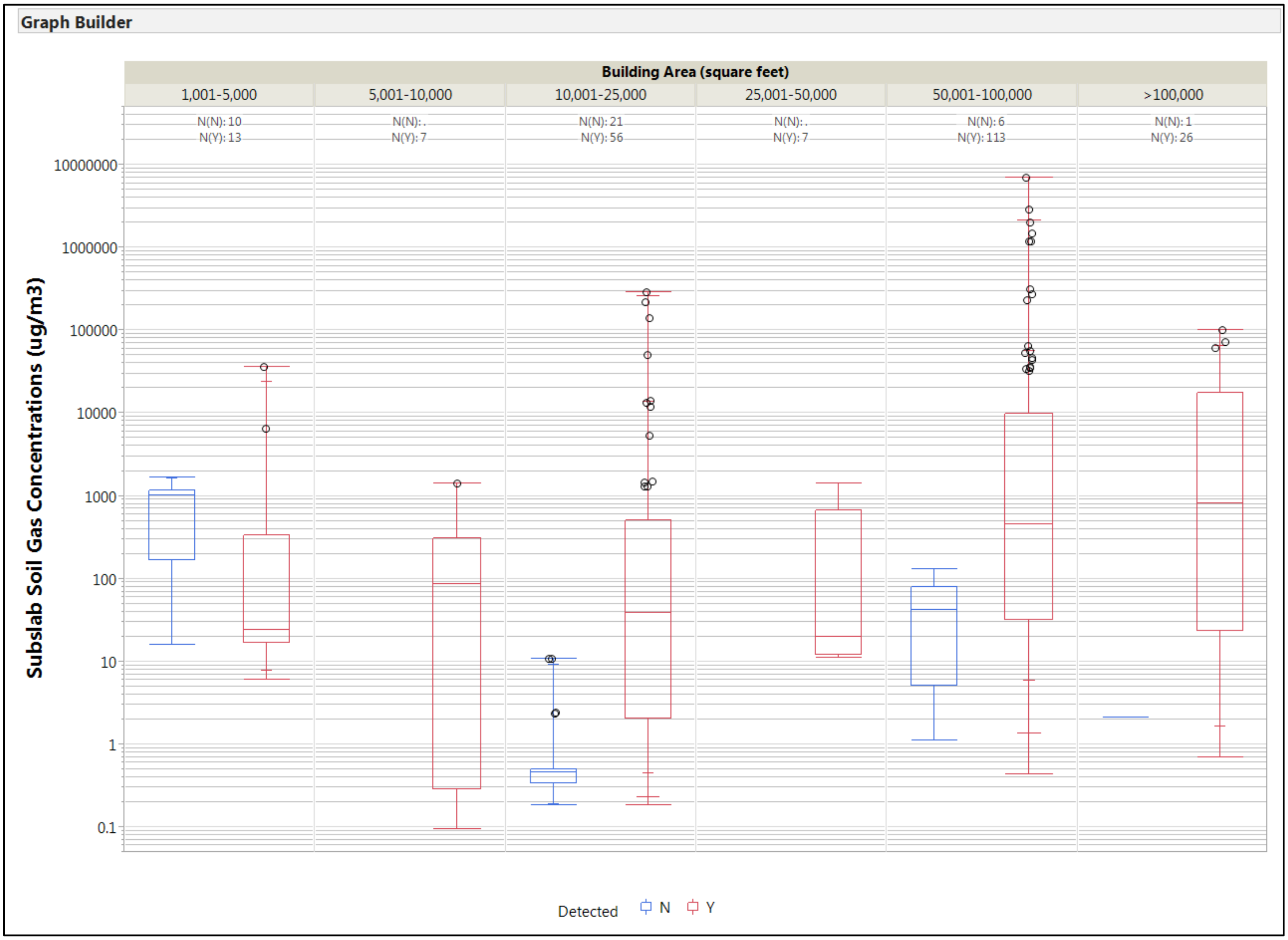


FIGURE E108

TCE Sub-slab Soil Gas Concentration by Building Area

NESDI Project #476

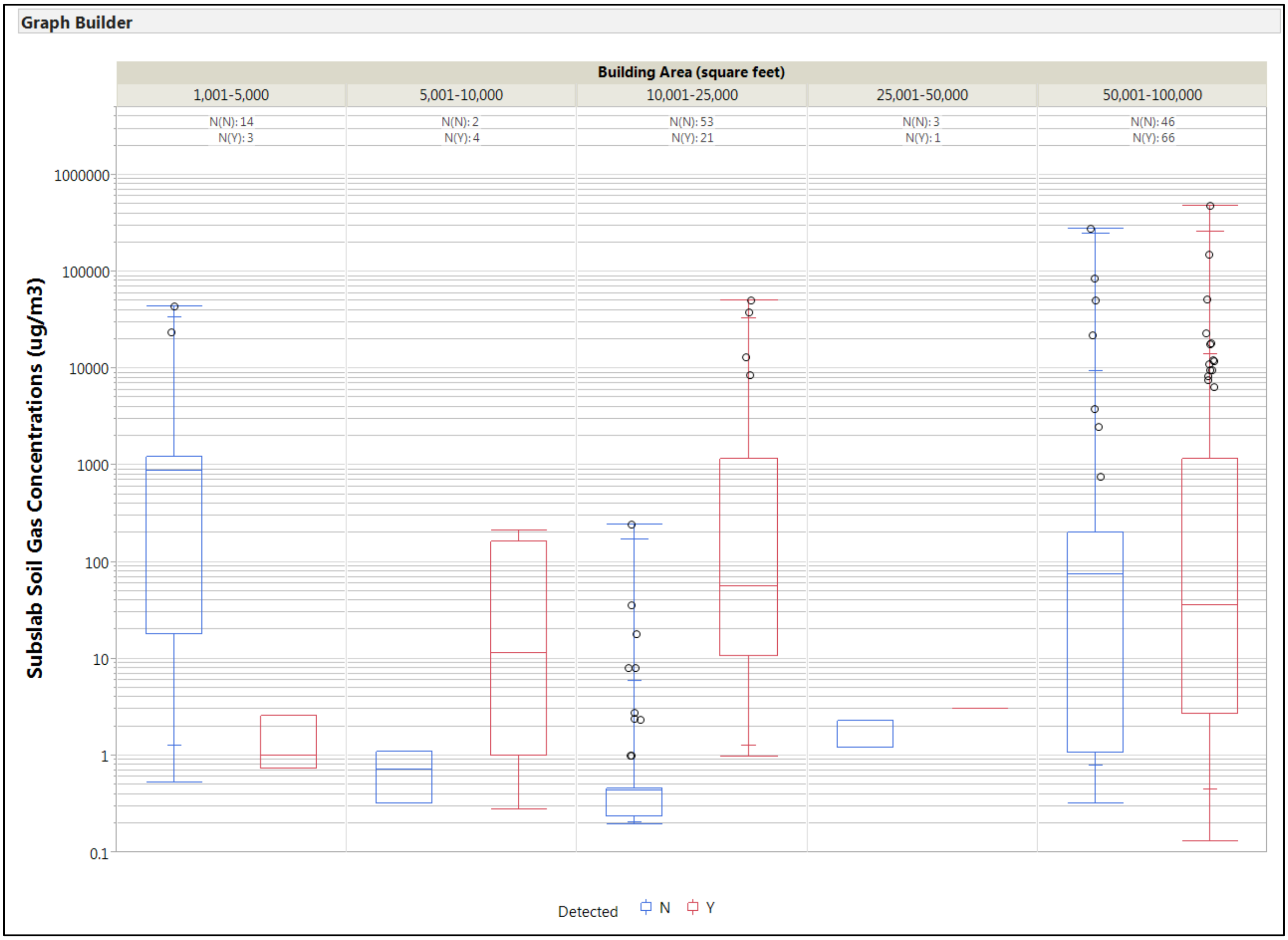


FIGURE E109
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Building Area
NESDI Project #476

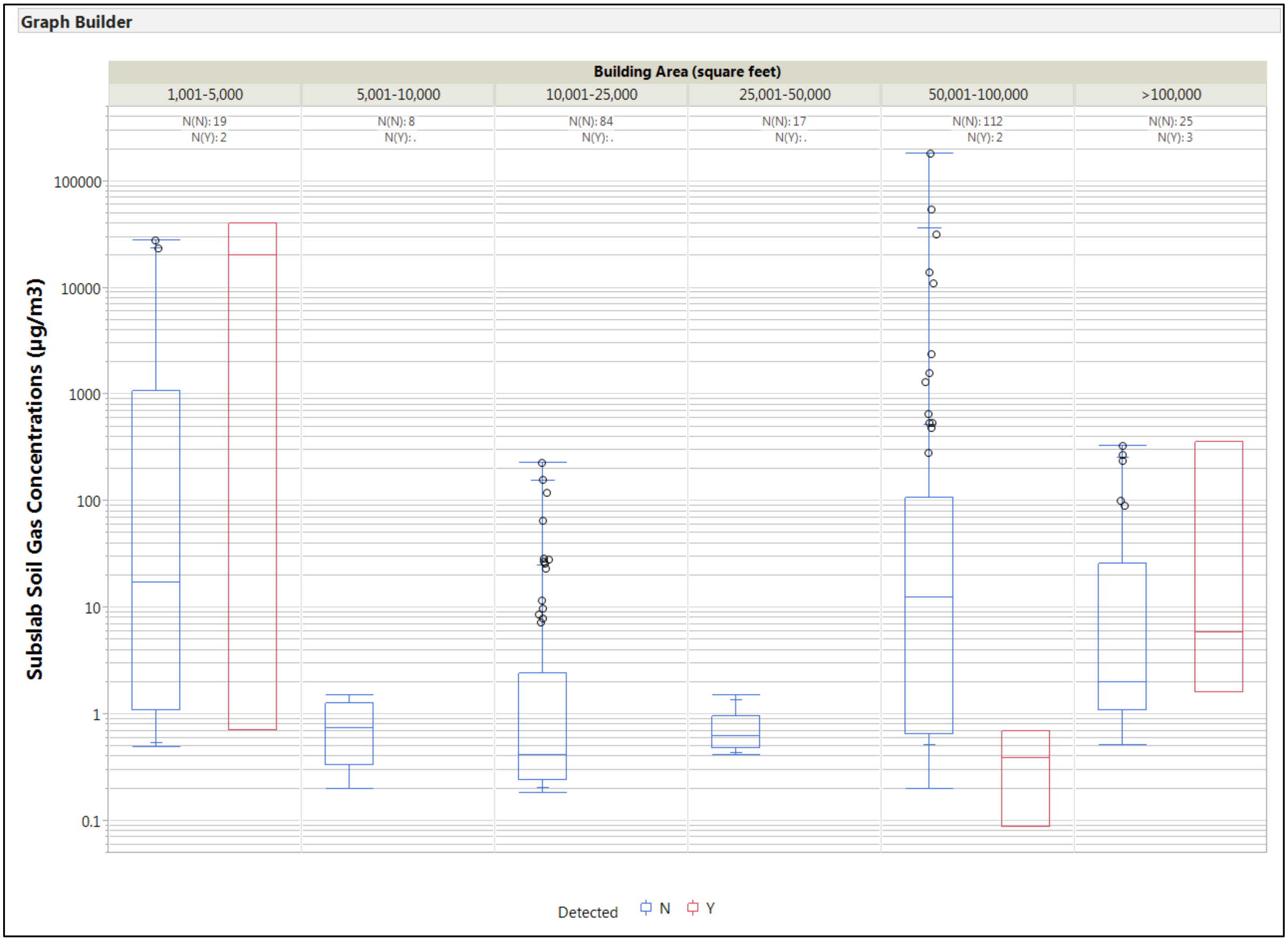


FIGURE E110

Vinyl Chloride Sub-slab Soil Gas Concentration by Building Area

NESDI Project #476

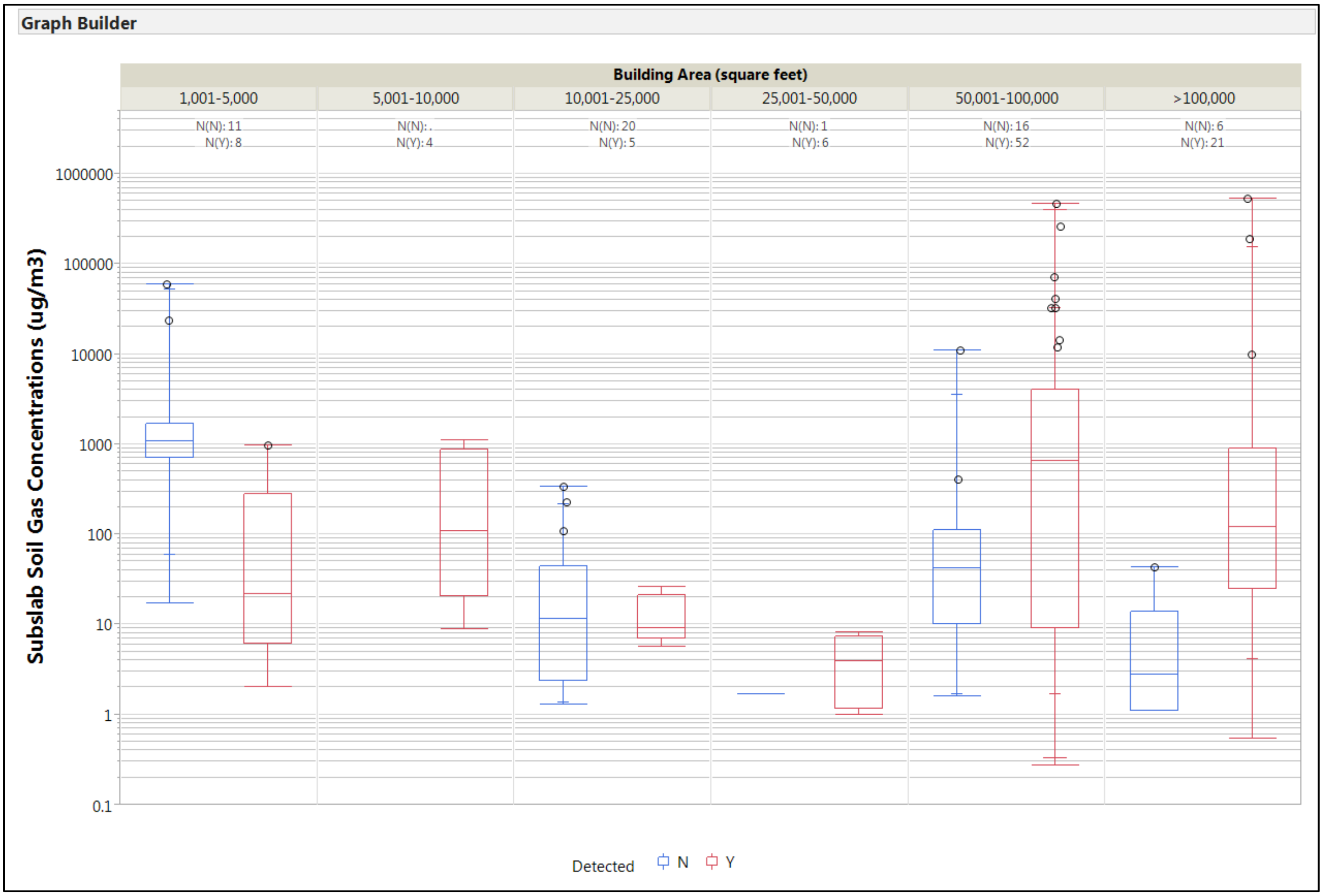


FIGURE E111

1,1,1-TCA Sub-slab Soil Gas Concentration by Building Area

NESDI Project #476

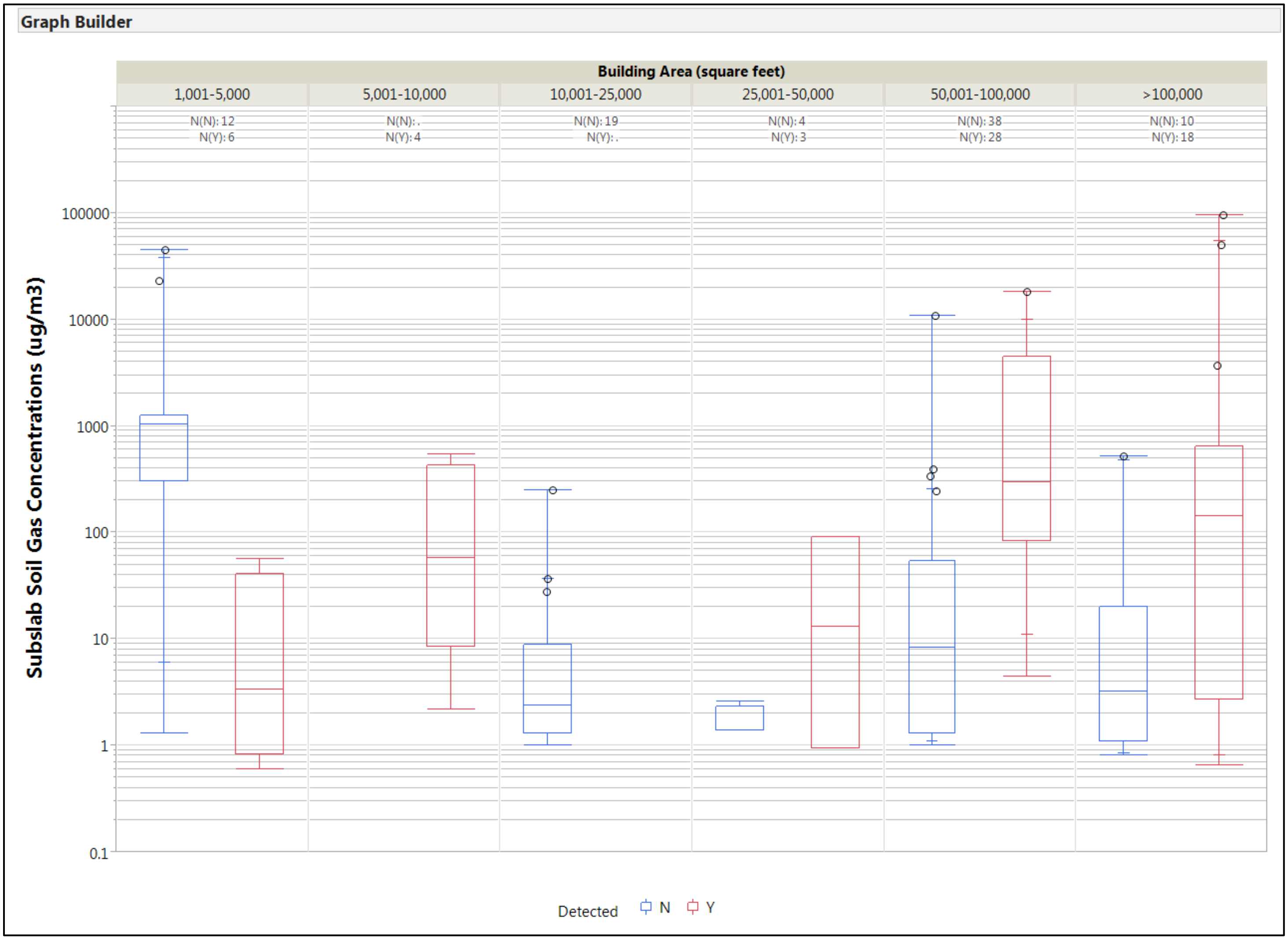


FIGURE E112
1,1-DCA Sub-slab Soil Gas Concentration by Building Area
NESDI Project #476

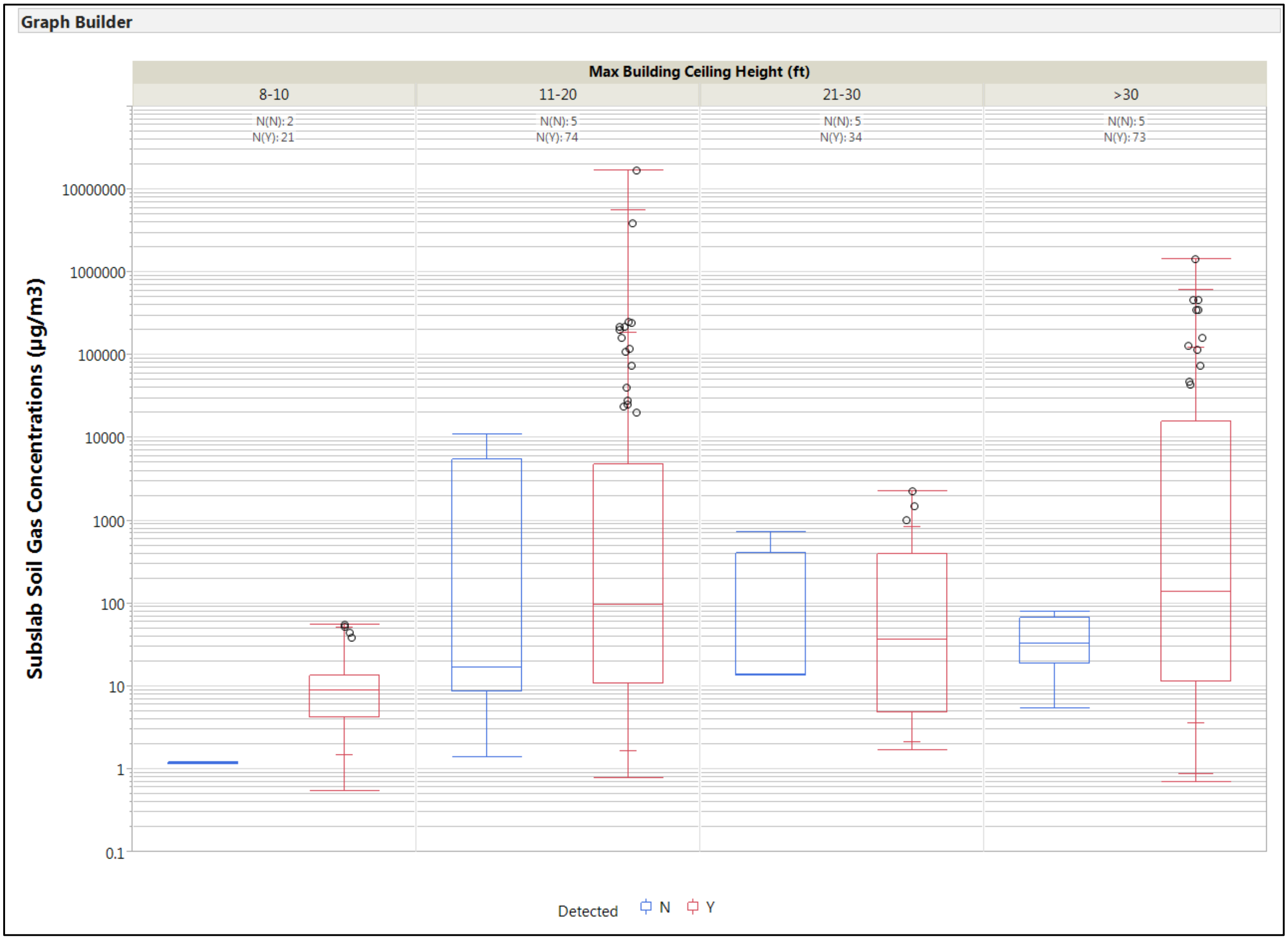


FIGURE E113
PCE Sub-slab Soil Gas Concentration by Maximum Building Ceiling Height
NESDI Project #476

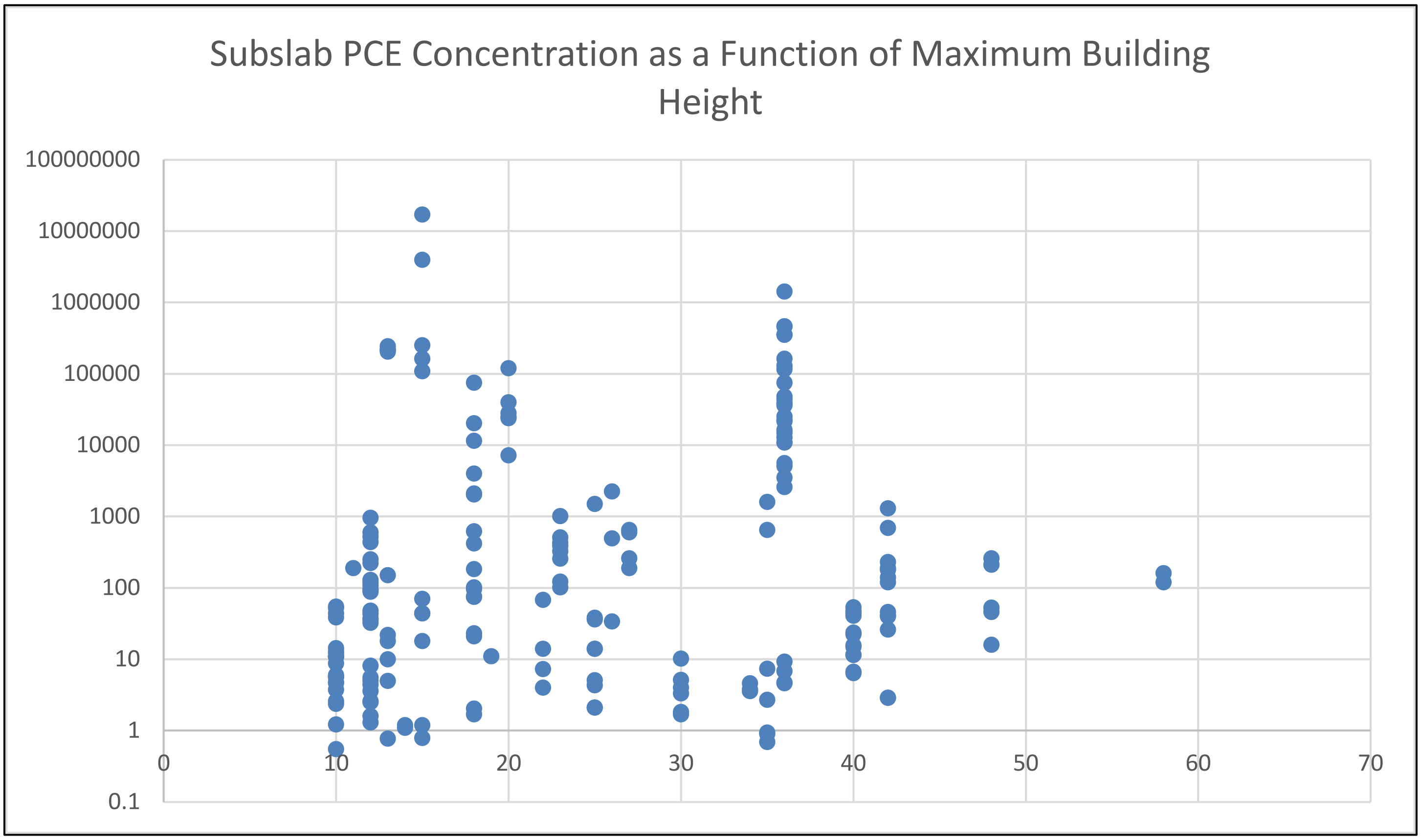


FIGURE E114
PCE Sub-slab Soil Gas Concentration vs Maximum Building Height
NESDI Project #476

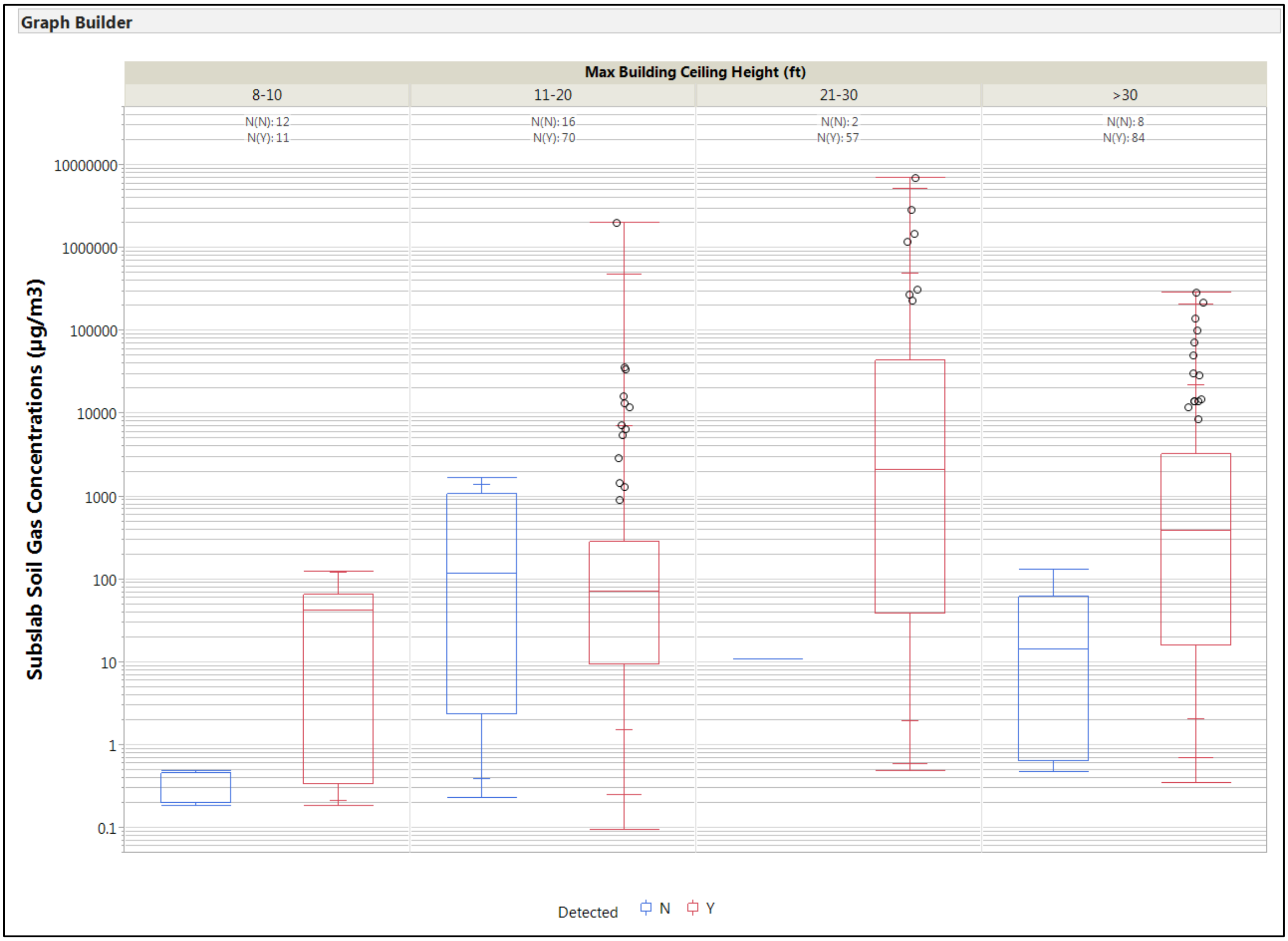


FIGURE E115

TCE Sub-slab Soil Gas Concentration by Maximum Building Ceiling Height

NESDI Project #476

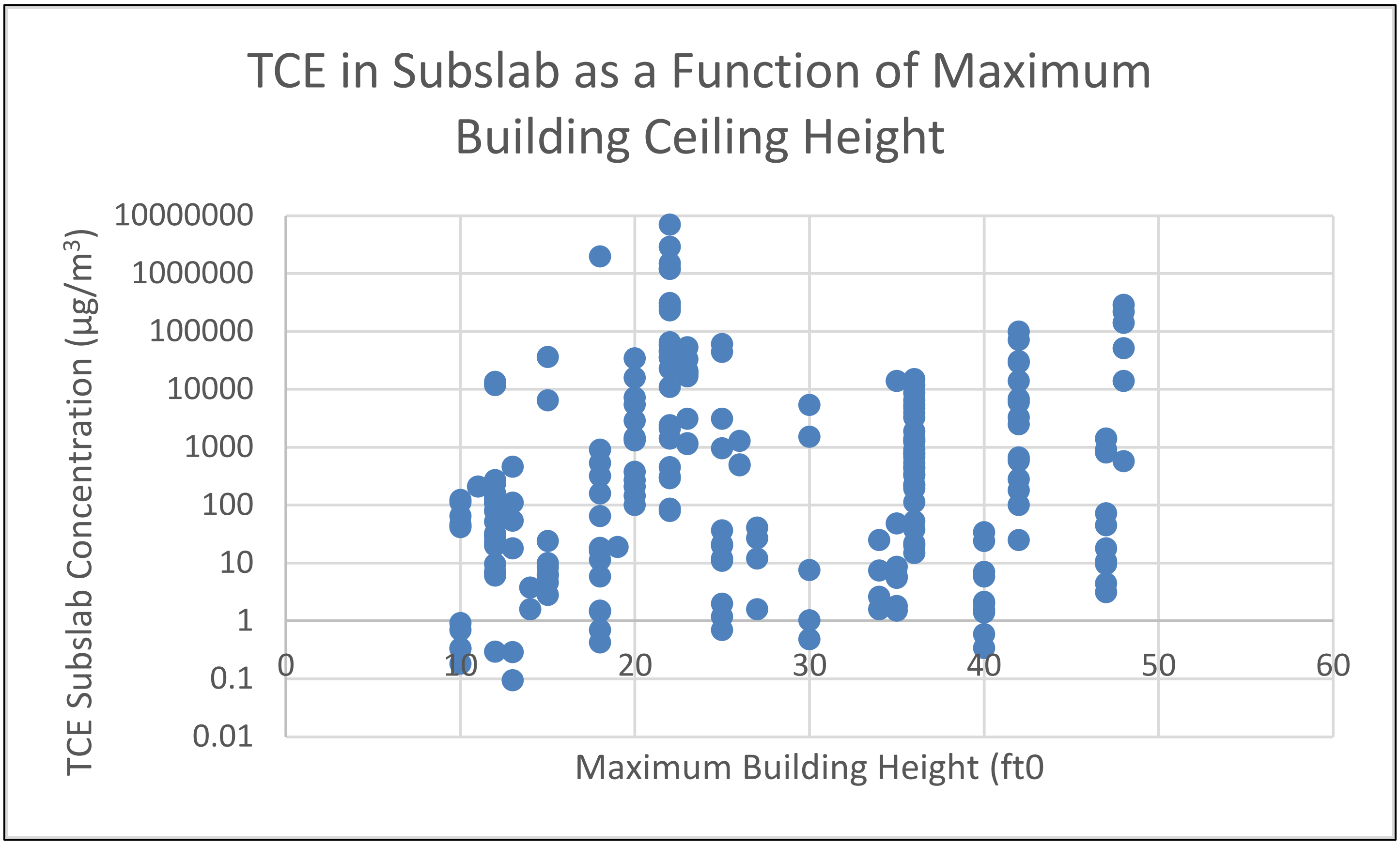


FIGURE E116
TCE Sub-slab Soil Gas Concentration vs Building Height
NESDI Project #476

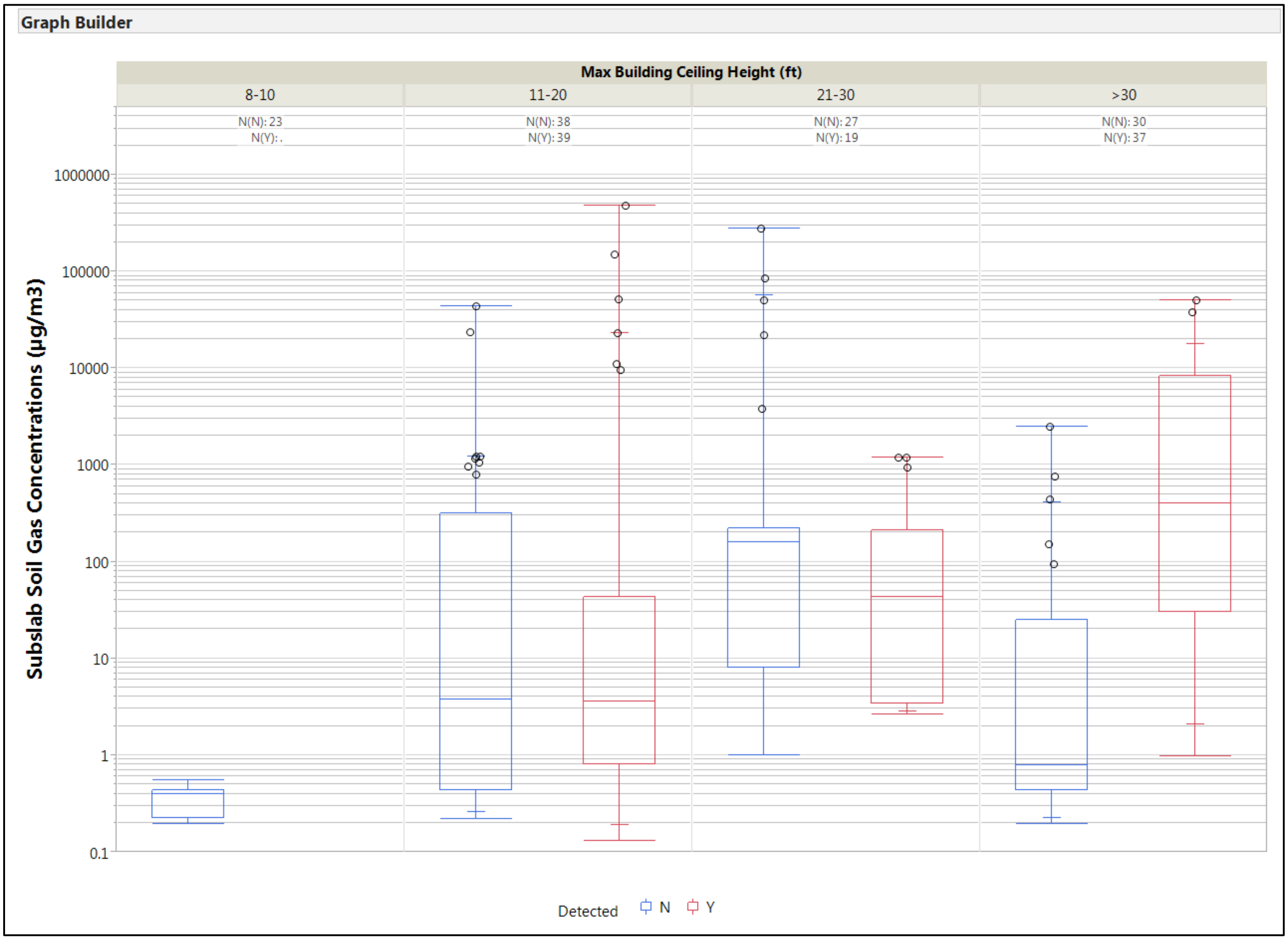


FIGURE E117
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Maximum Building Ceiling Height
NESDI Project #476

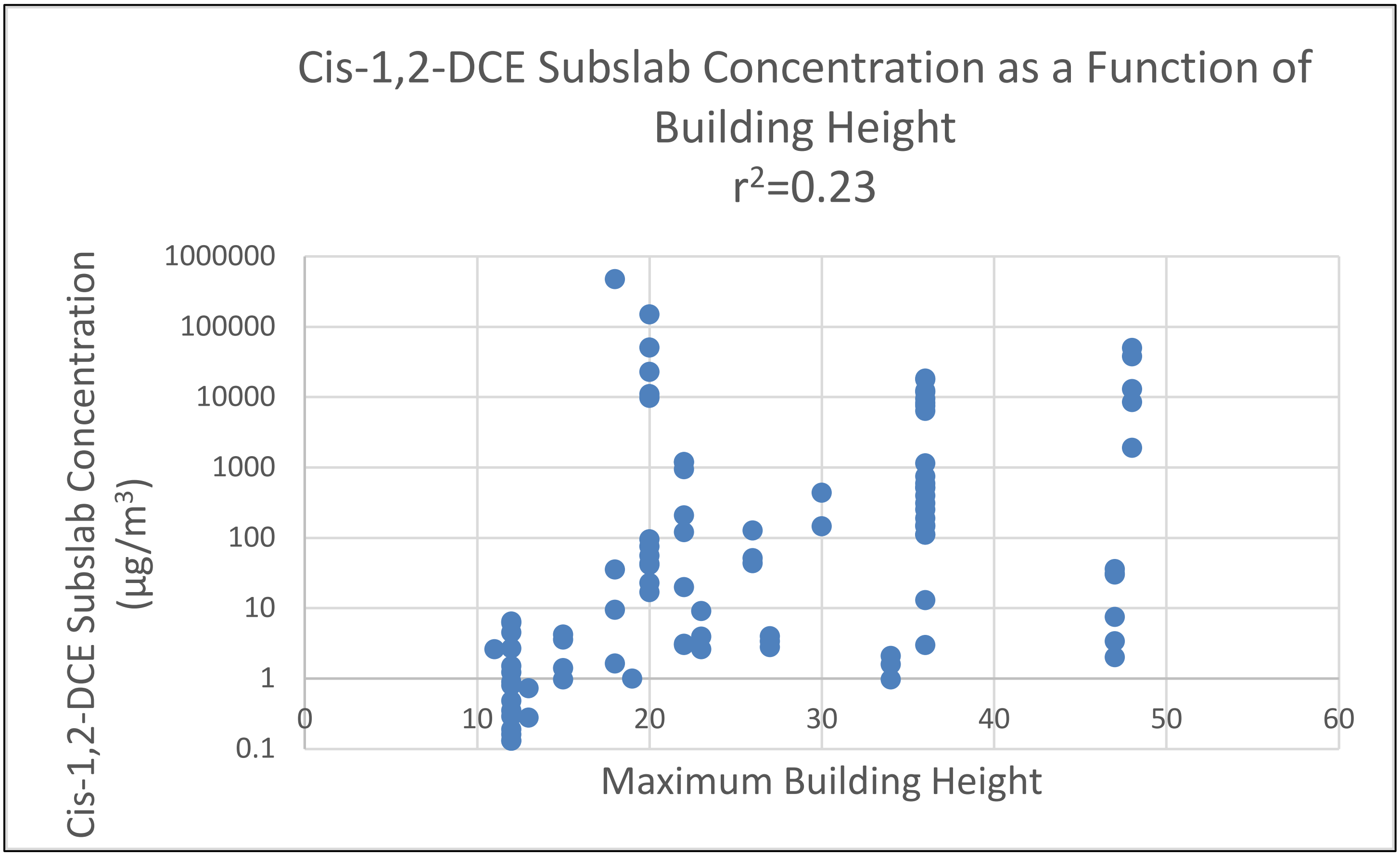


FIGURE E118

Cis-1,2-DCE Sub-slab Soil Gas Concentration vs Building Height

NESDI Project #476

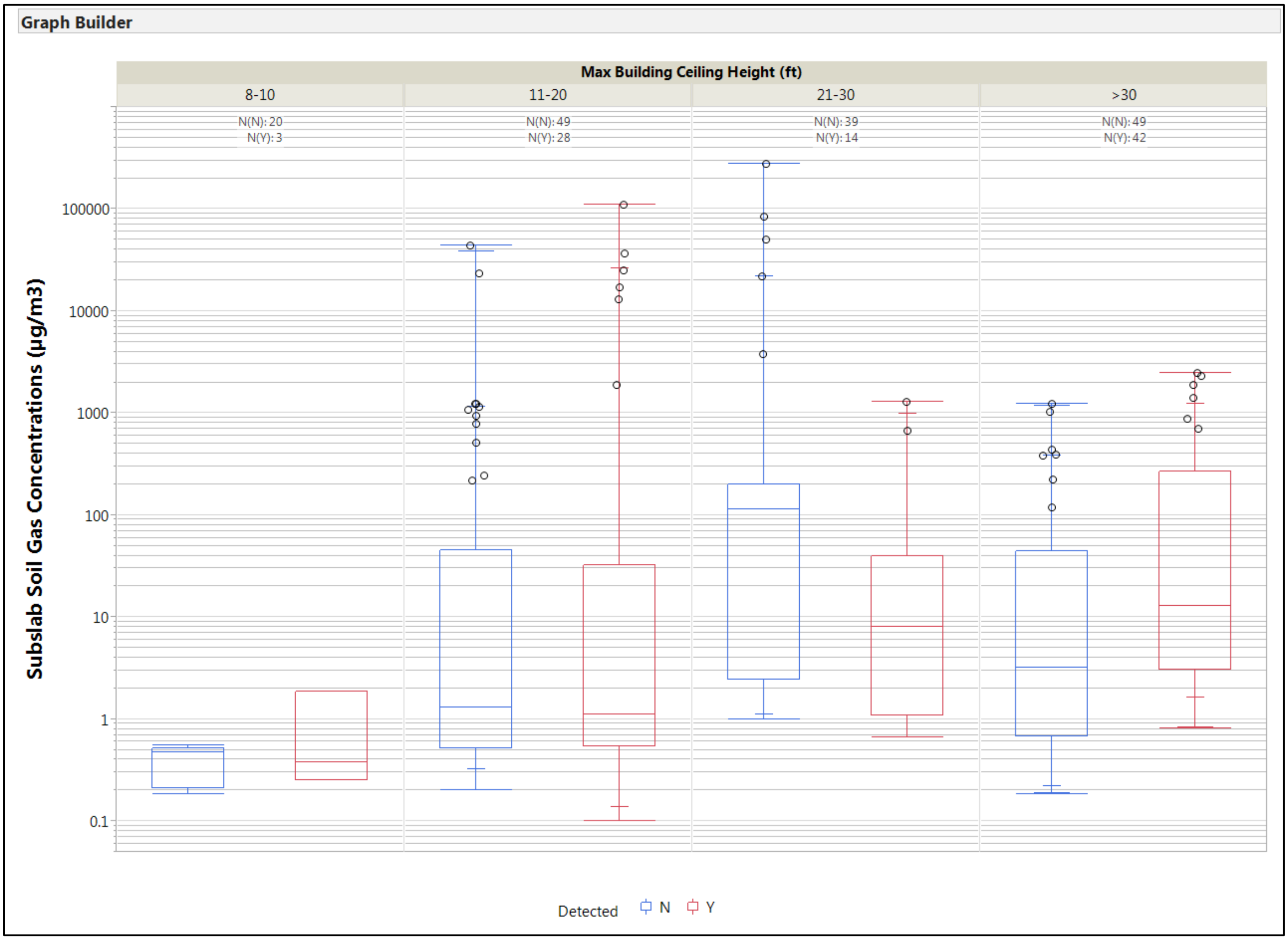


FIGURE E119

Trans-1,2-DCE Sub-slab Soil Gas Concentration by Maximum Building Ceiling Height

NESDI Project #476

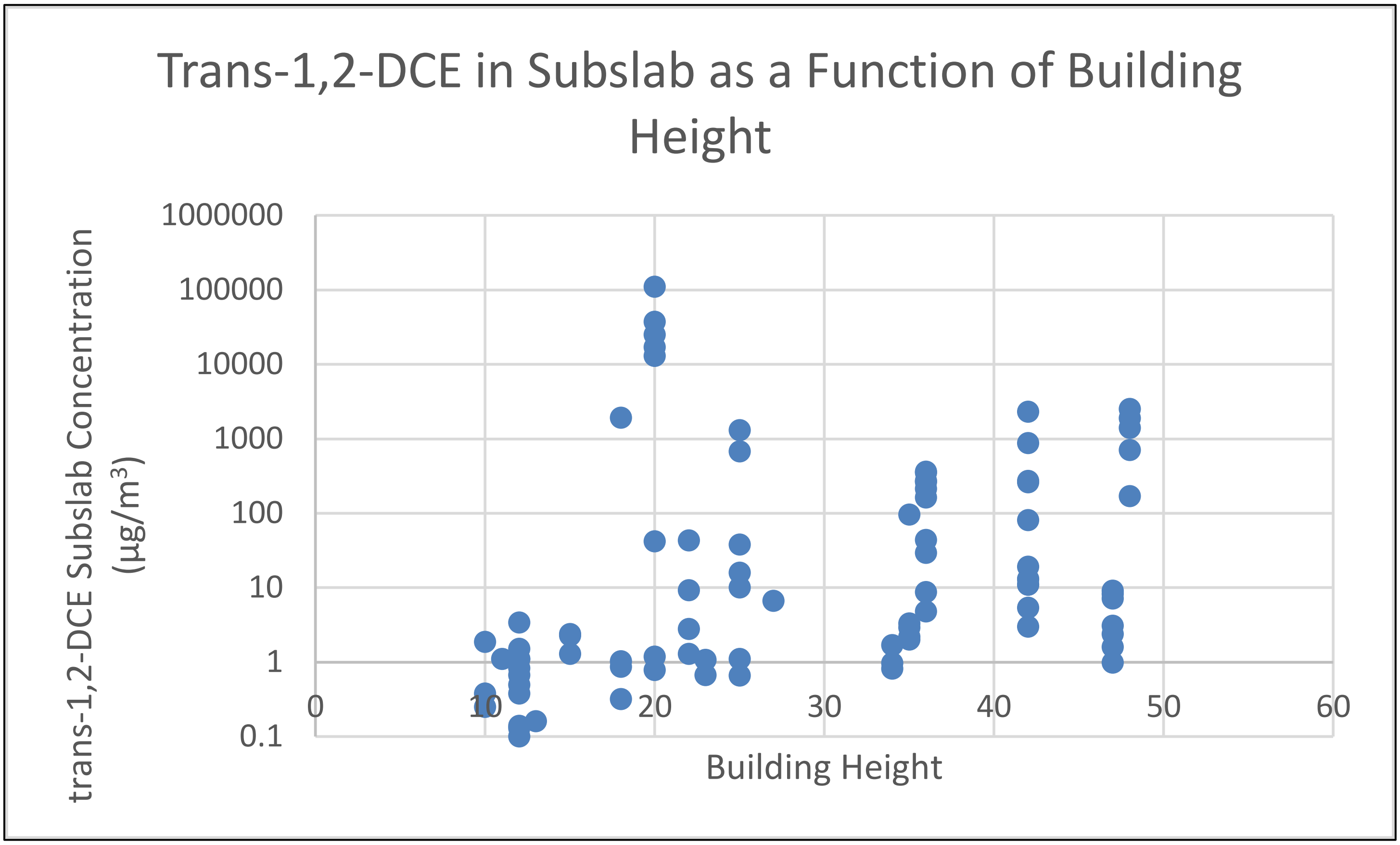


FIGURE E120

Trans-1,2-DCE Sub-slab Soil Gas Concentration vs Building Height; Detectable Results Only

NESDI Project #476

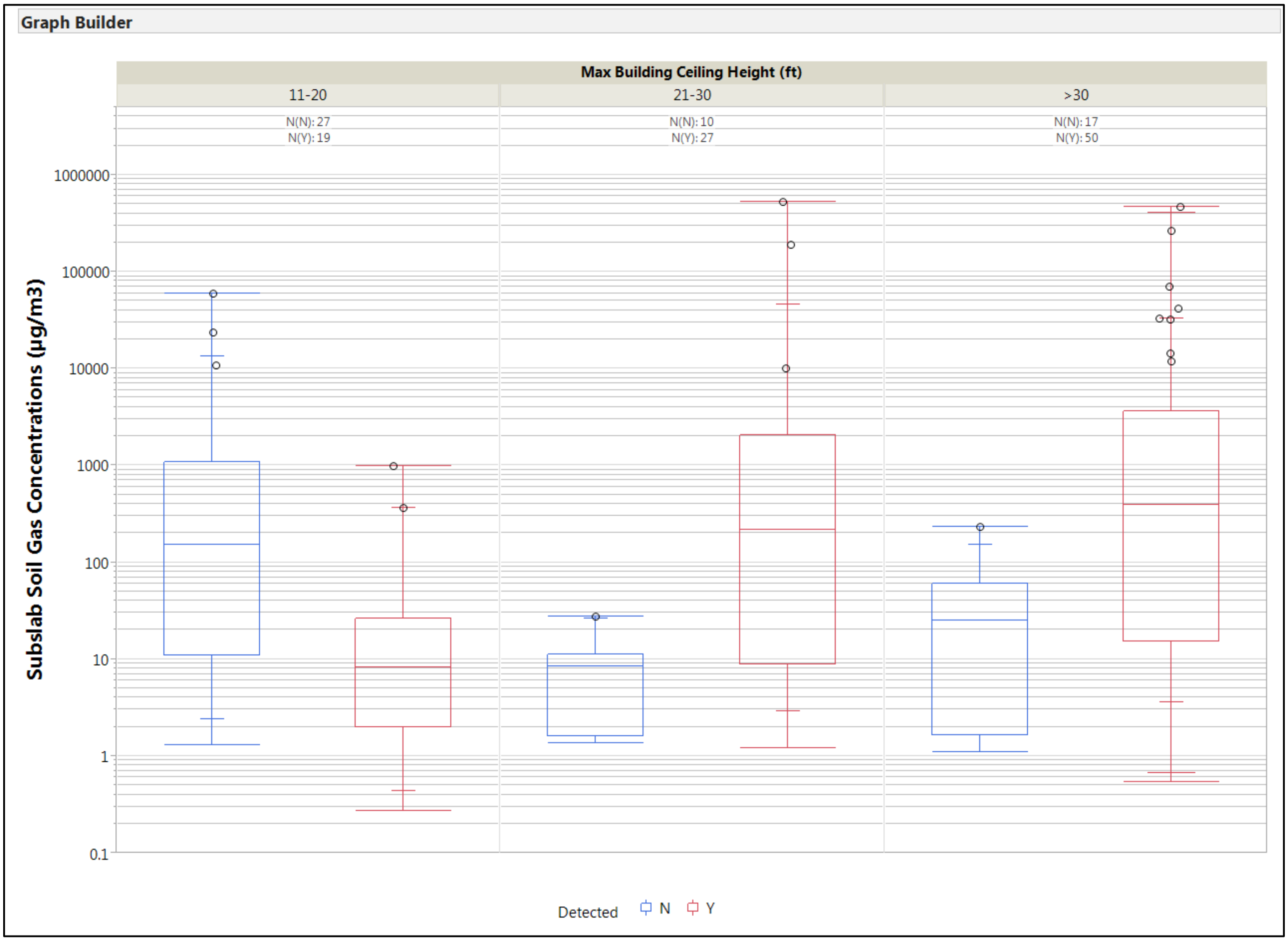


FIGURE E121
1,1,1-TCA Sub-slab Soil Gas Concentration by Maximum Building Ceiling Height
NESDI Project #476

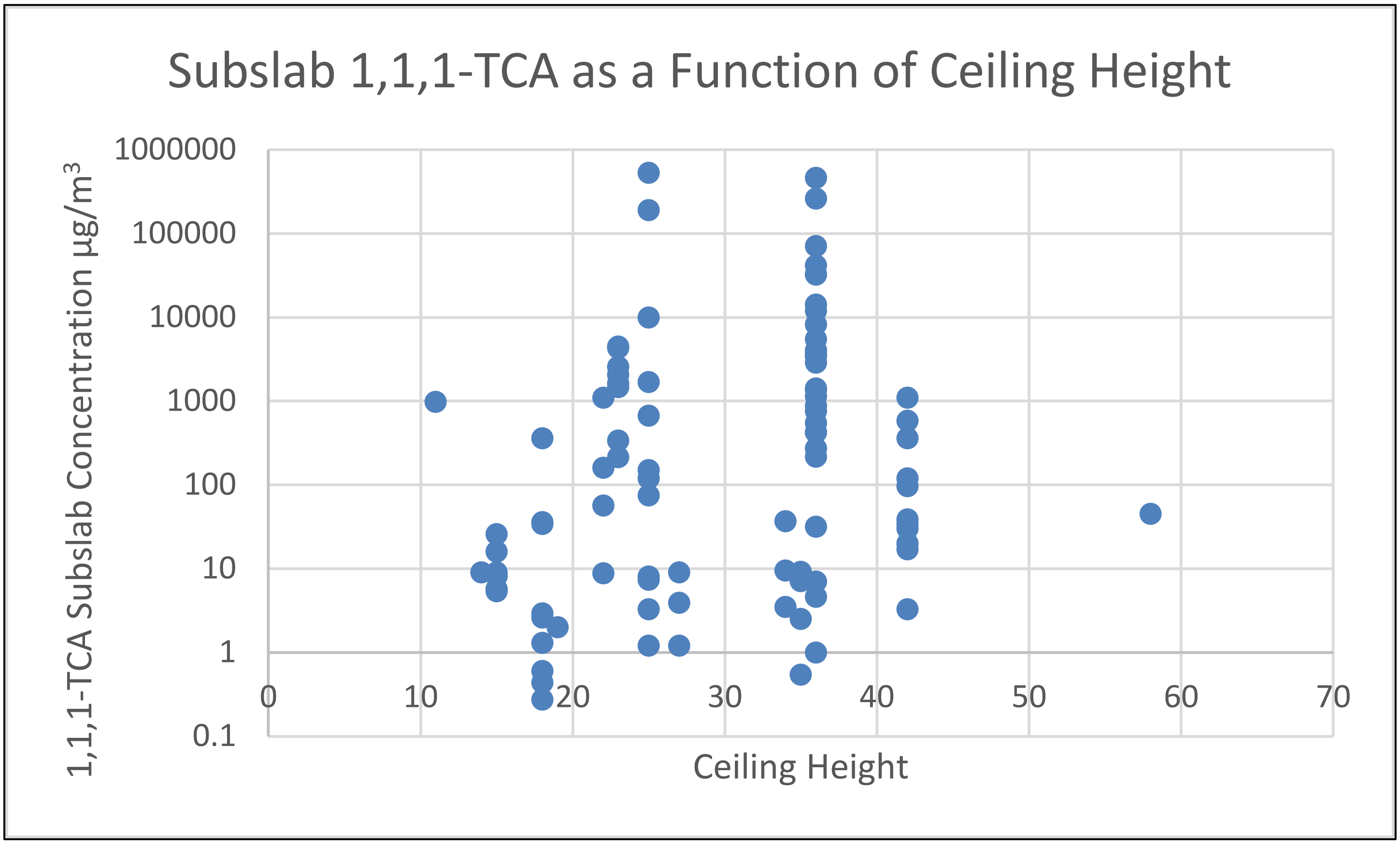


FIGURE E122

1,1,1-TCA Sub-slab Soil Gas Concentration vs Ceiling Height; Detectable Results Only

NESDI Project #476

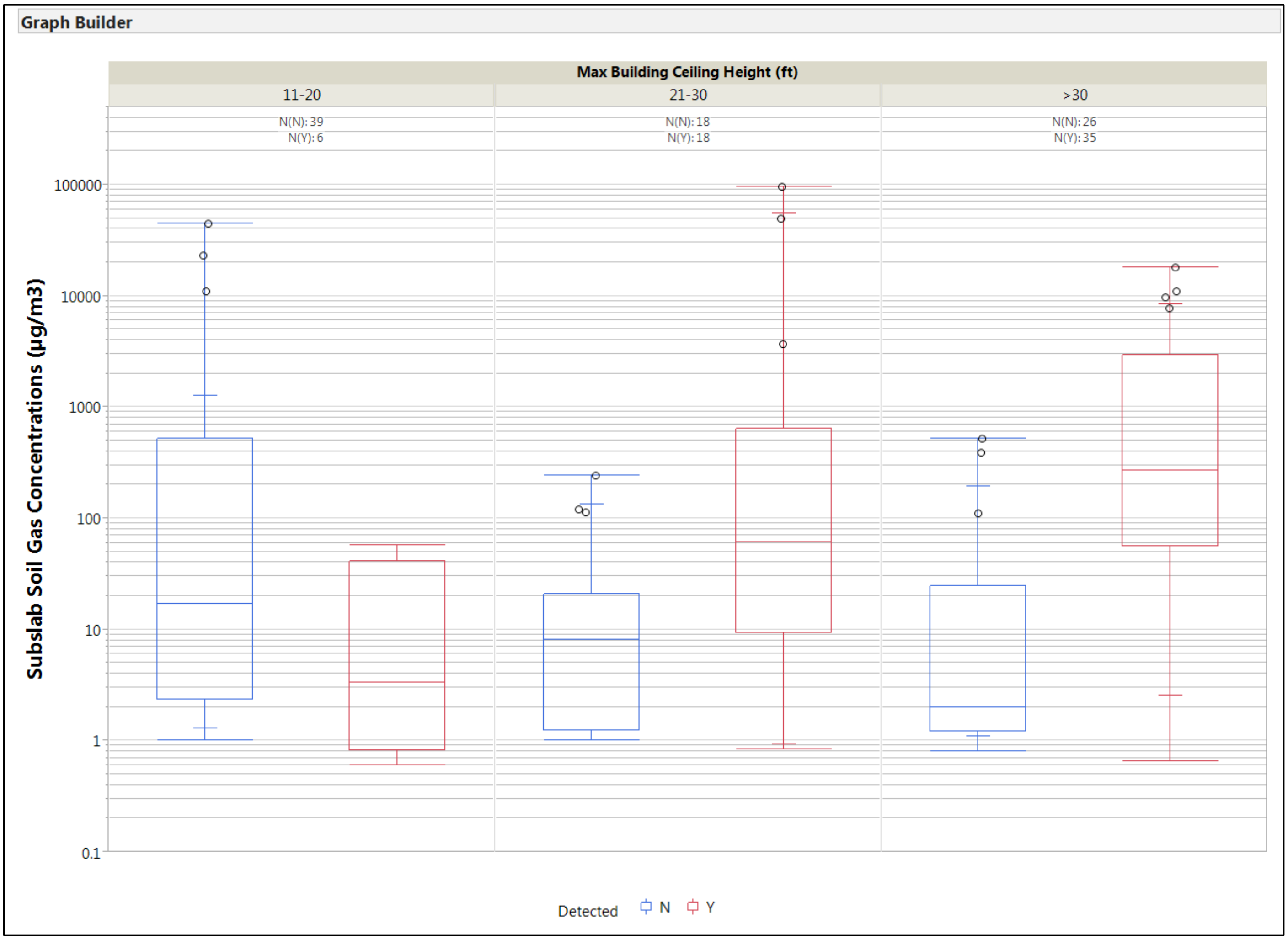


FIGURE E123
1,1-DCA Sub-slab Soil Gas Concentration by Maximum Building Ceiling Height
NESDI Project #476

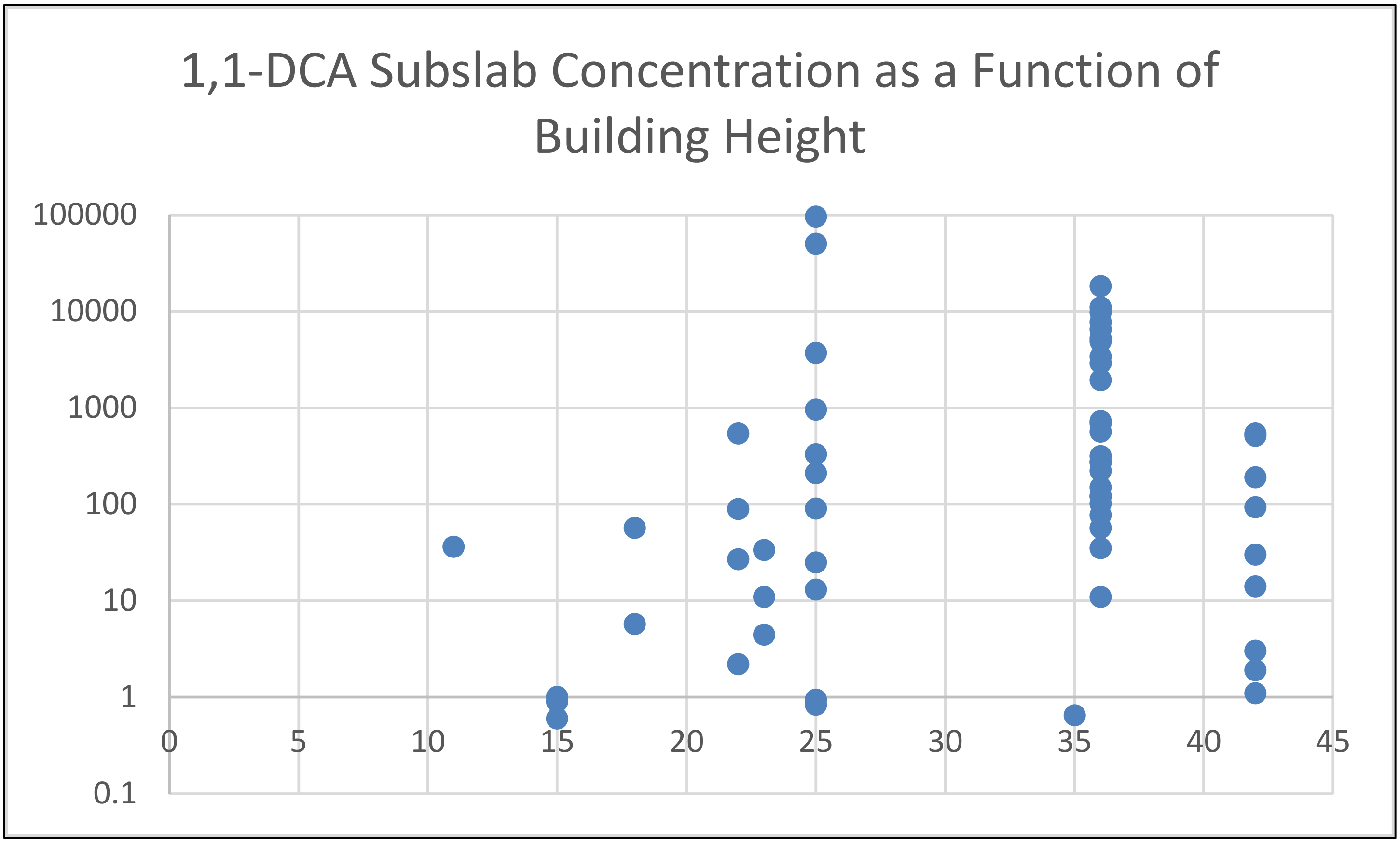


FIGURE E124
1,1-DCA Sub-slab Soil Gas Concentration vs Building Height; Detectable Results Only
NESDI Project #476

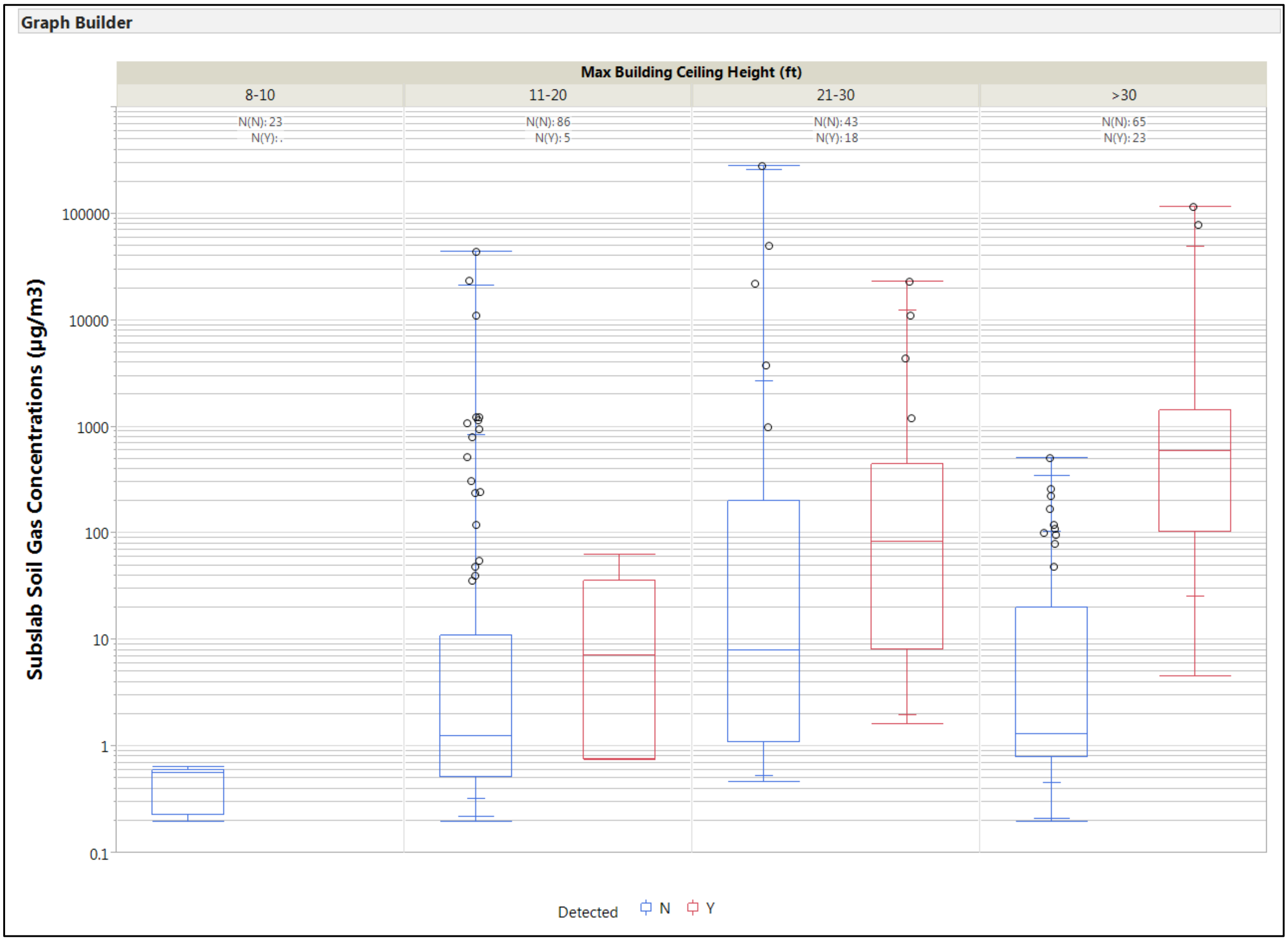


FIGURE E125

1,1-DCE Sub-slab Concentration by Maximum Building Ceiling Height

NESDI Project #476

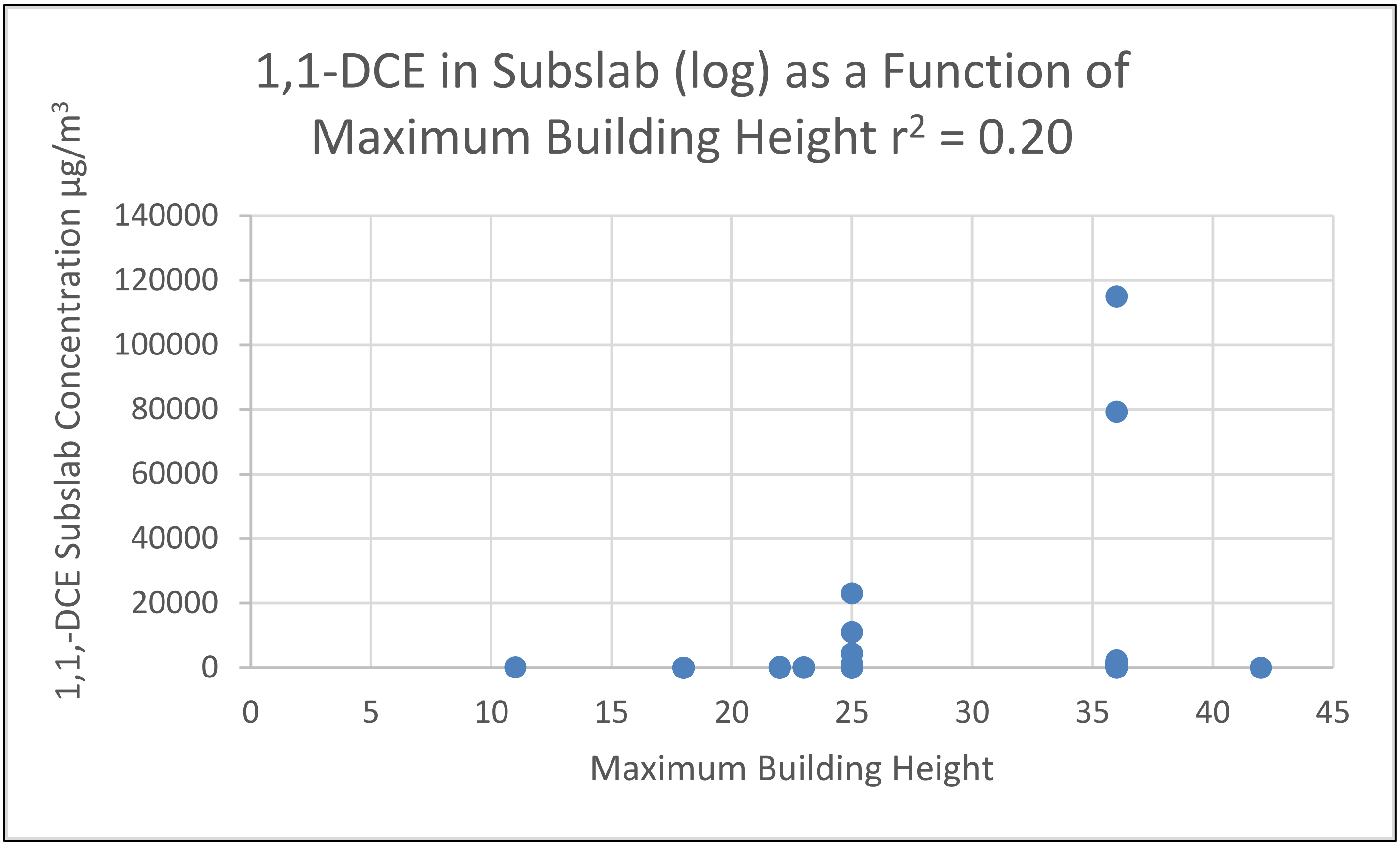


FIGURE E126

1,1-DCE Sub-slab Soil Gas Concentration vs Maximum Building Ceiling Height

NESDI Project #476

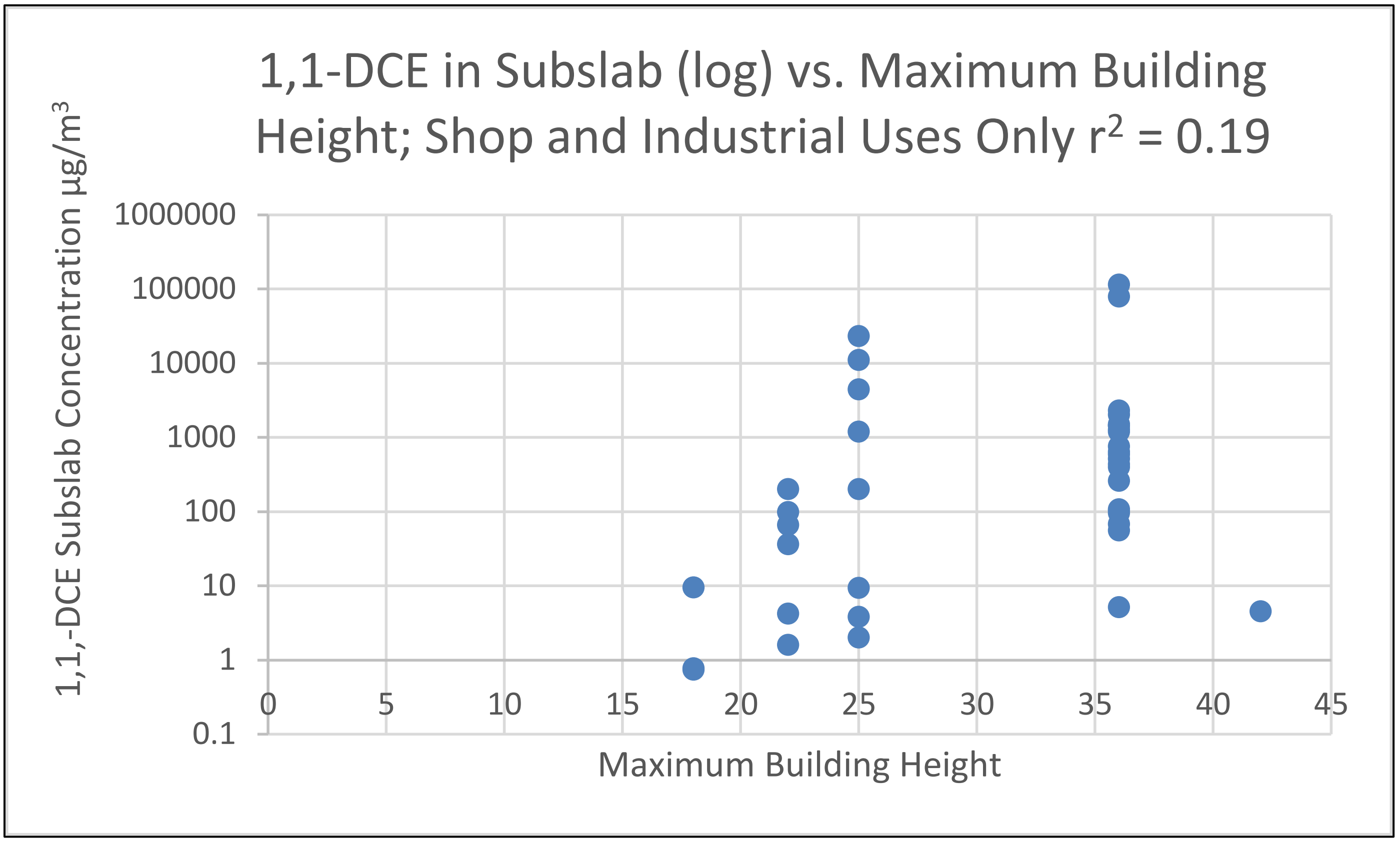


FIGURE E127

1,1-DCE Sub-slab Soil Gas Concentration vs Maximum Building Height
Shop and Industrial Uses Only
NESDI Project #476

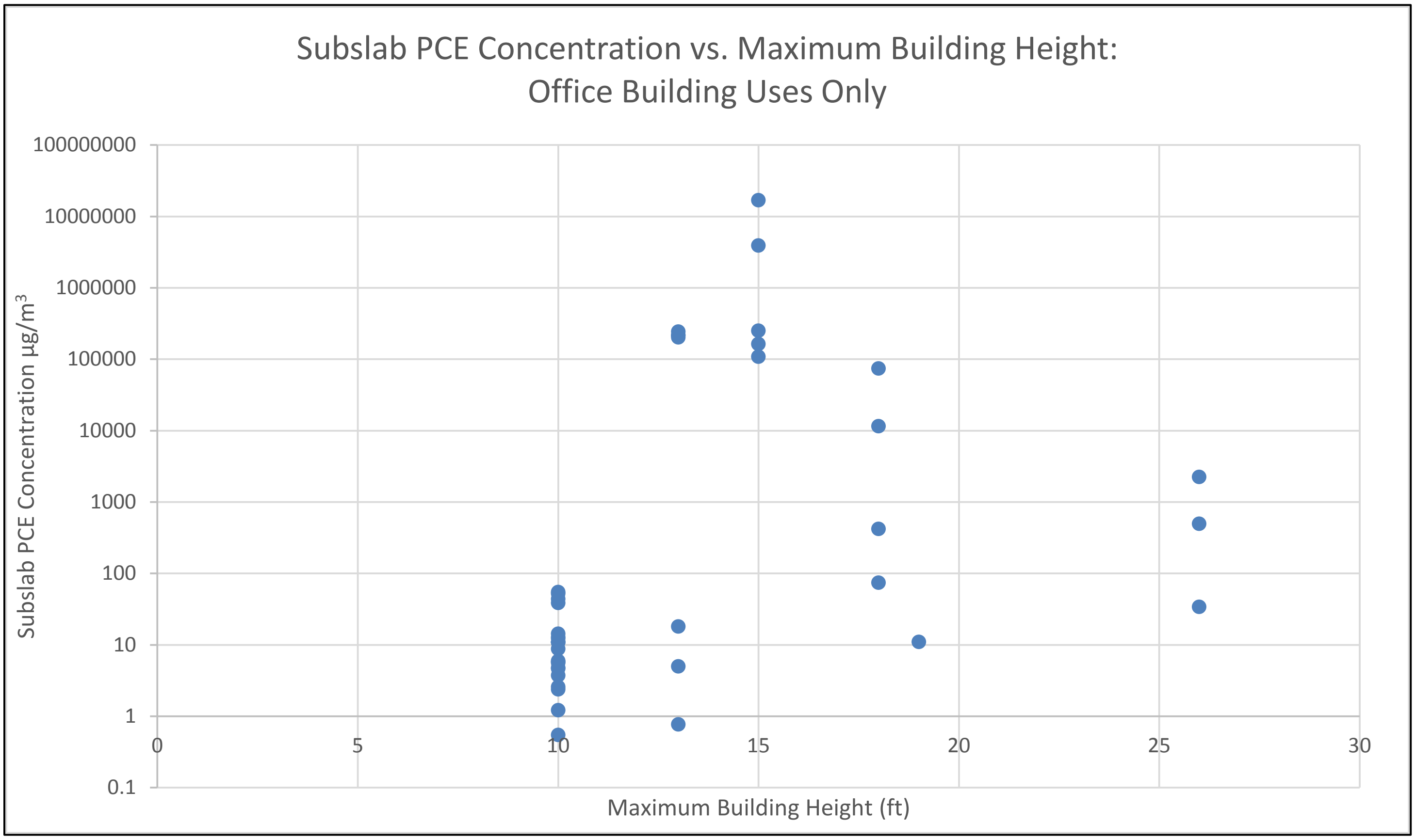


FIGURE E128

PCE Sub-slab Soil Gas Concentration vs Building Height

Office Building Uses Only

NESDI Project #476

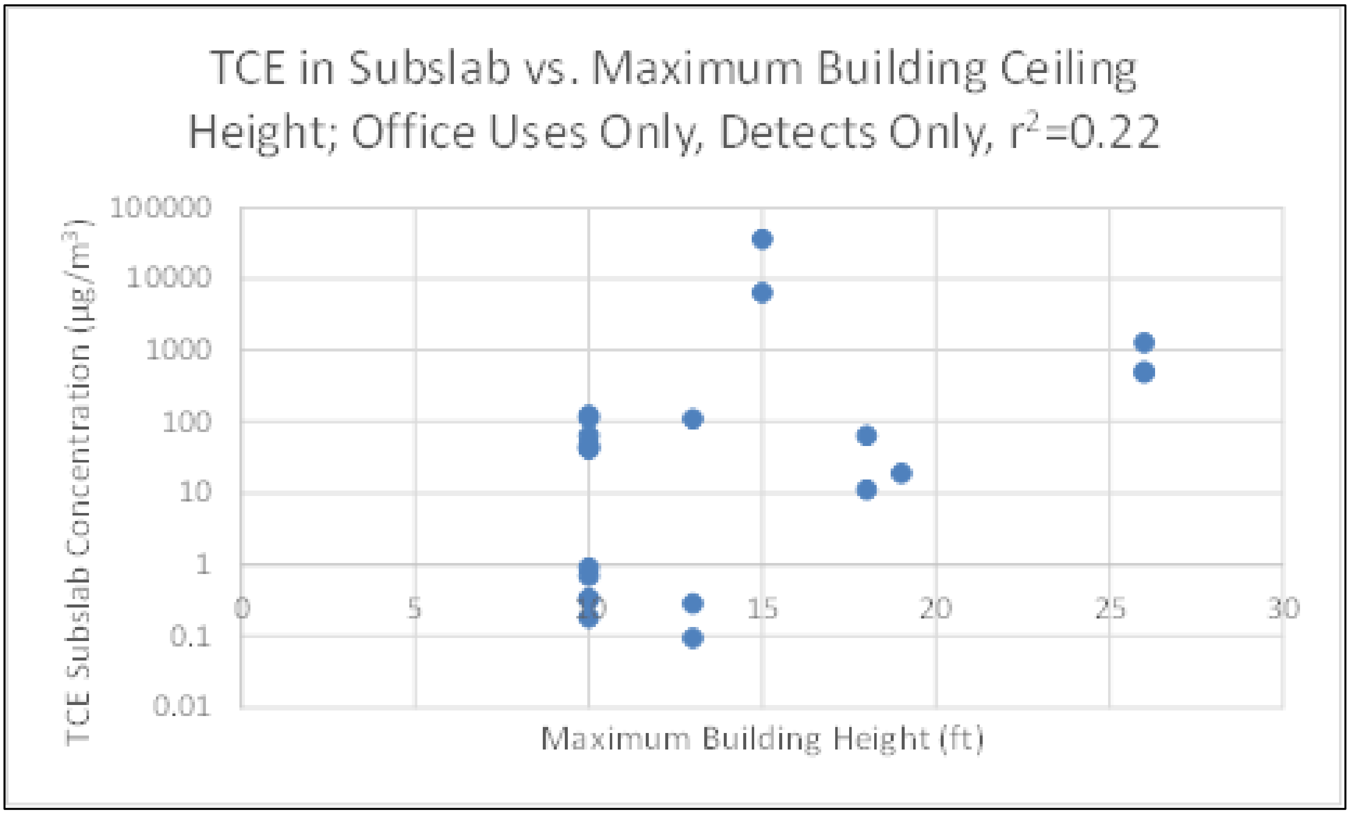


FIGURE E129

TCE Sub-slab Soil Gas Concentration vs Maximum Building Ceiling Height
Office Building Uses Only
NESDI Project #476

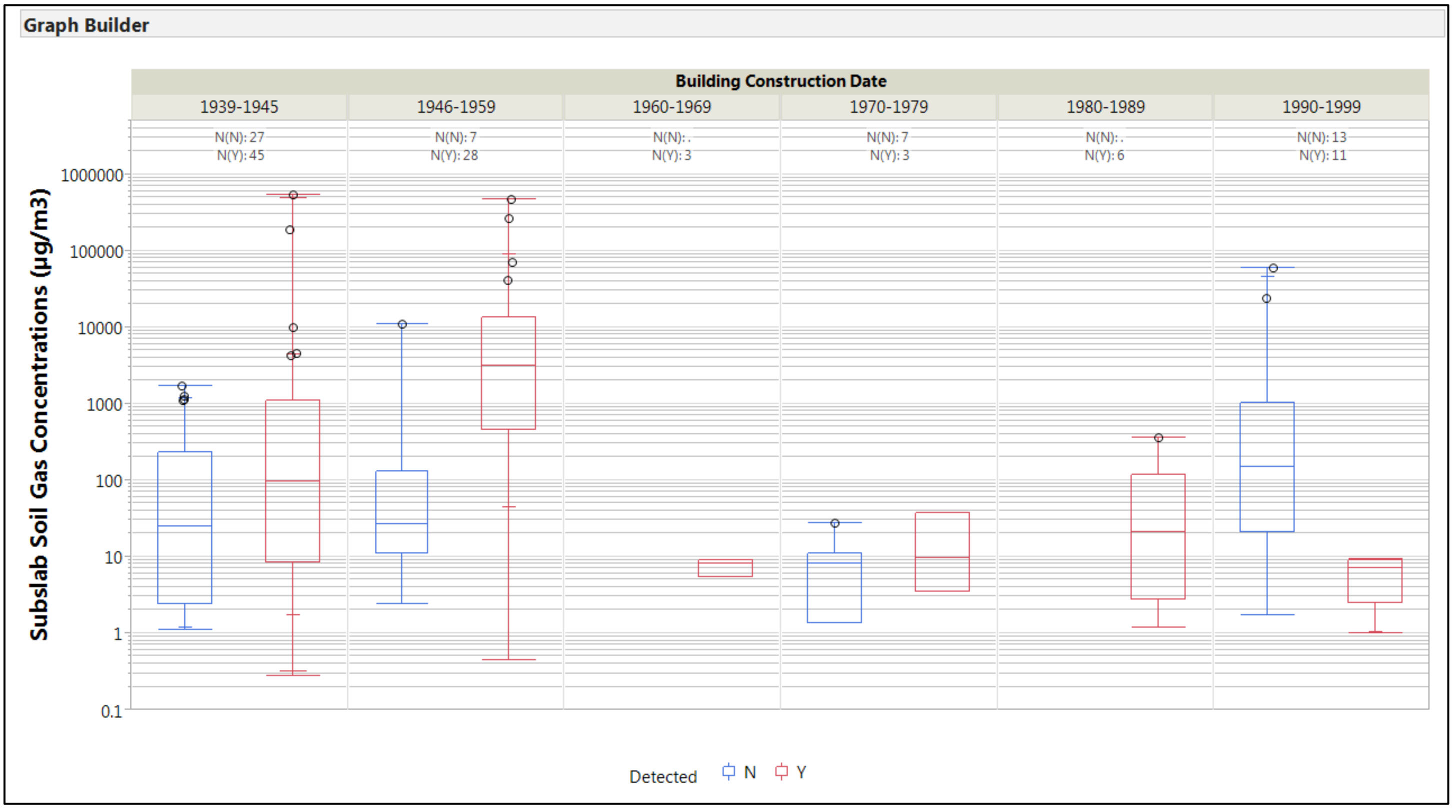


FIGURE E130
1,1,1 TCA Sub-slab Soil Gas Concentration by Building Construction Date
NESDI Project #476

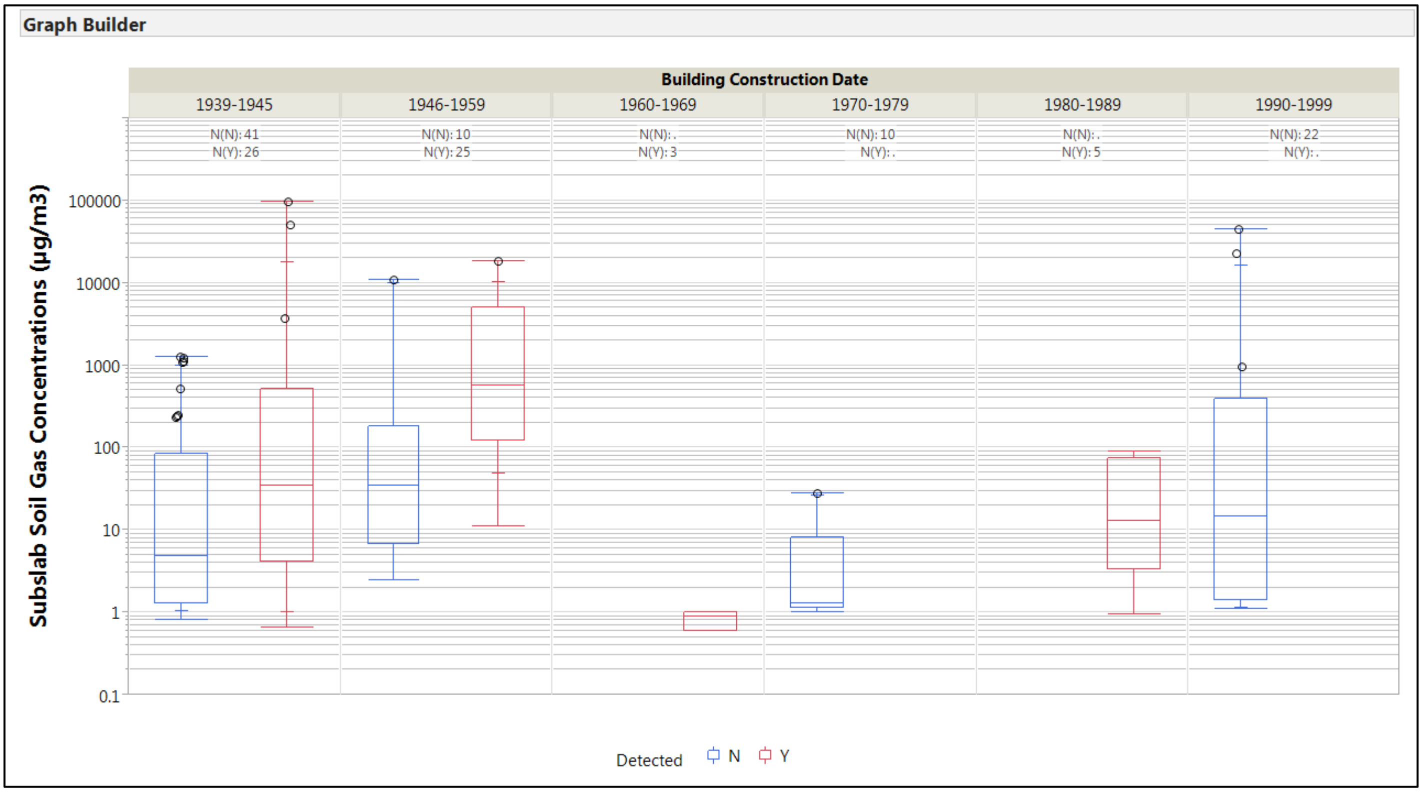


FIGURE E131

1,1-DCA Sub-slab Soil Gas Concentration by Building Construction Date

NESDI Project #476

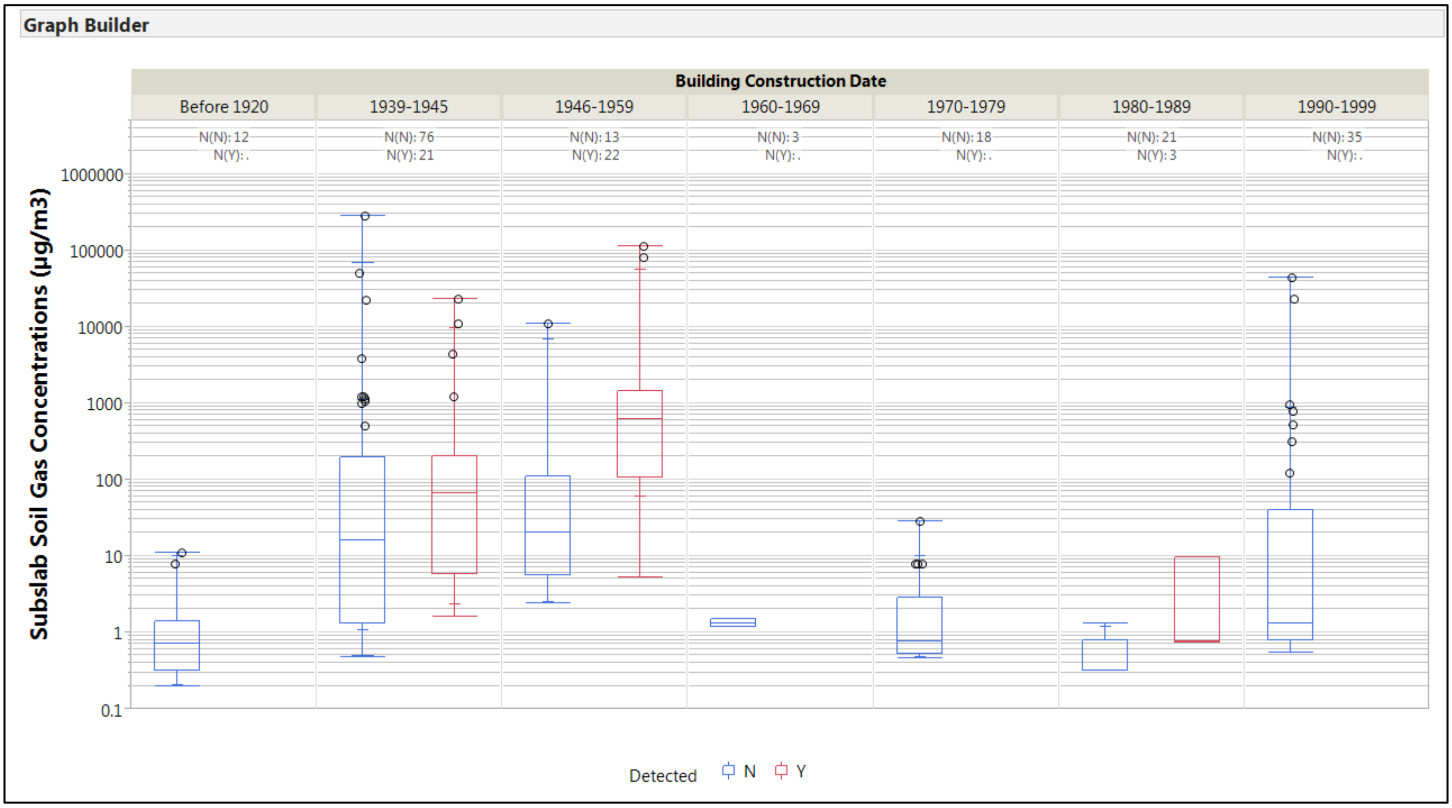


FIGURE E132
1,1-DCE Sub-slab Soil Gas Concentration by Building Construction Date
NESDI Project #476

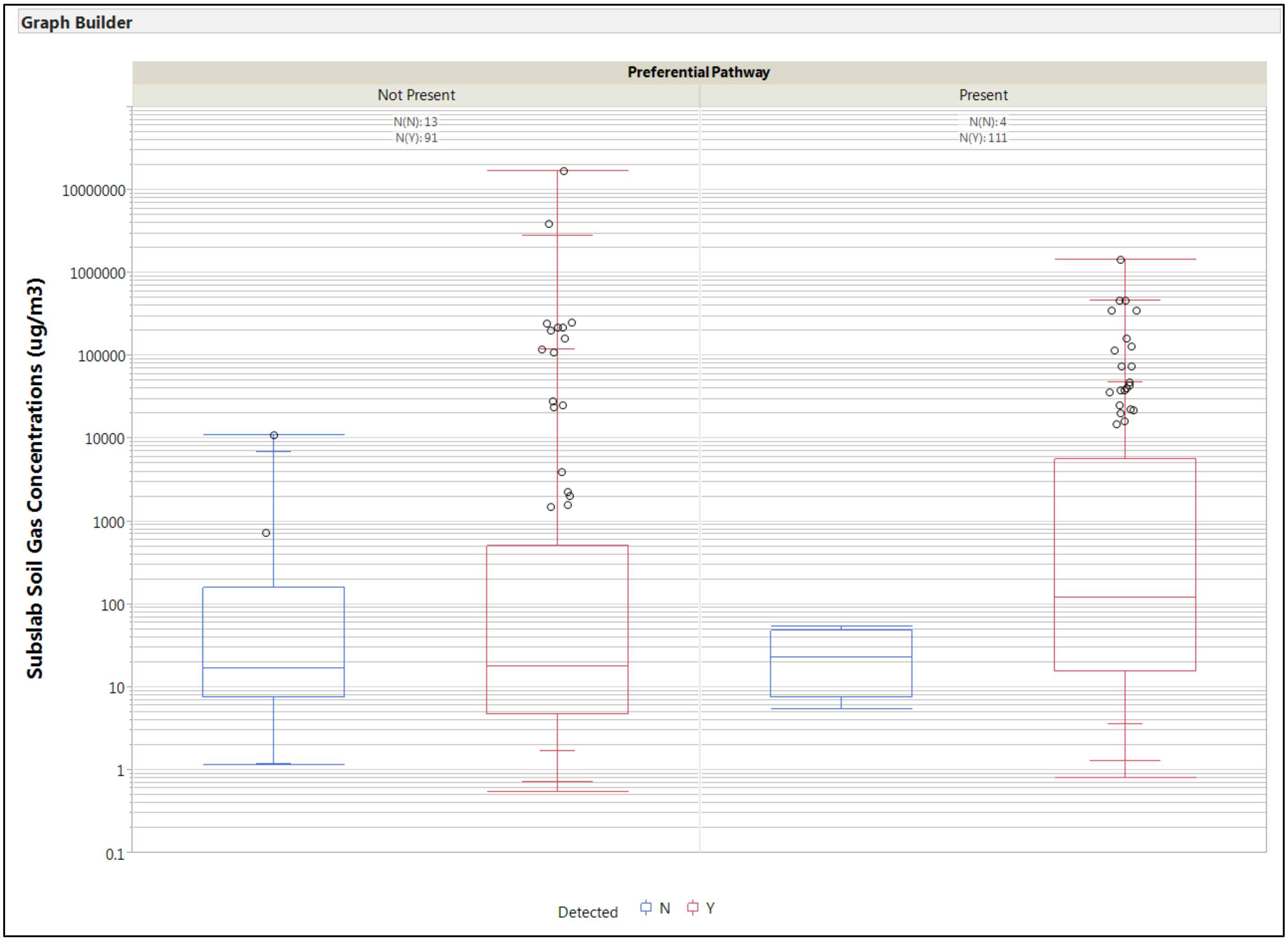


FIGURE E133

PCE Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)

NESDI Project #476

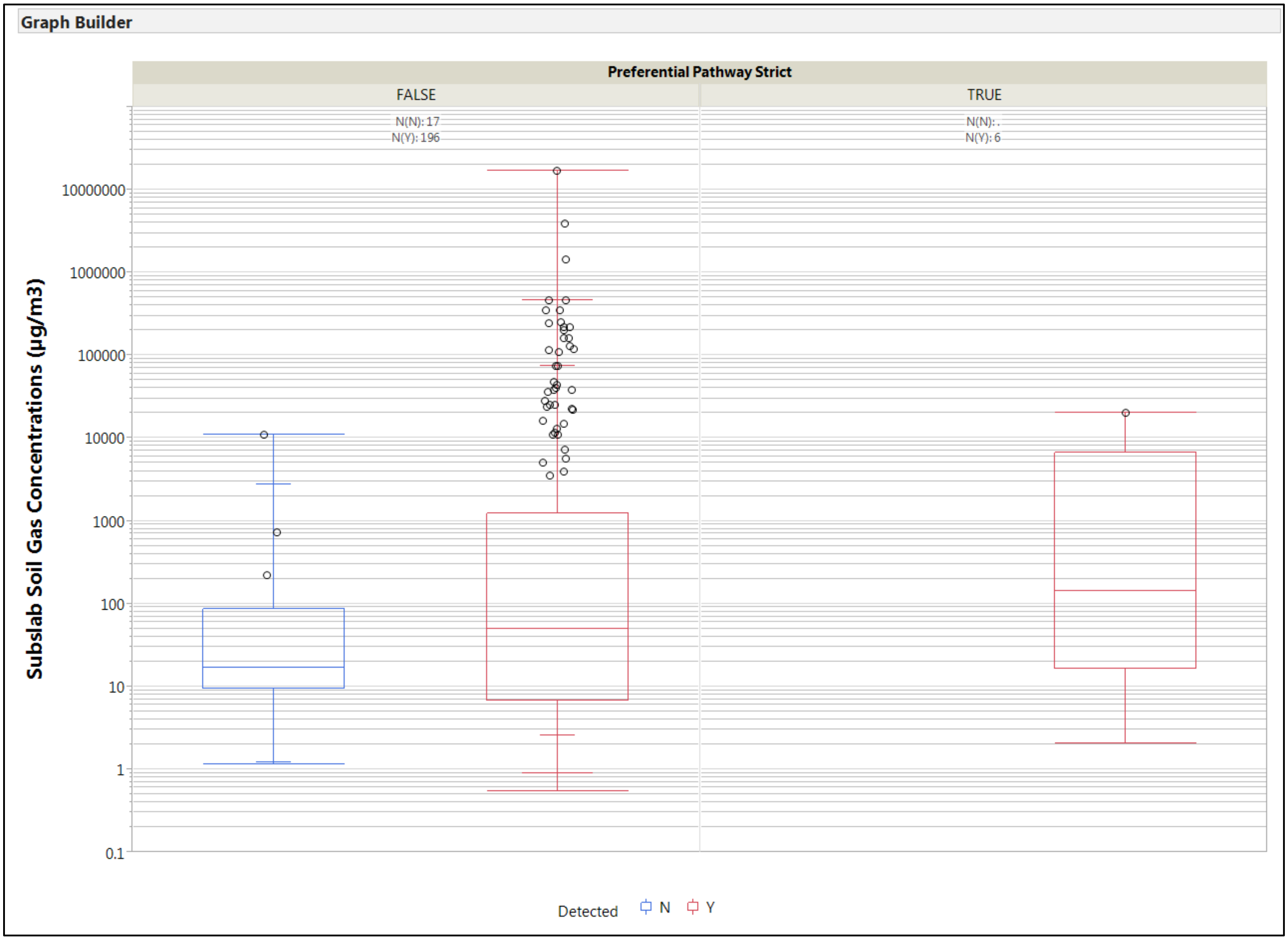


FIGURE E134
PCE Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)
NESDI Project #476

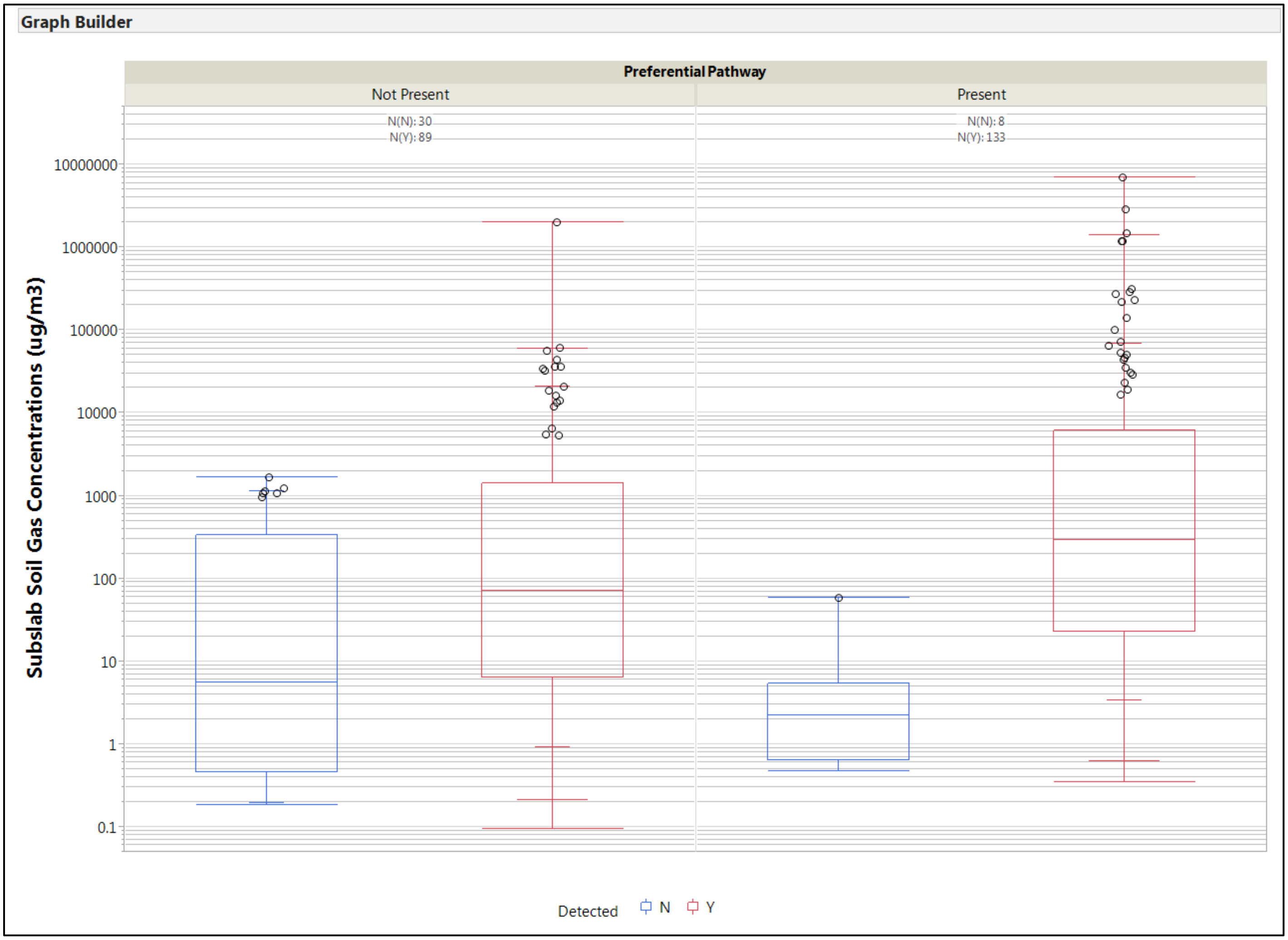


FIGURE E135

TCE Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)

NESDI Project #476

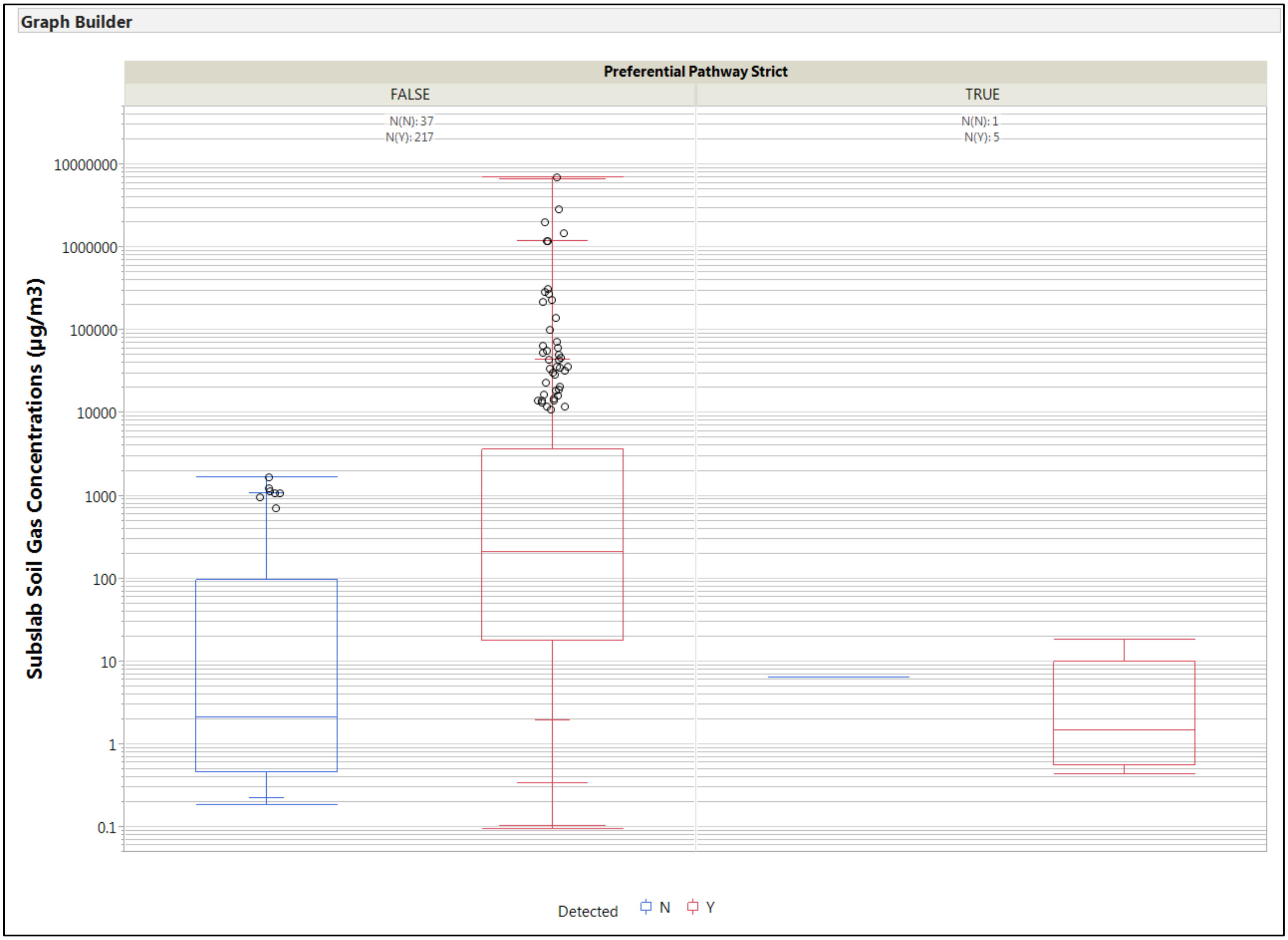


FIGURE E136
TCE Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)
NESDI Project #476

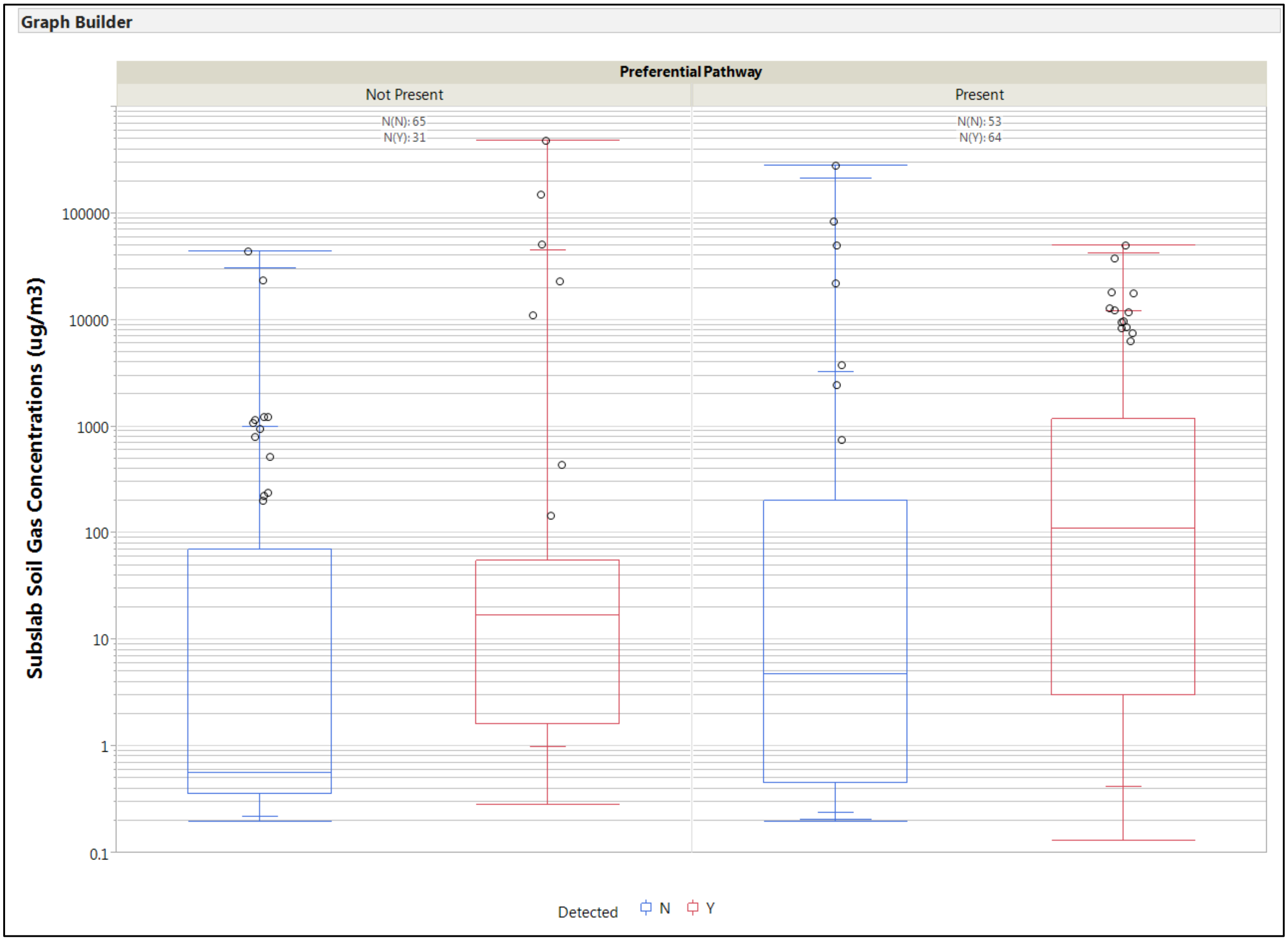


FIGURE E137
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)
NESDI Project #476

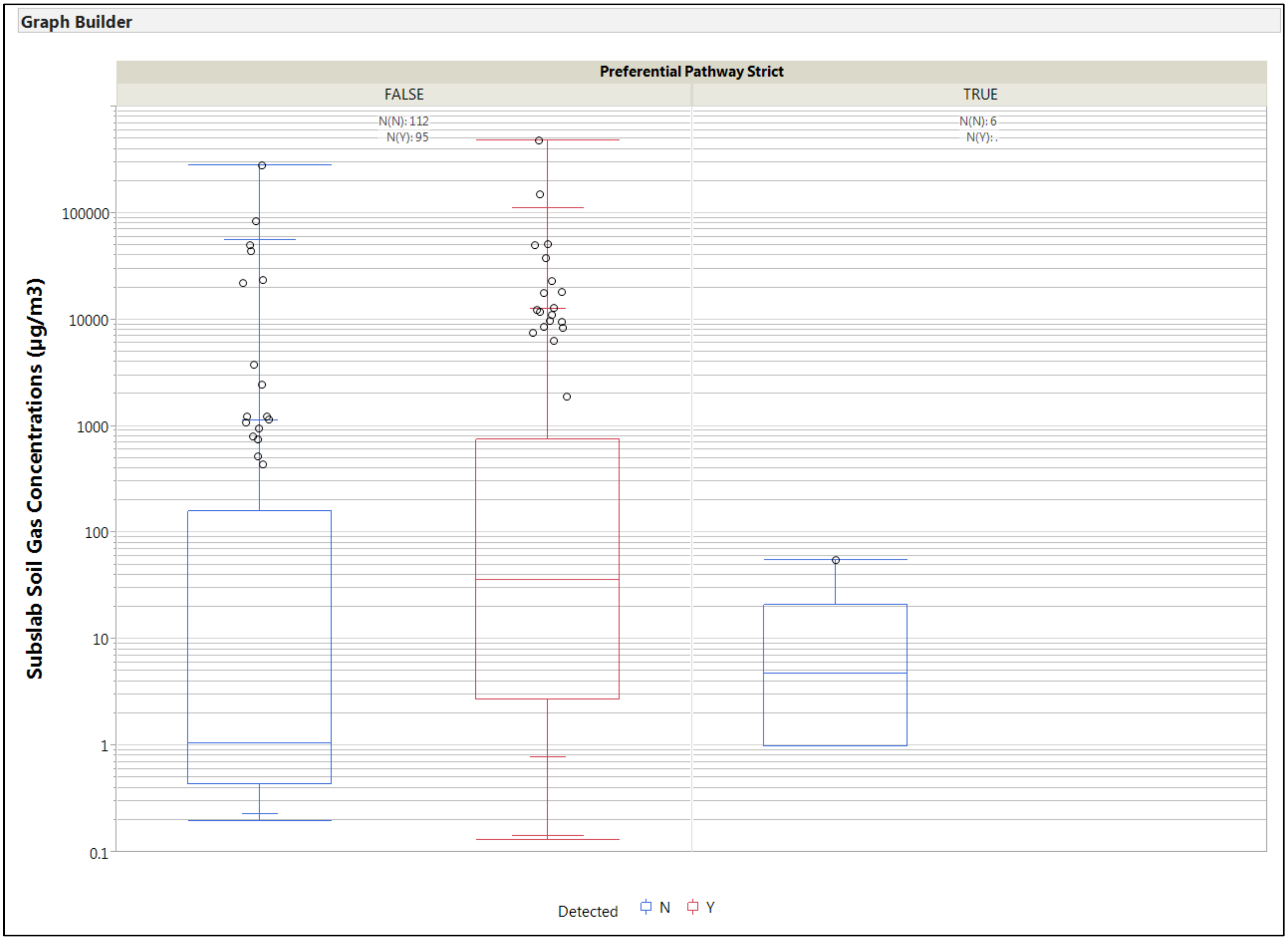


FIGURE E138
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)
NESDI Project #476

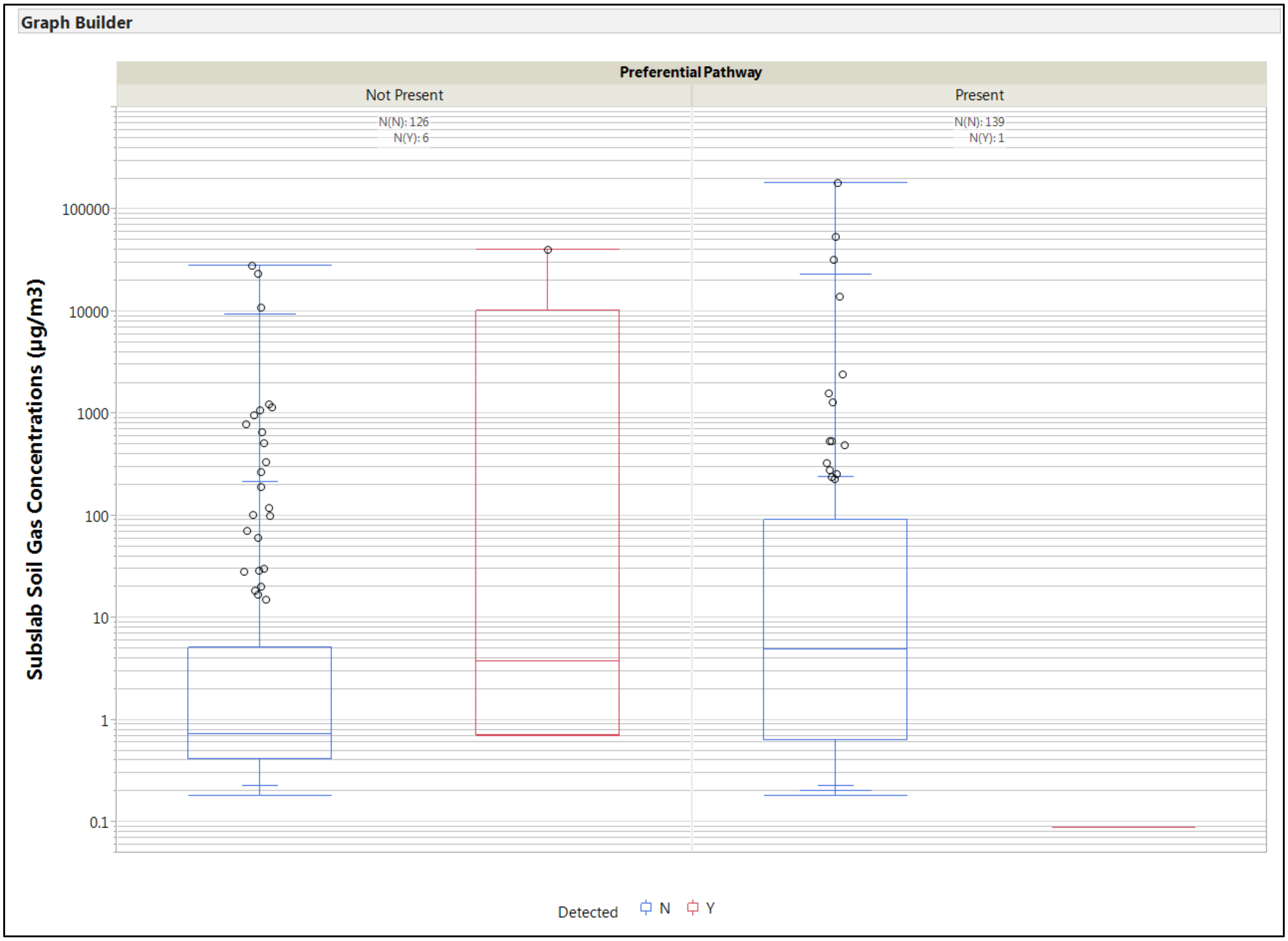


FIGURE E139
Vinyl Chloride Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)
NESDI Project #476

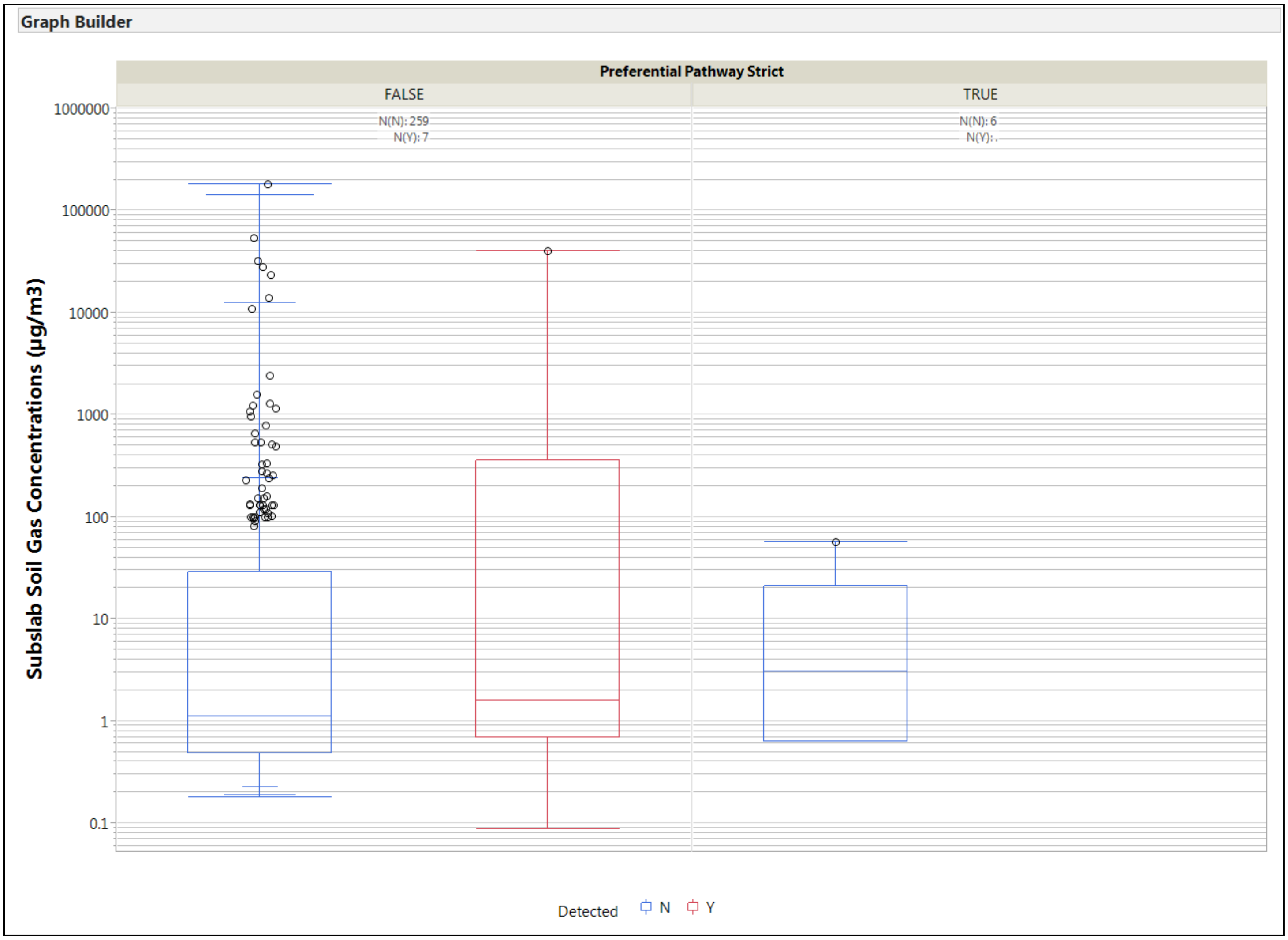


FIGURE E140
Vinyl Chloride Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)
NESDI Project #476

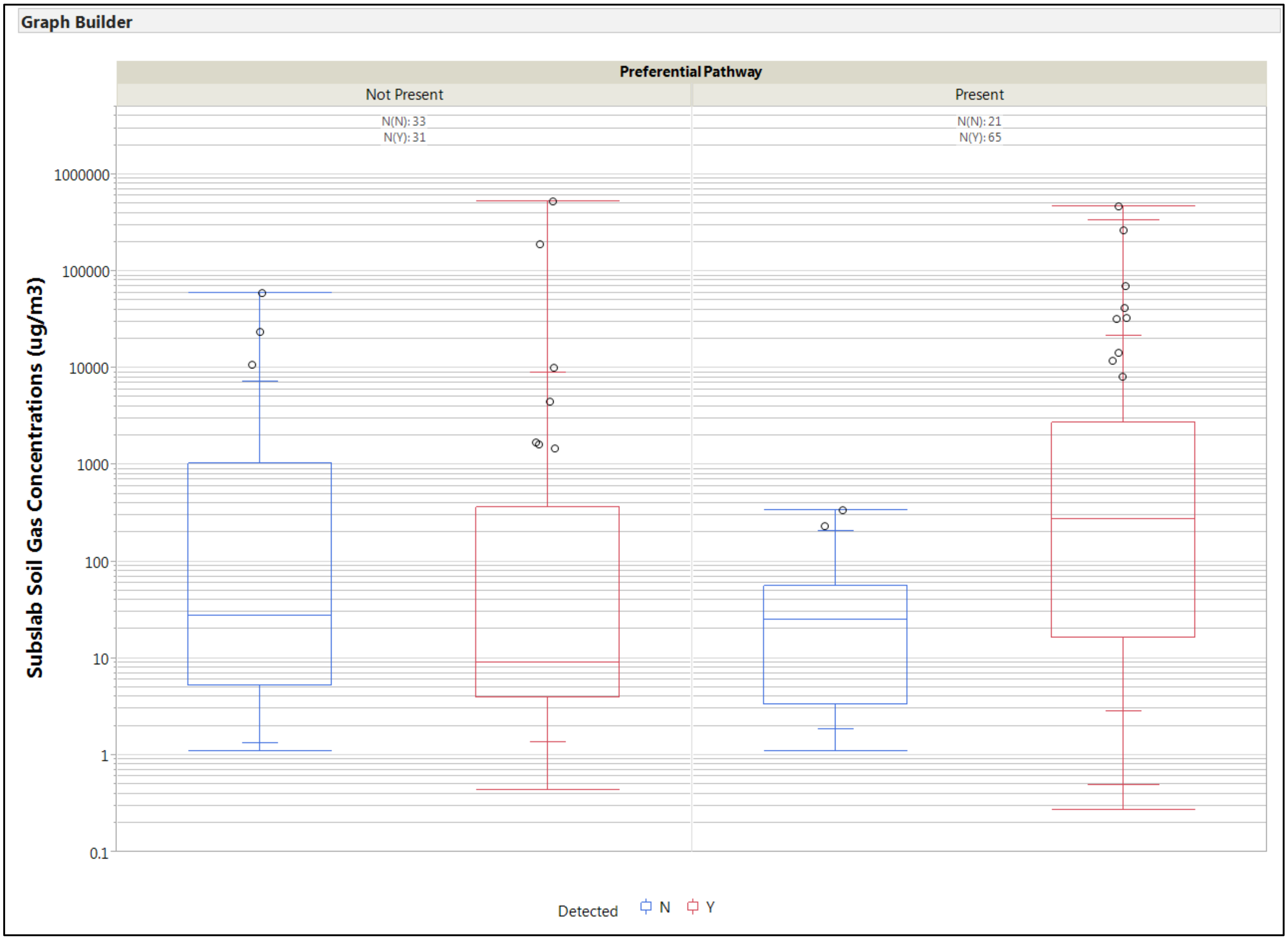


FIGURE E141
1,1,1-TCA Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)
NESDI Project #476

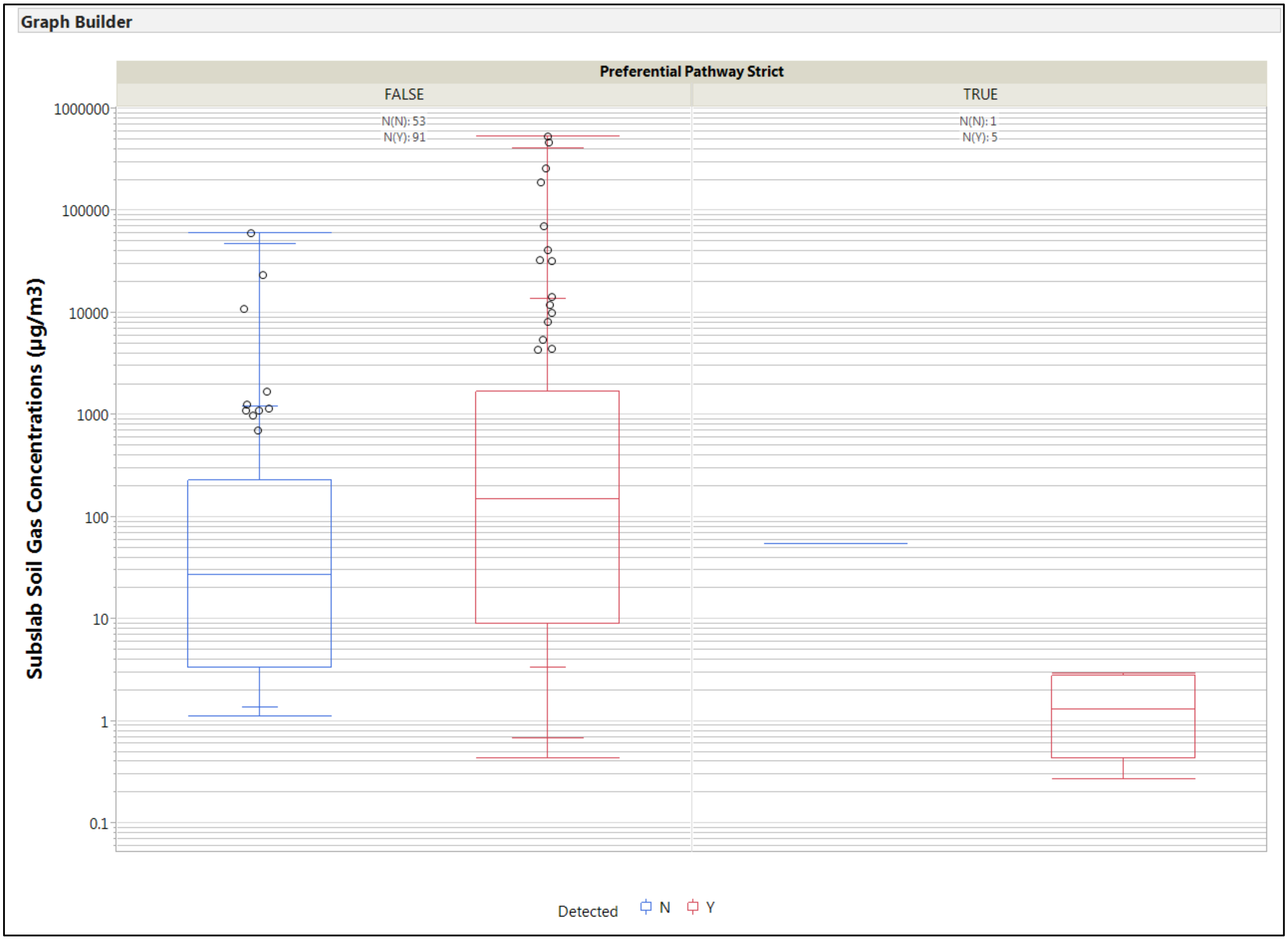


FIGURE E142
1,1,1-TCA Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)
NESDI Project #476

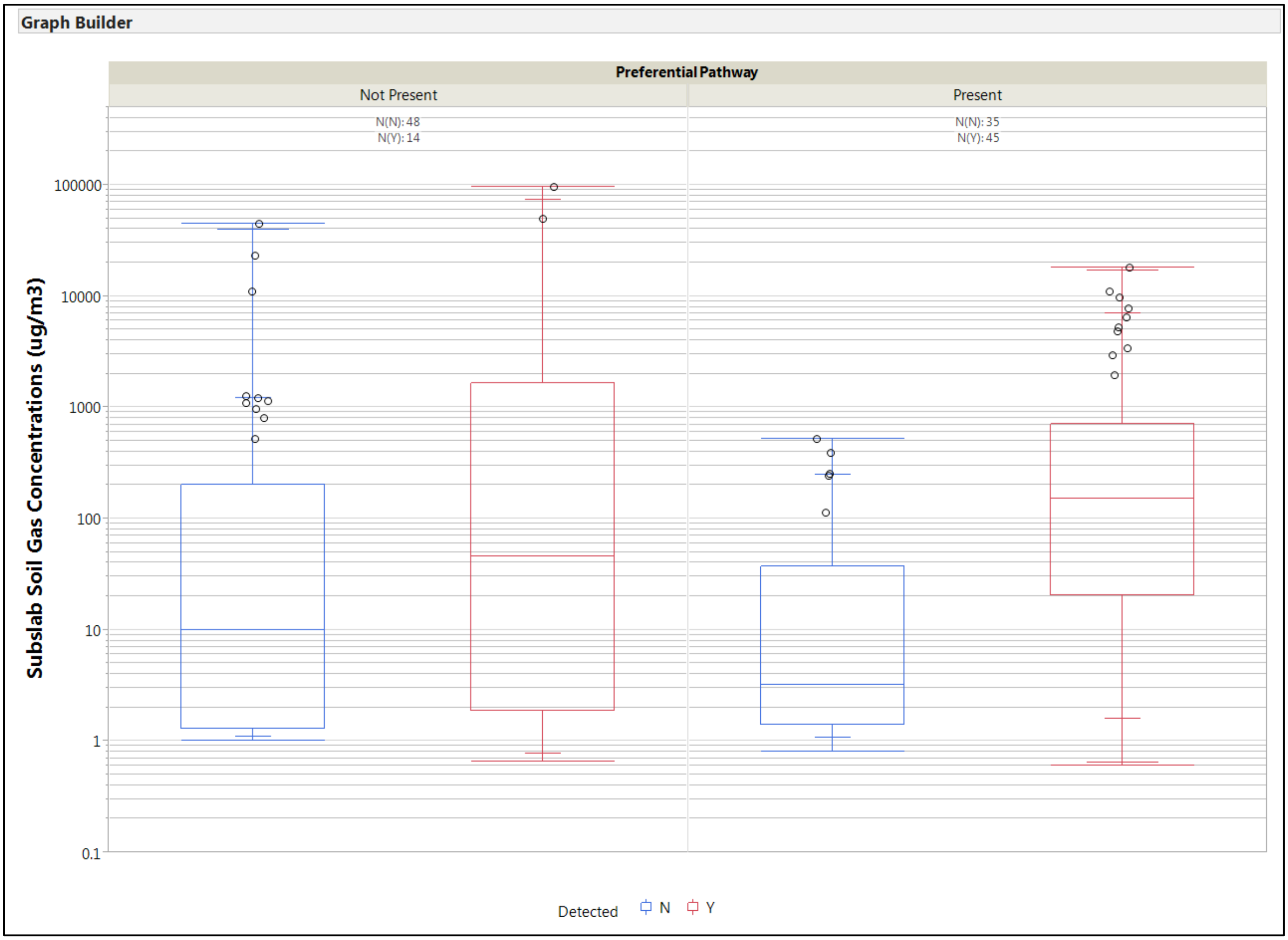


FIGURE E143

1,1-DCA Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)

NESDI Project #476

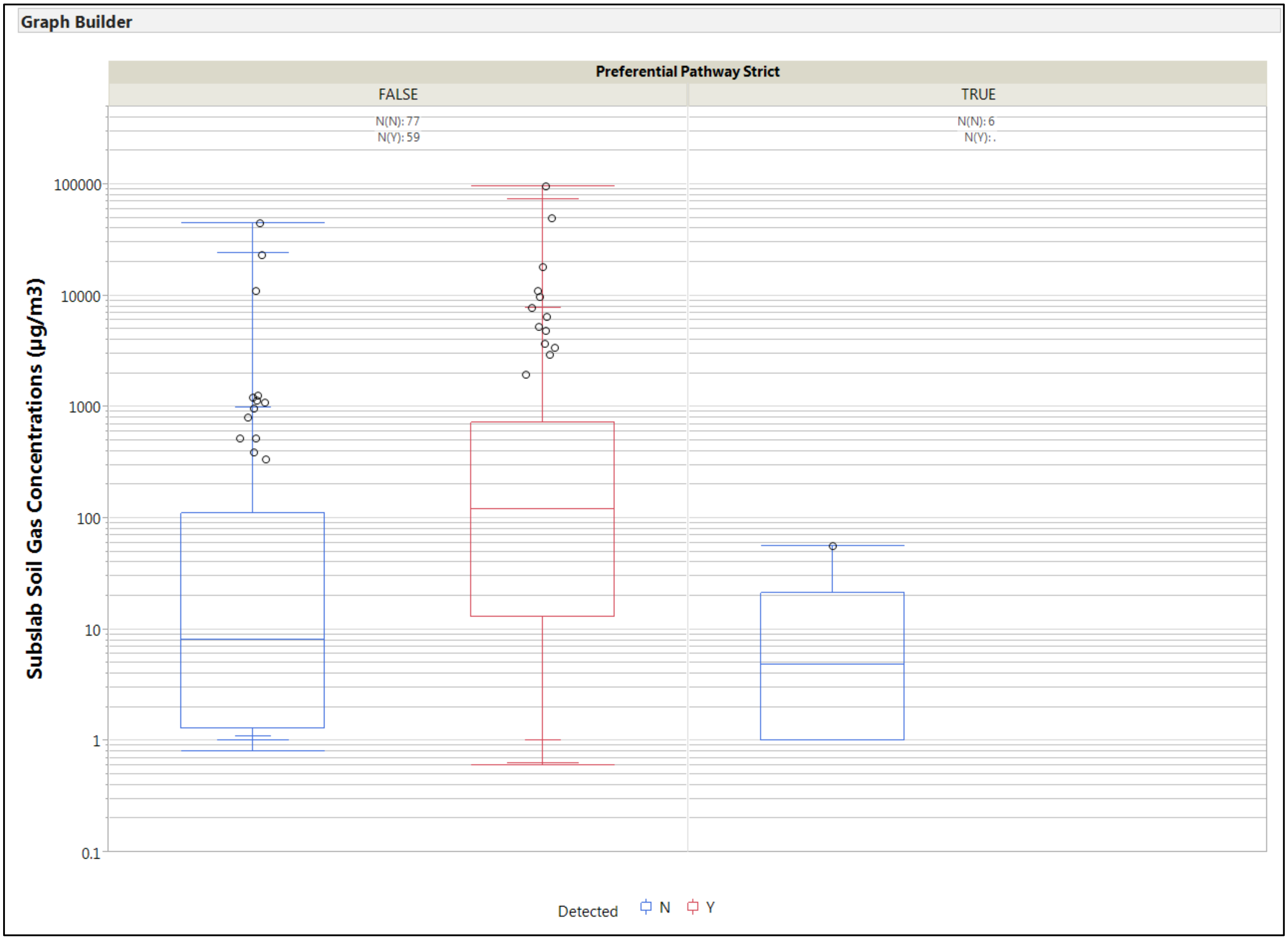


FIGURE E144

1,1,-DCA Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)

NESDI Project #476

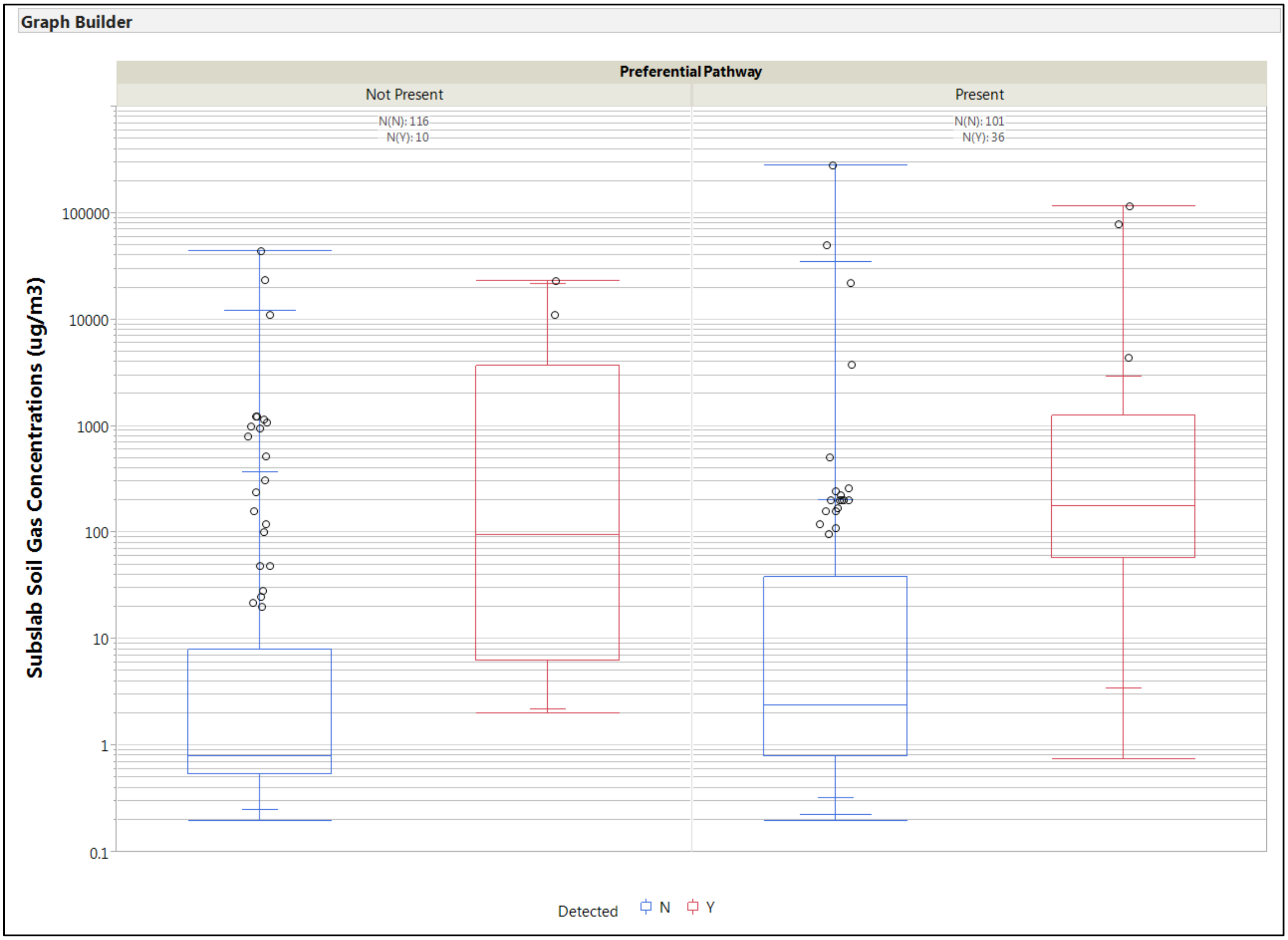


FIGURE E145
1,1-DCE Sub-slab Soil Gas Concentration by Preferential Pathway (Original Definition)
NESDI Project #476

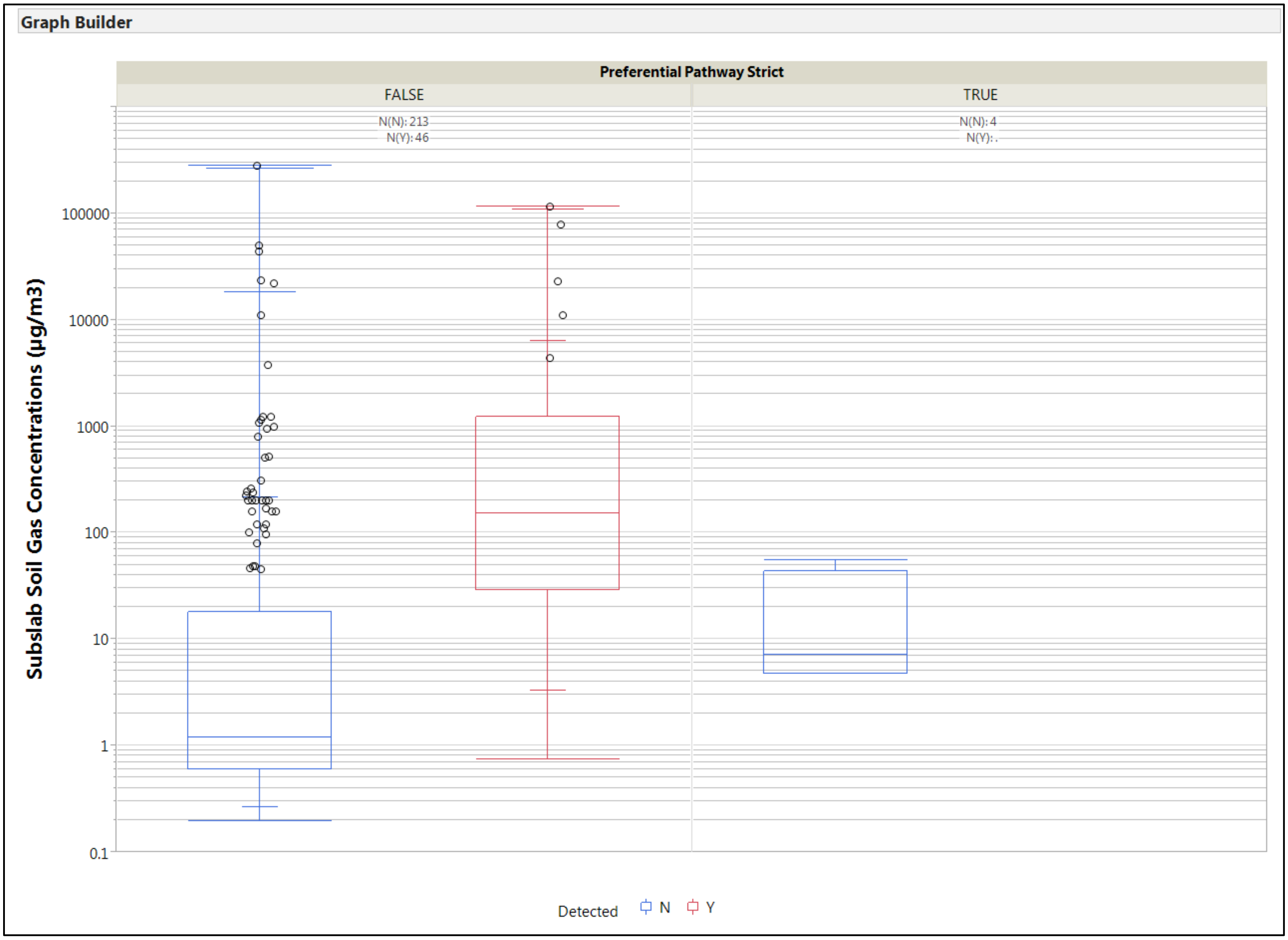


FIGURE E146
1,1-DCE Sub-slab Soil Gas Concentration by Preferential Pathway (Strict Definition)
NESDI Project #476

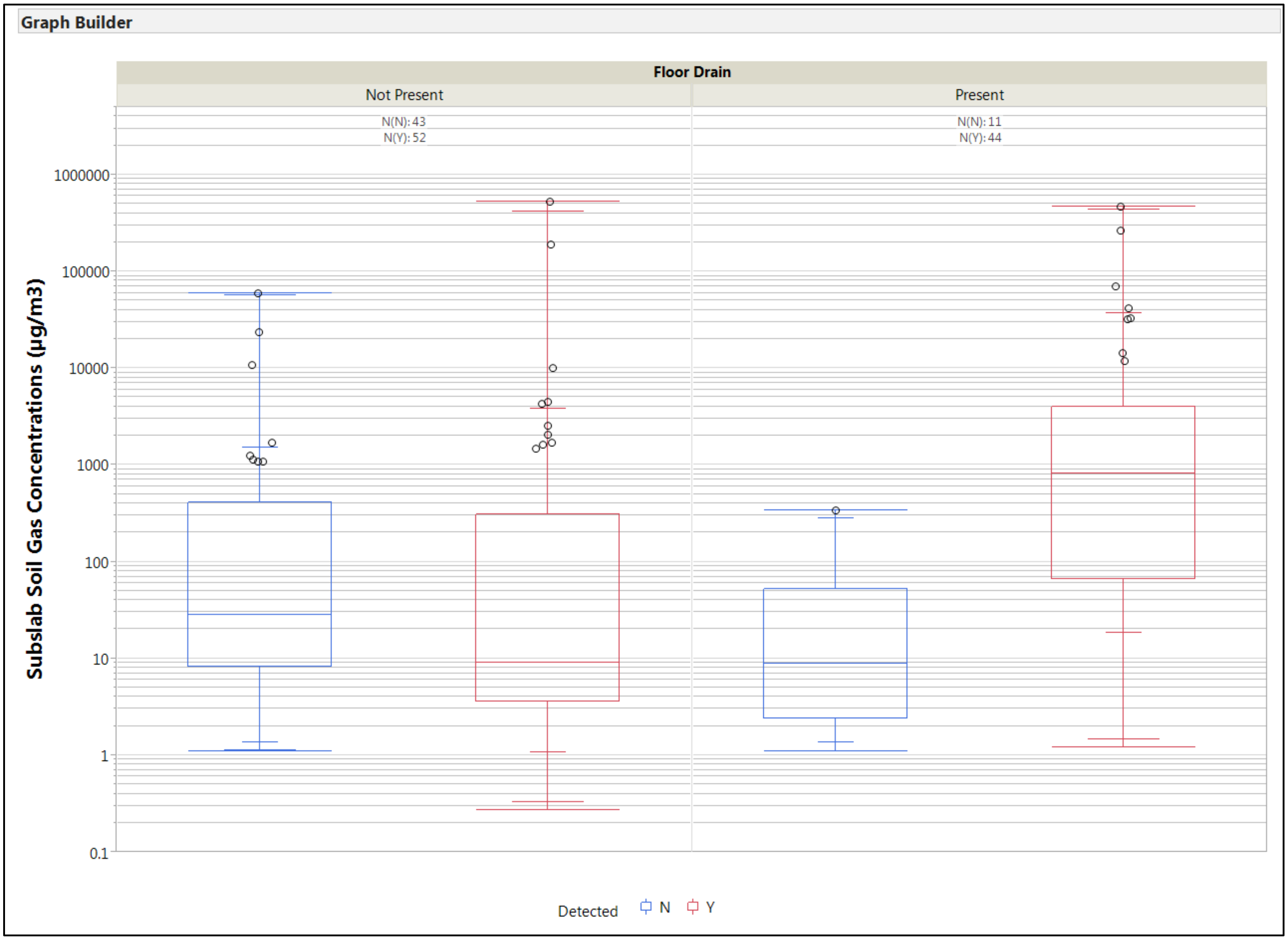


FIGURE E147
1,1,1-TCA Sub-slab Soil Gas Concentration by Floor Drain Presence
NESDI Project #476

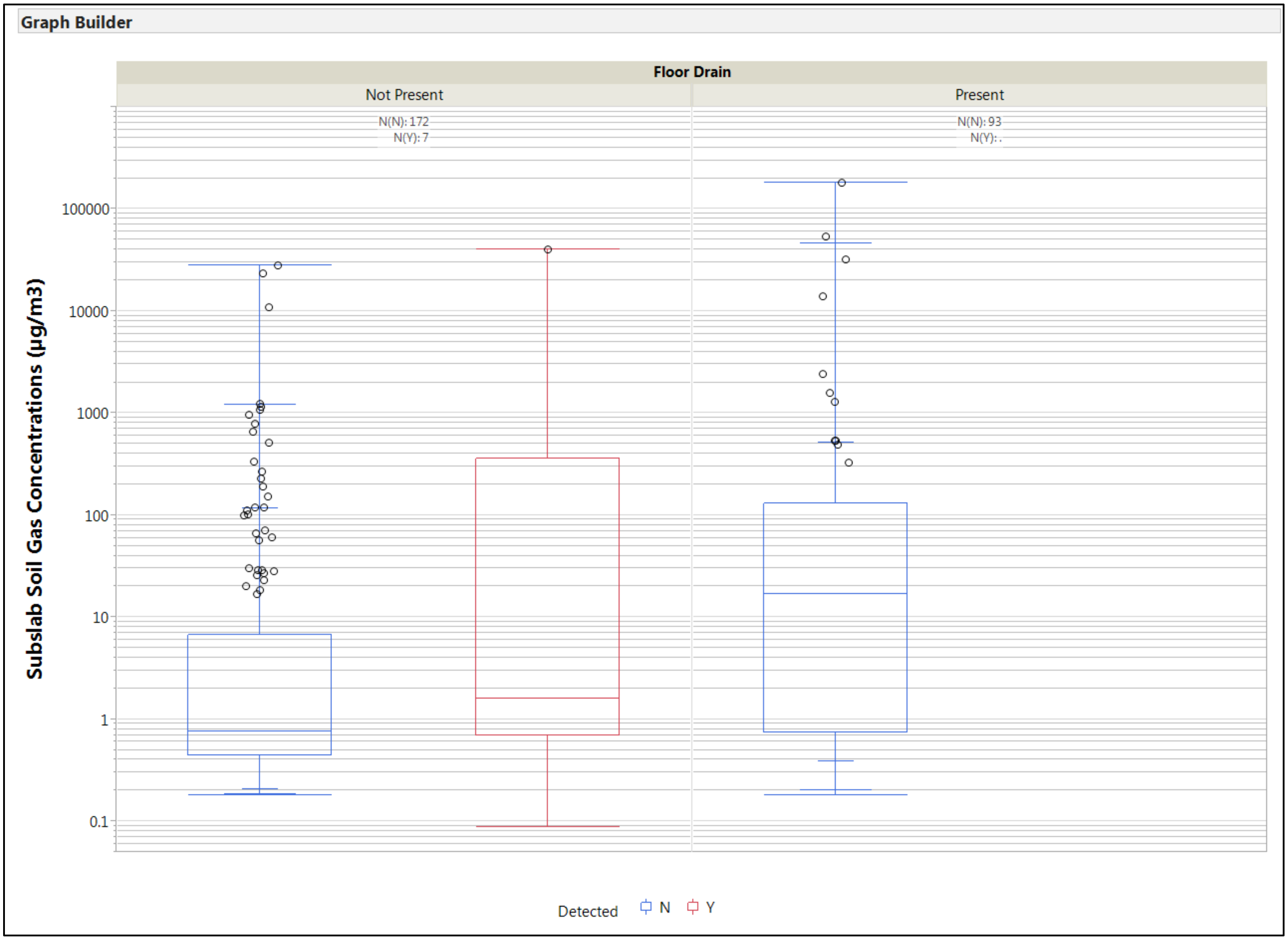


FIGURE E148
Vinyl Chloride Sub-slab Soil Gas Concentration by Floor Drain Presence
NESDI Project #476

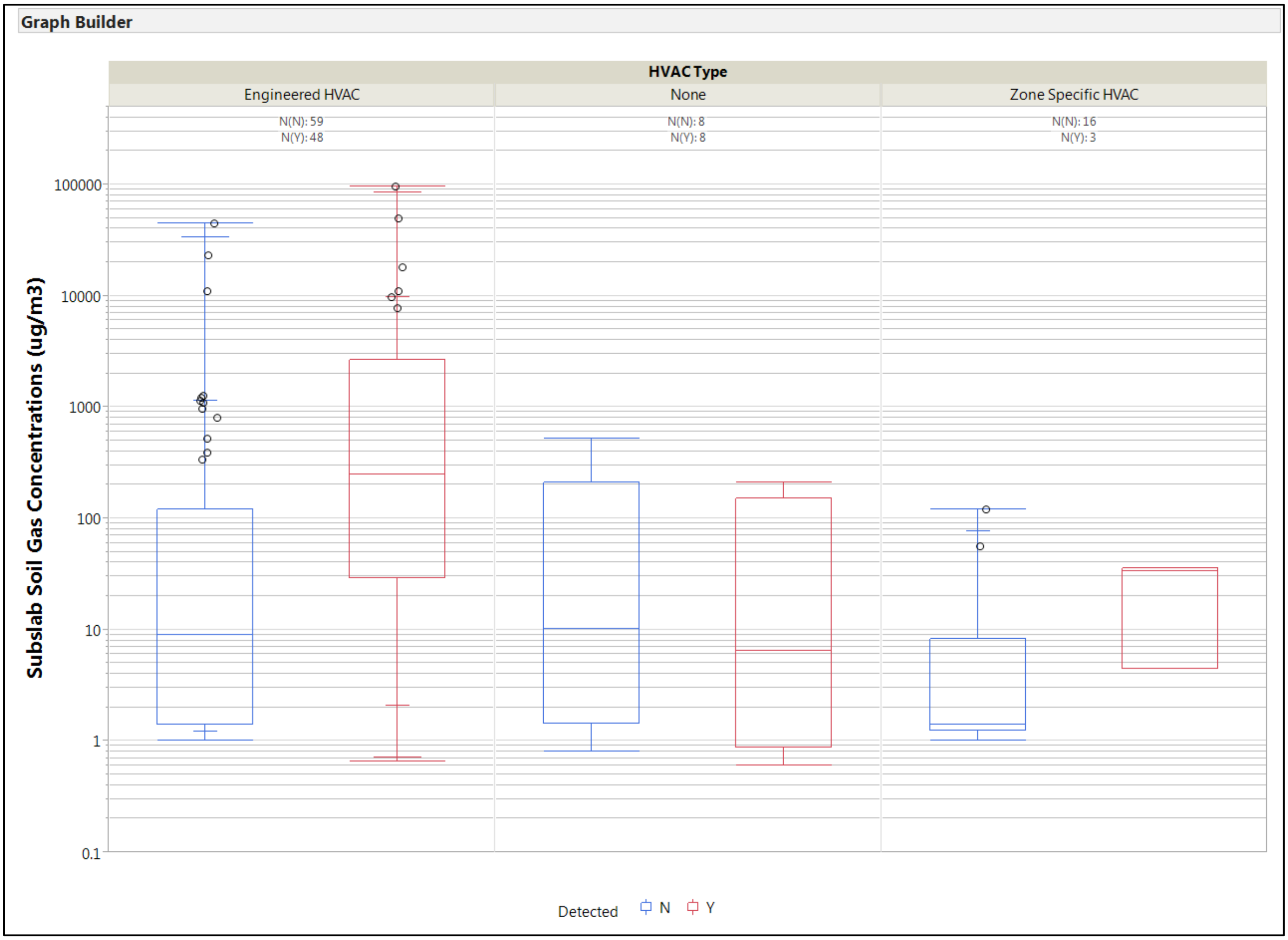


FIGURE E149
1,1-DCA Sub-slab Soil Gas Concentration by HVAC Type
NESDI Project #476

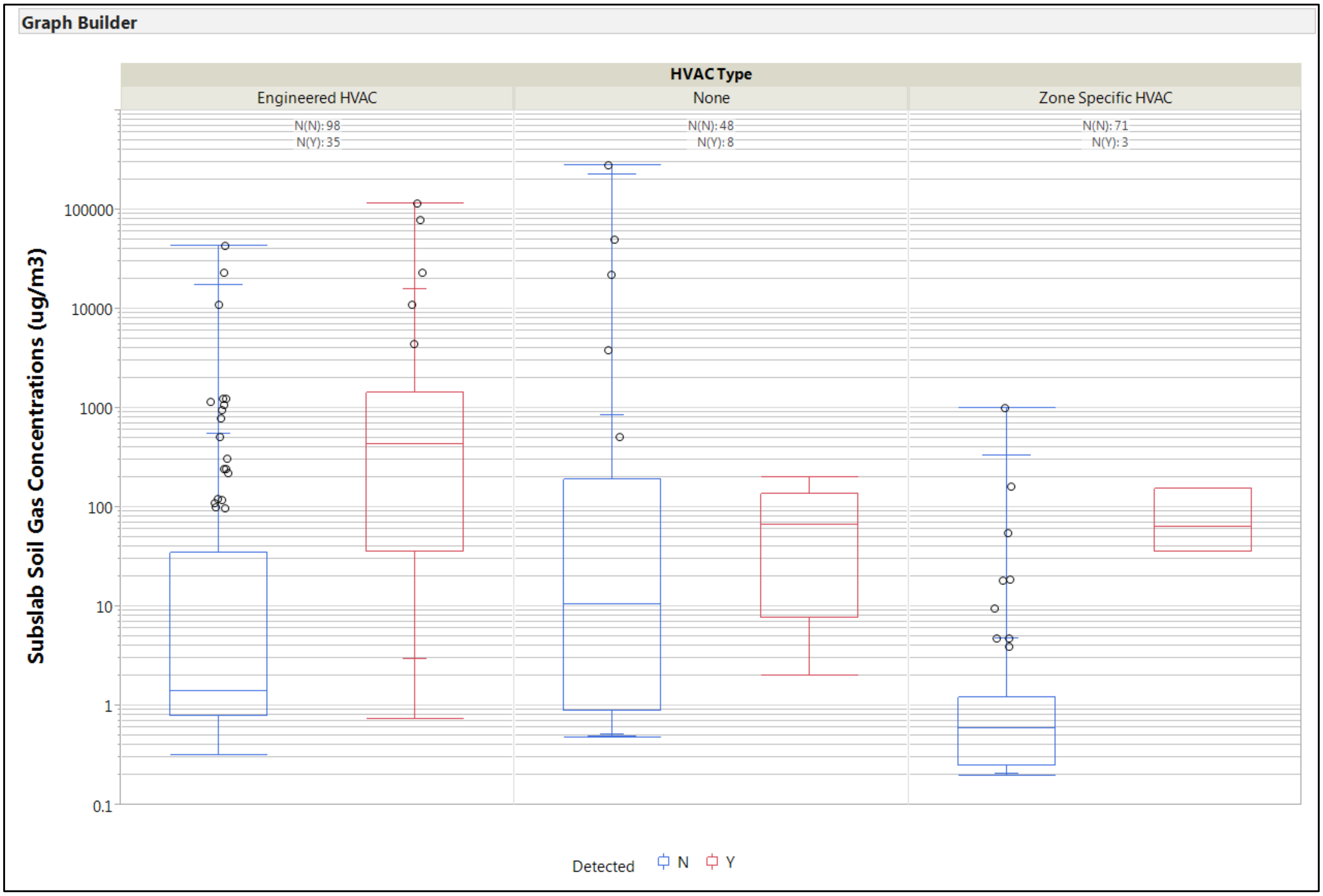


FIGURE E150

1,1-DCE Sub-slab Soil Gas Concentration by HVAC Type

NESDI Project #476

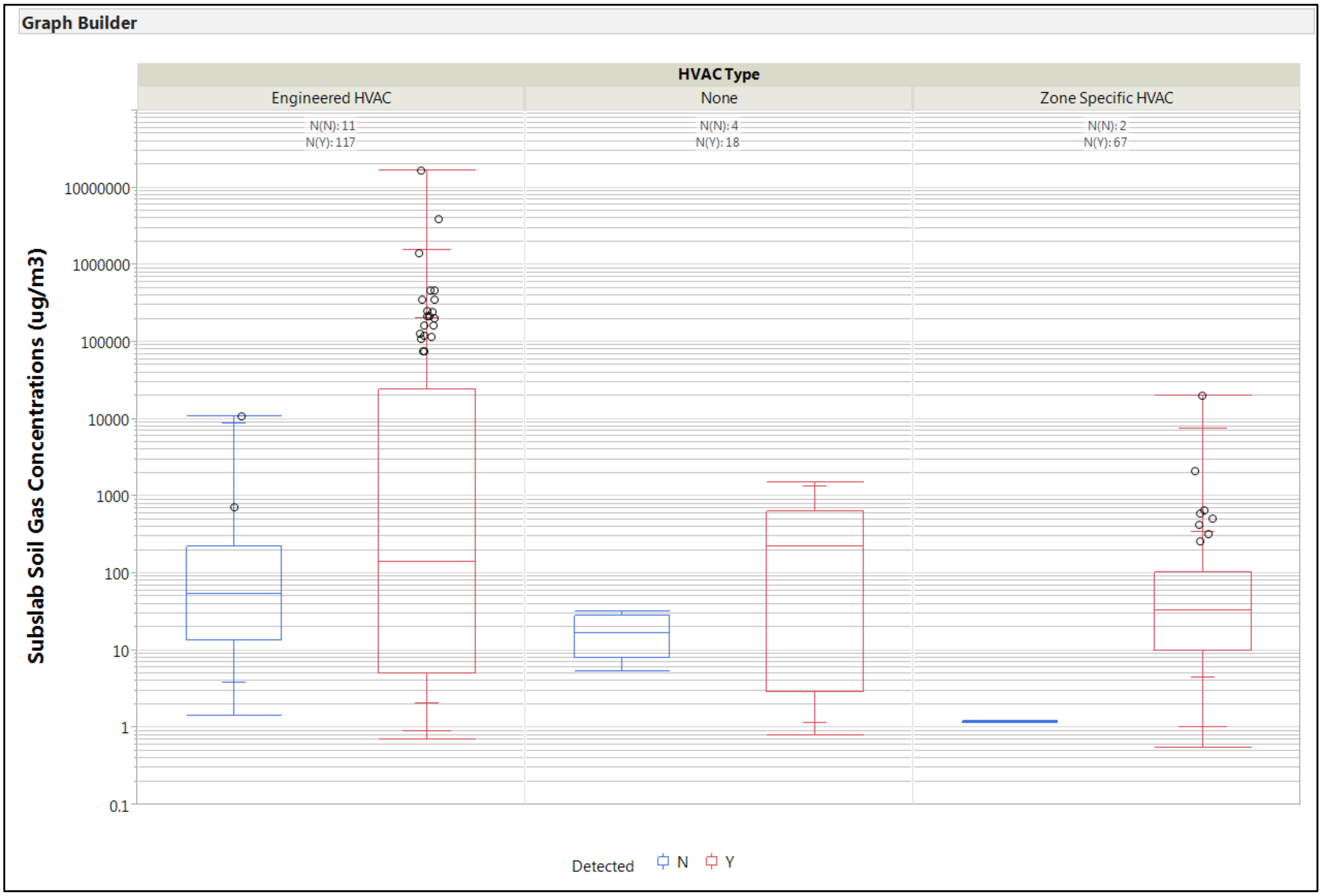


FIGURE E151
PCE Sub-slab Soil Gas Concentration by HVAC Type
NESDI Project #476

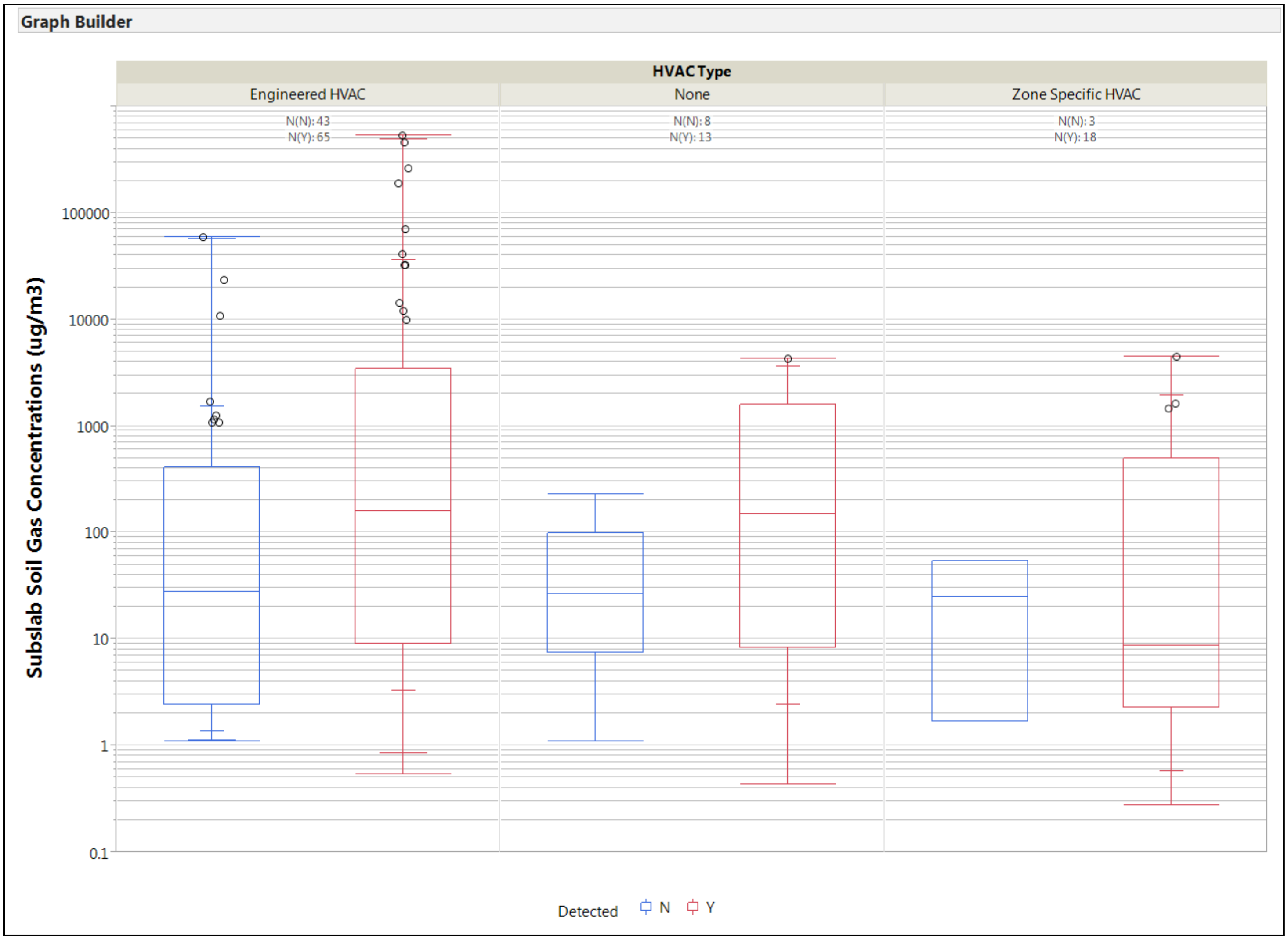


FIGURE E152
1,1,1-TCA Sub-slab Soil Gas Concentration by HVAC Type
NESDI Project #476

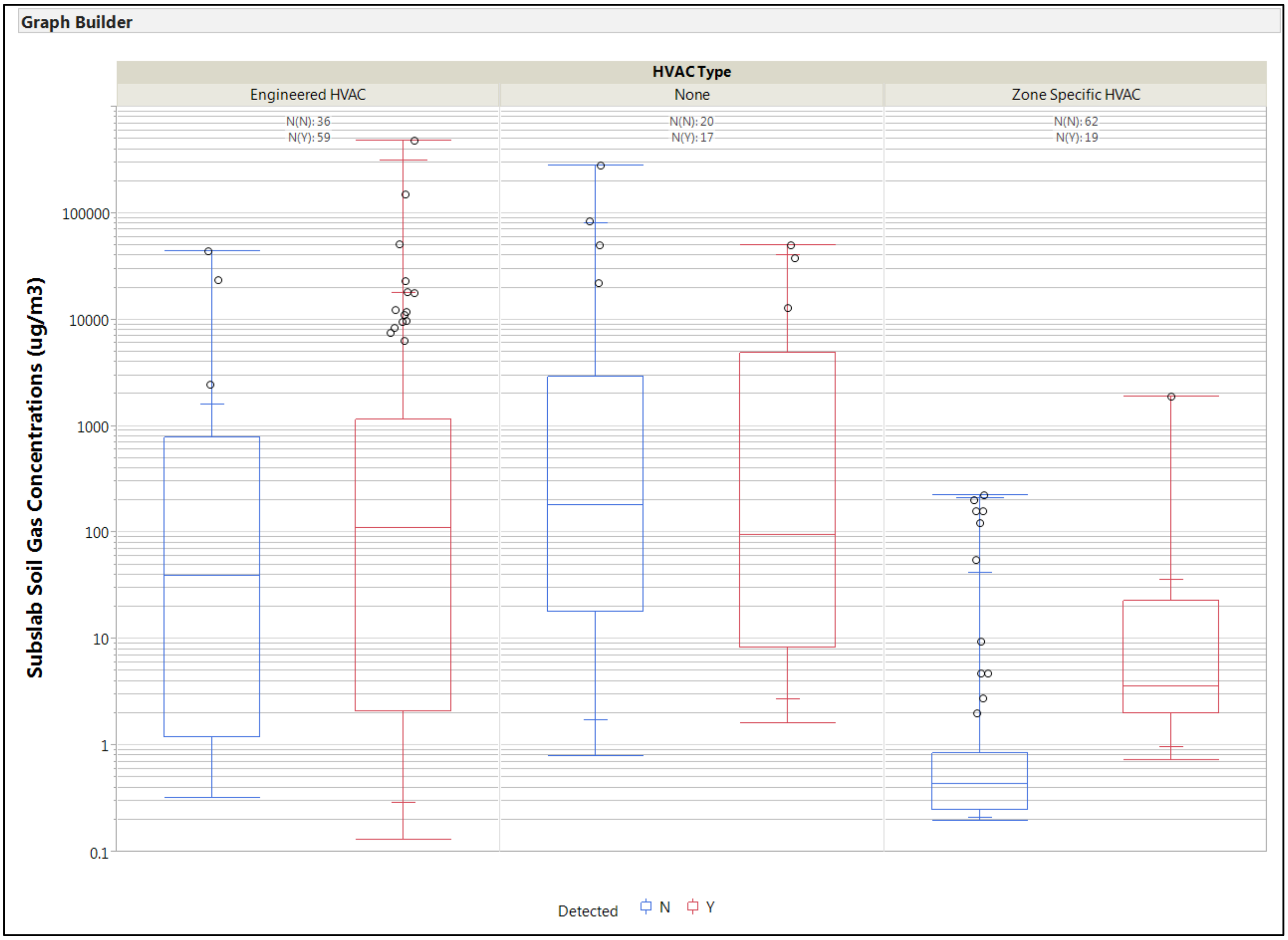


FIGURE E153

Cis-1,2-DCE Sub-Slab Soil Gas Concentration by HVAC Type

NESDI Project #476

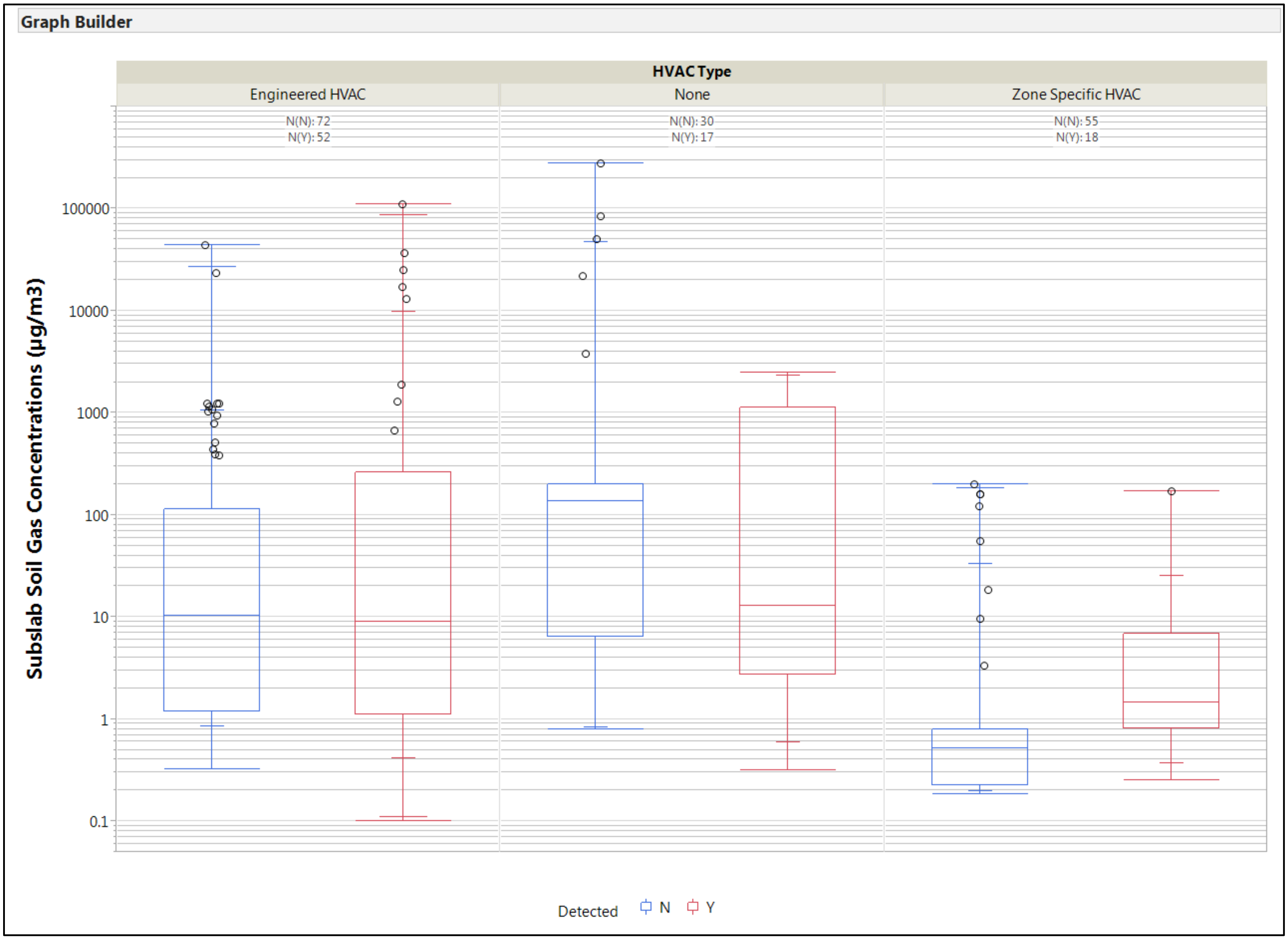


FIGURE E154

Trans-1,2-DCE Sub-slab Soil Gas Concentration by HVAC Type

NESDI Project #476

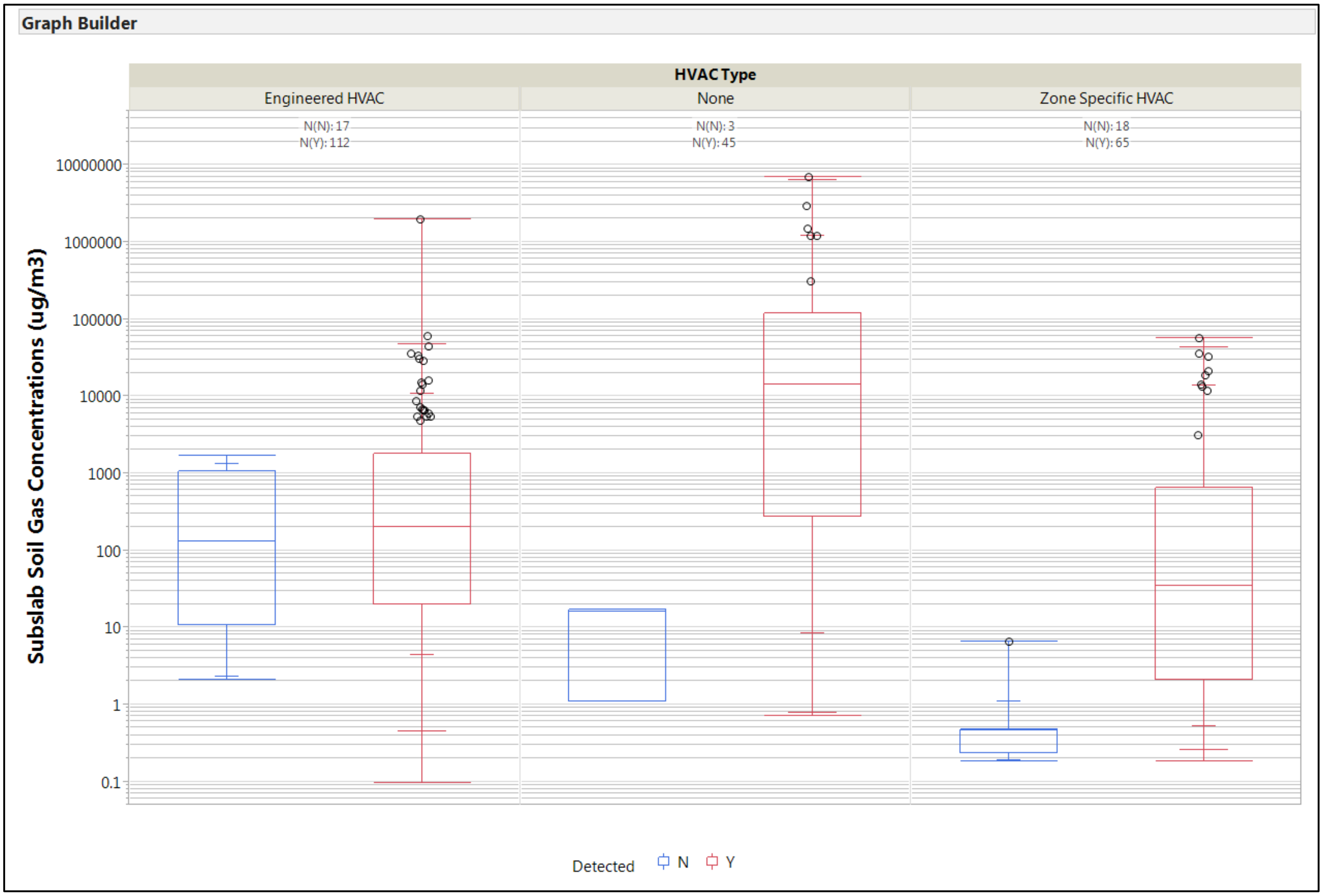


FIGURE E155
TCE Sub-slab Soil Gas Concentration by HVAC Type
NESDI Project #476

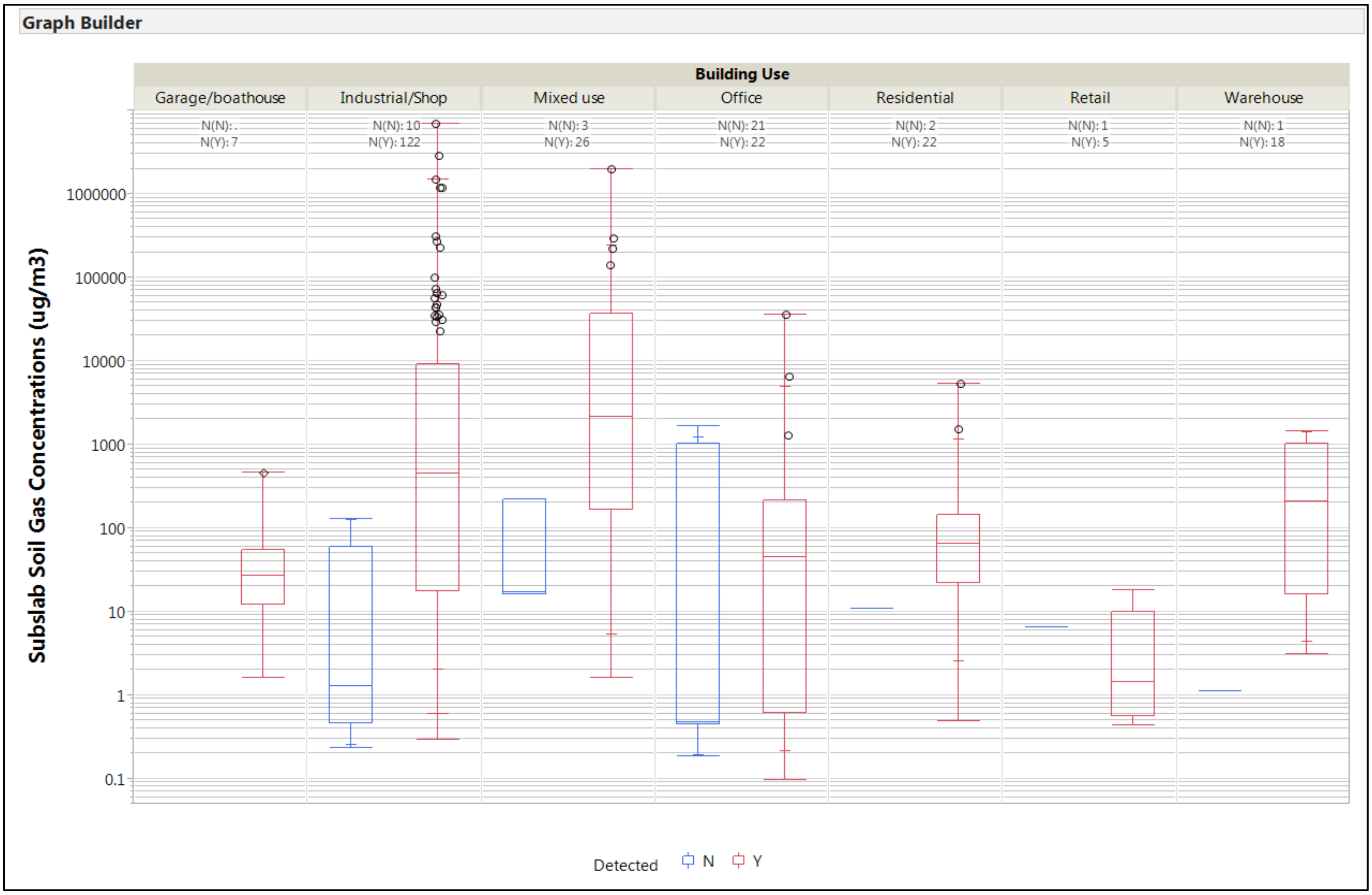


FIGURE E156
TCE Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

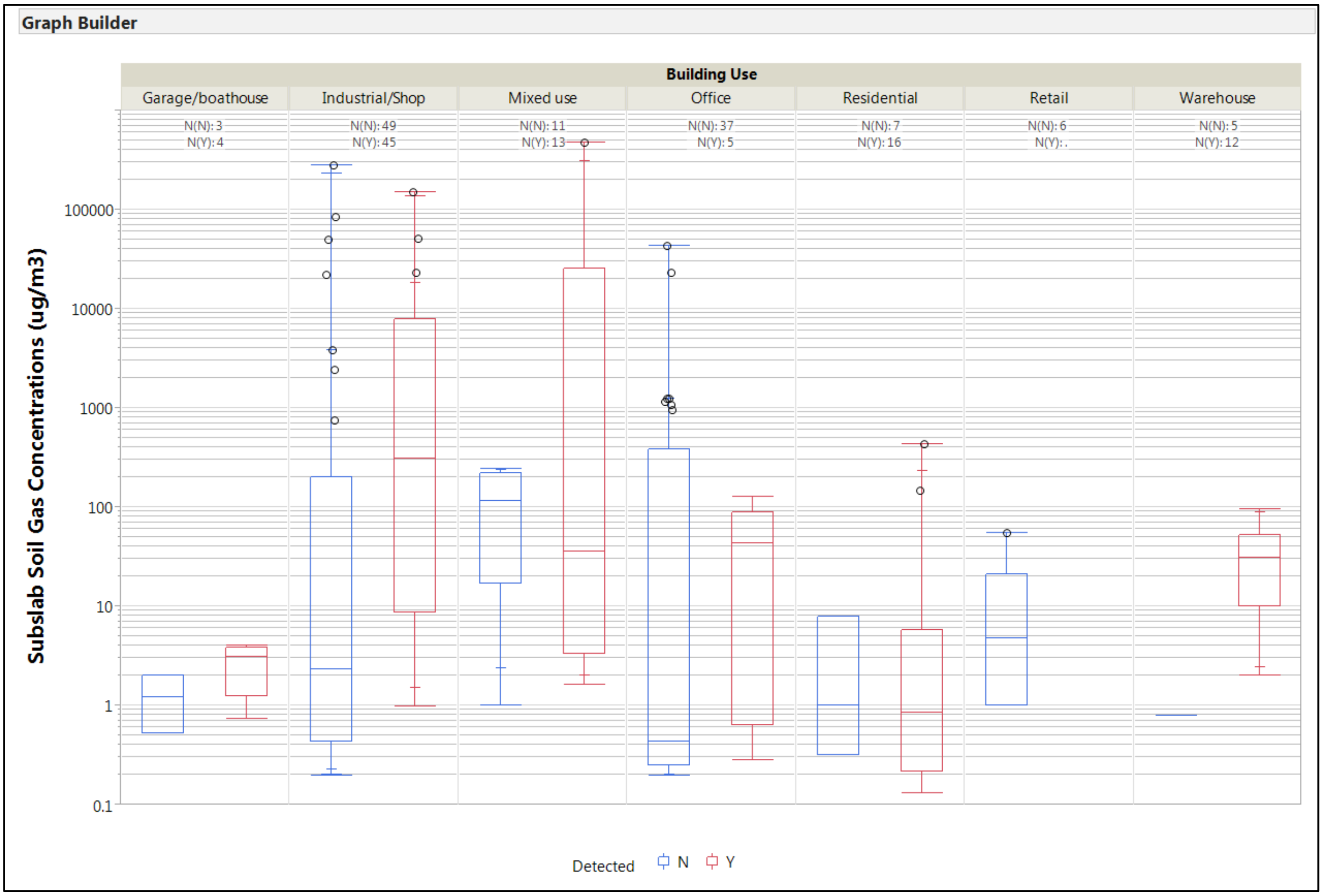


FIGURE E157
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

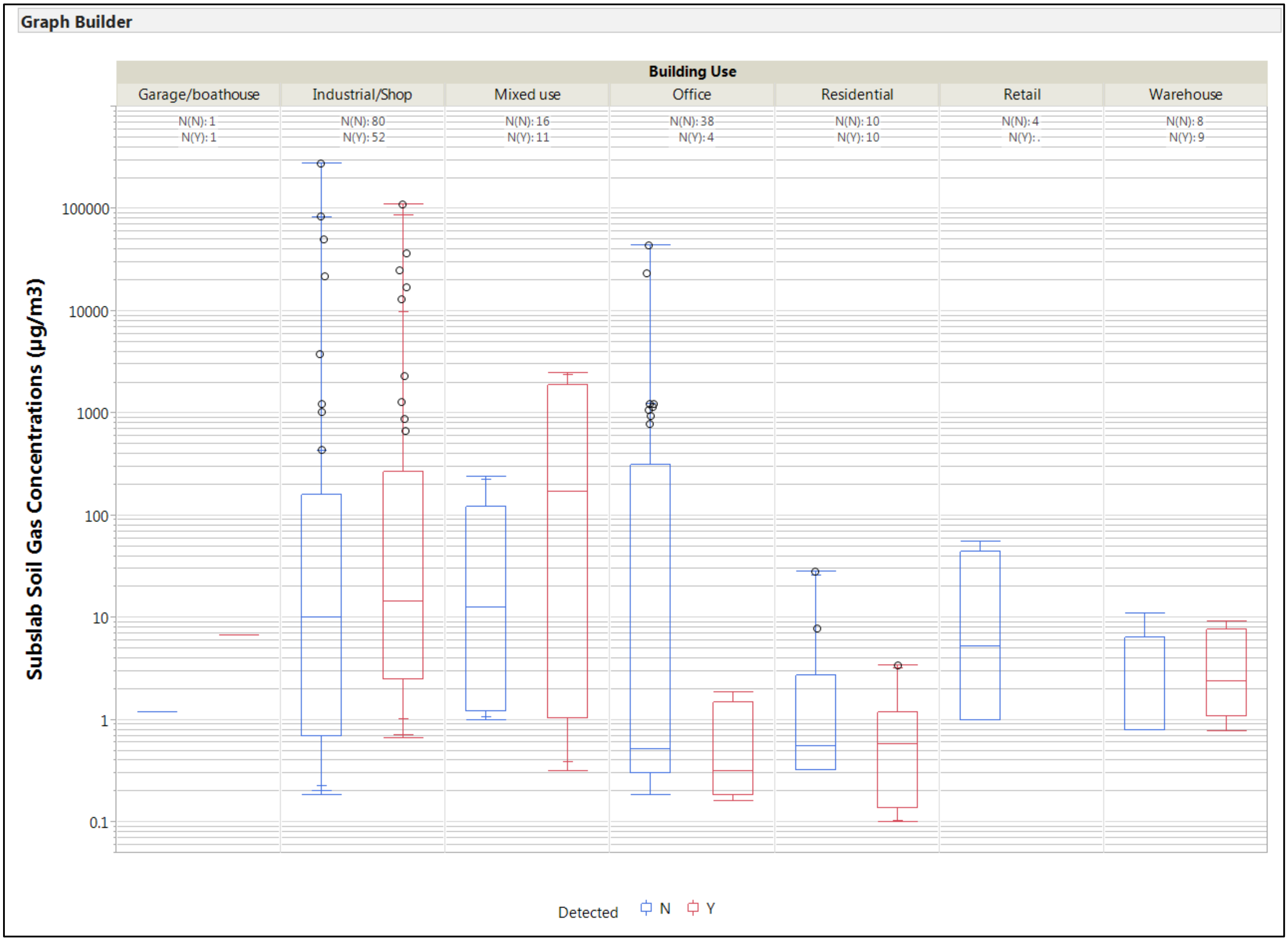


FIGURE E158
Trans-1,2-DCE Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

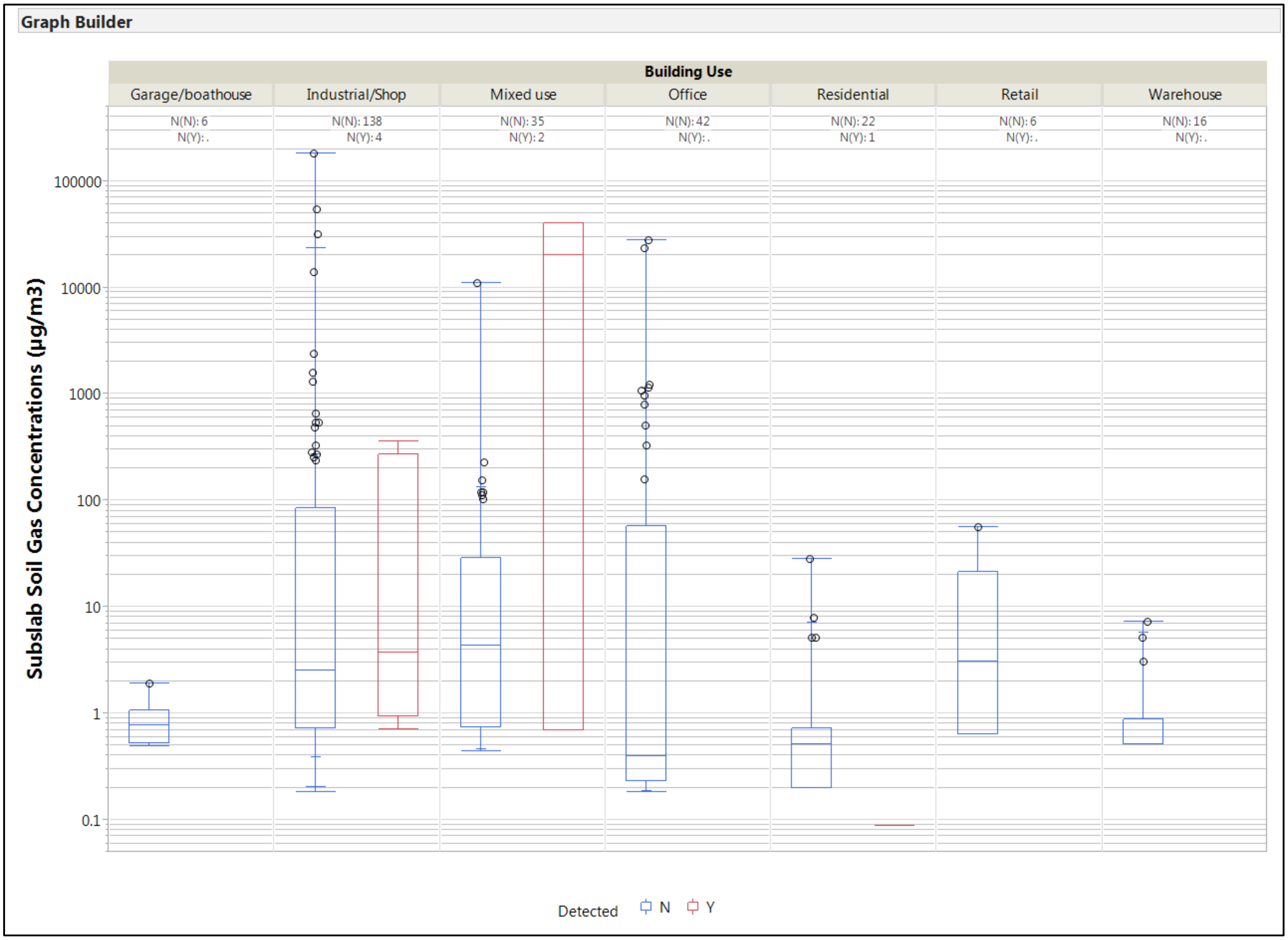


FIGURE E159
Vinyl Chloride Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

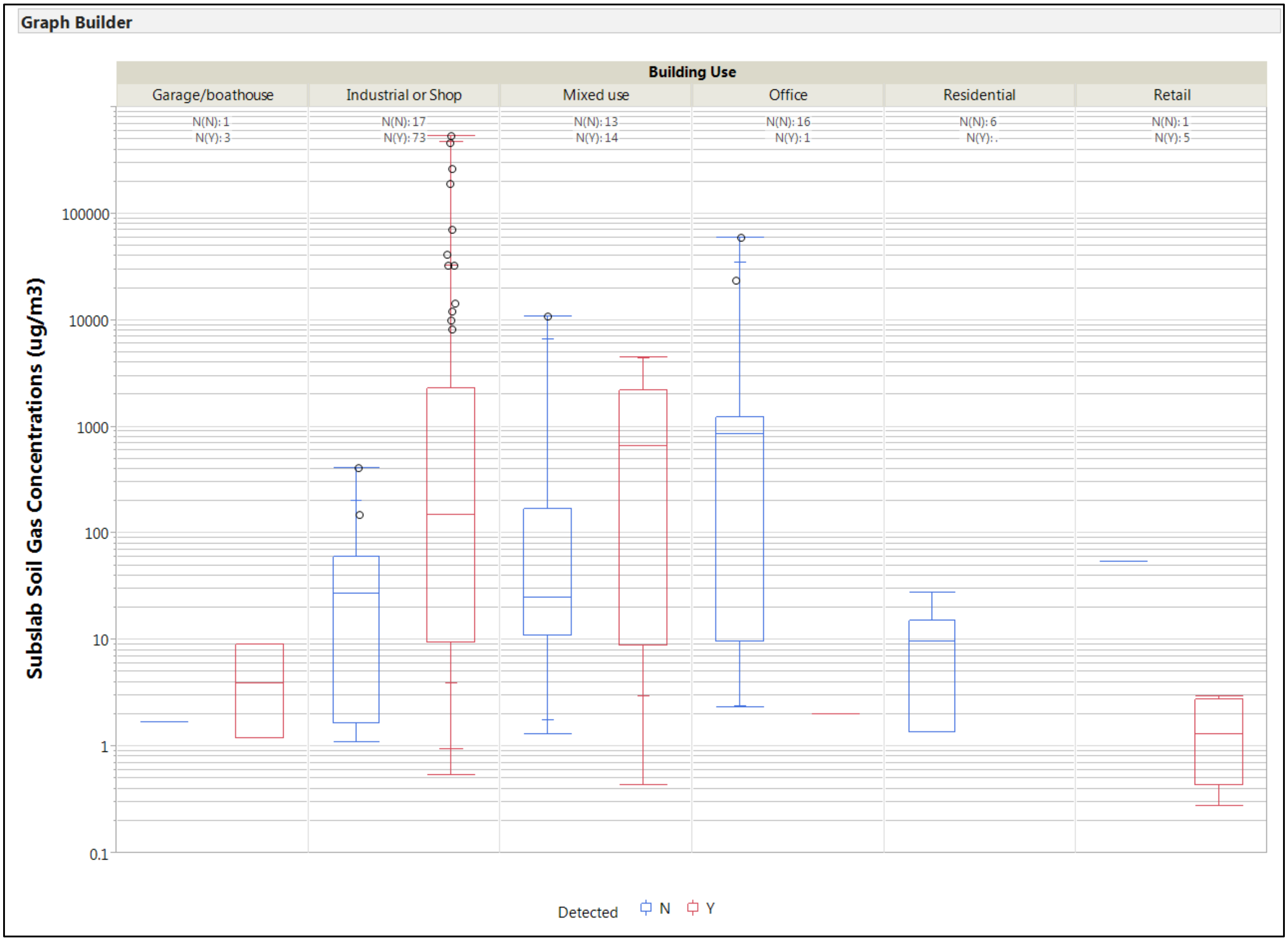


FIGURE E160
1,1,1-TCA Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

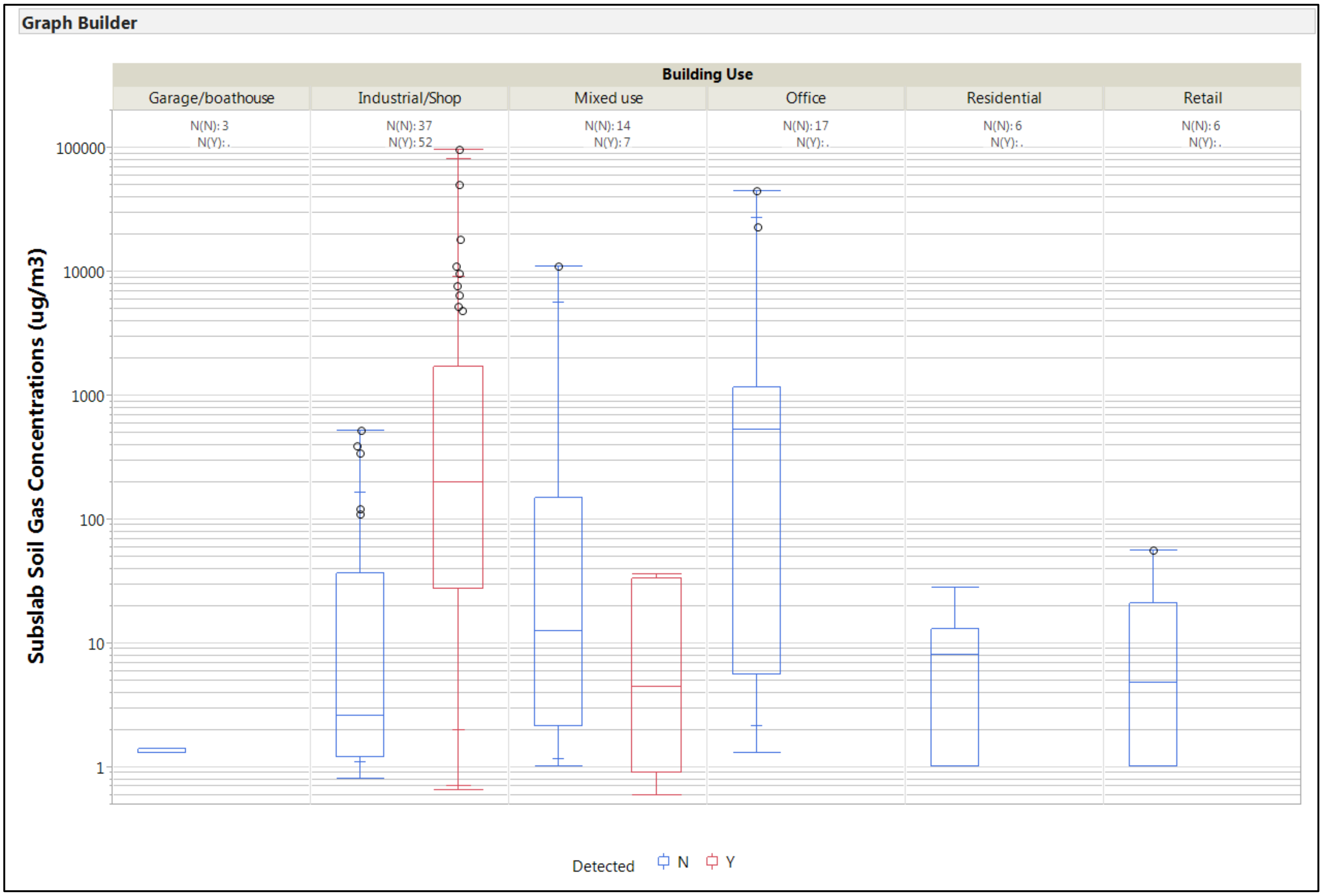


FIGURE E161
1,1-DCA Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

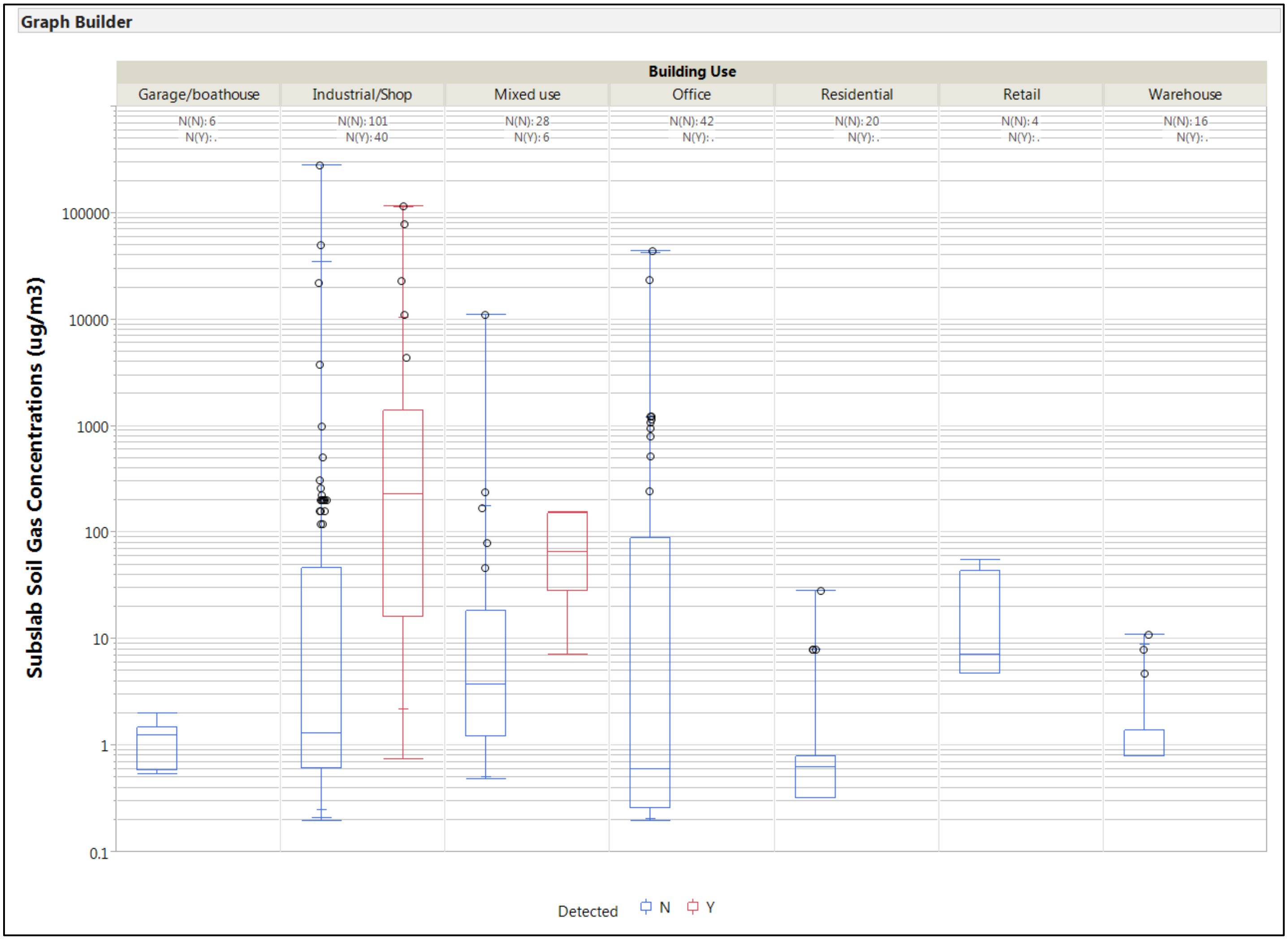


FIGURE E162

1,1-DCE Sub-slab Soil Gas Concentration by Building Use

NESDI Project #476

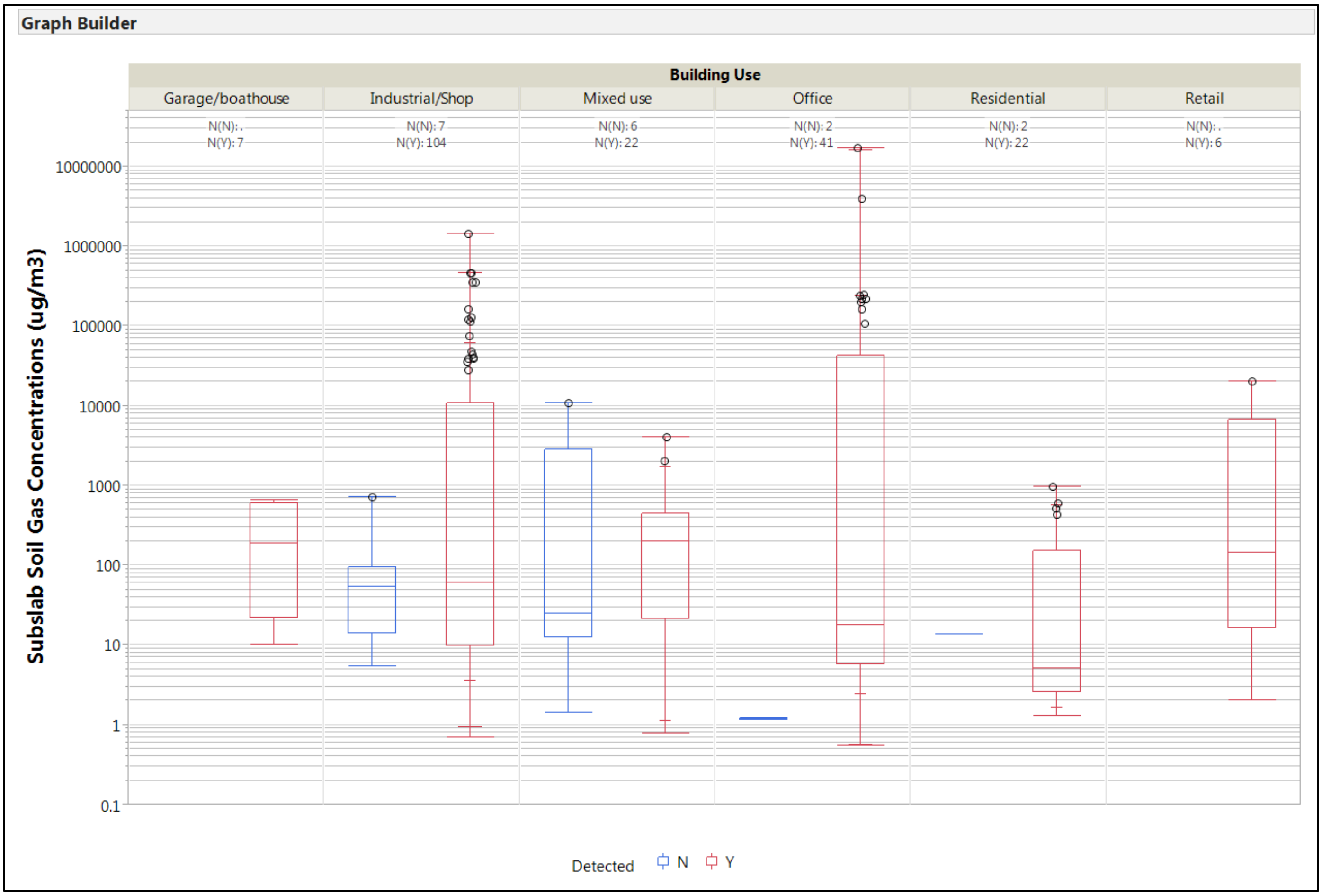


FIGURE E163
PCE Sub-slab Soil Gas Concentration by Building Use
NESDI Project #476

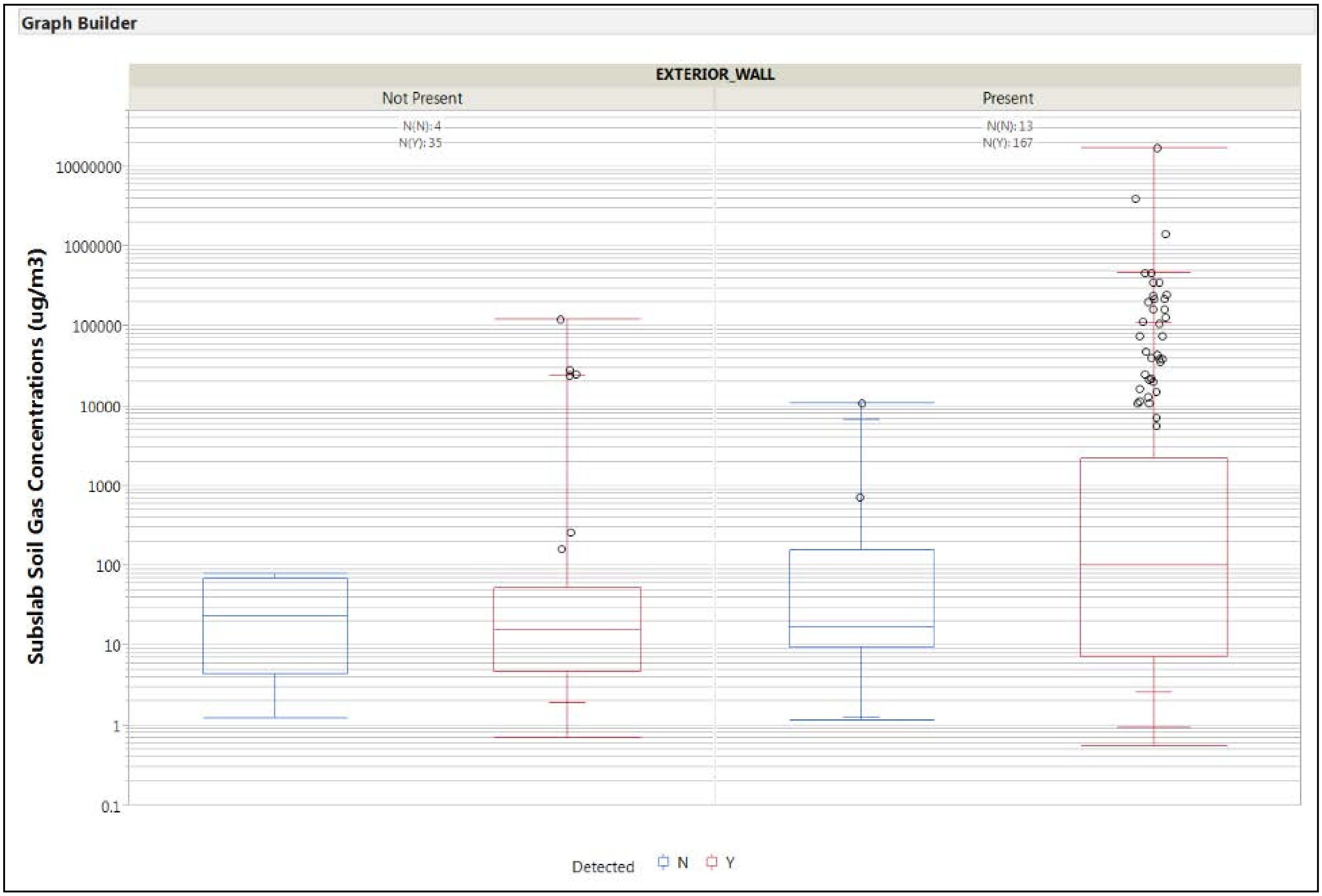


FIGURE E164

PCE Sub-slab Soil Gas Concentration by Exterior Wall Presence

NESDI Project #476

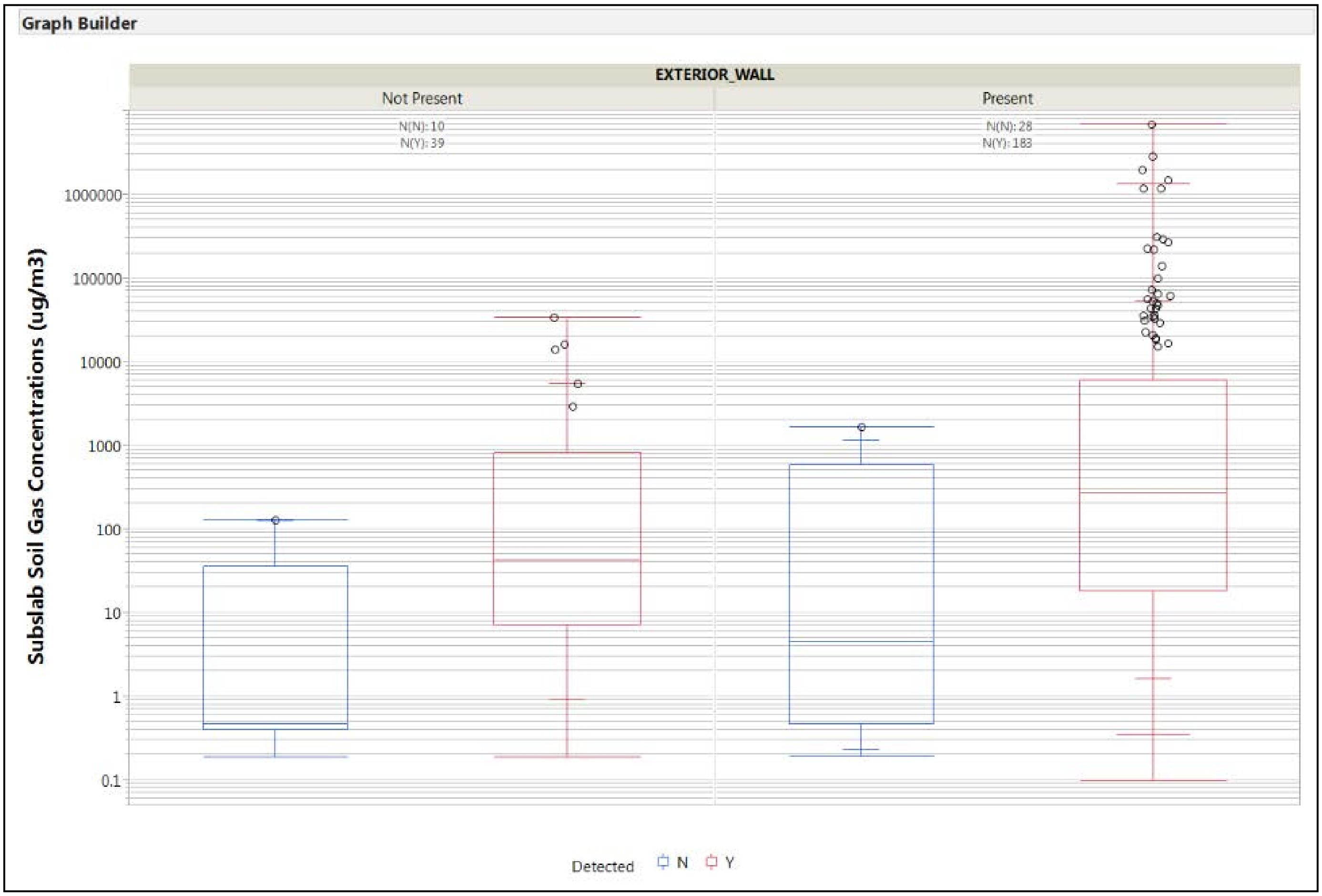


FIGURE E165

TCE Sub-slab Soil Gas Concentration by Exterior Wall Presence

NESDI Project #476

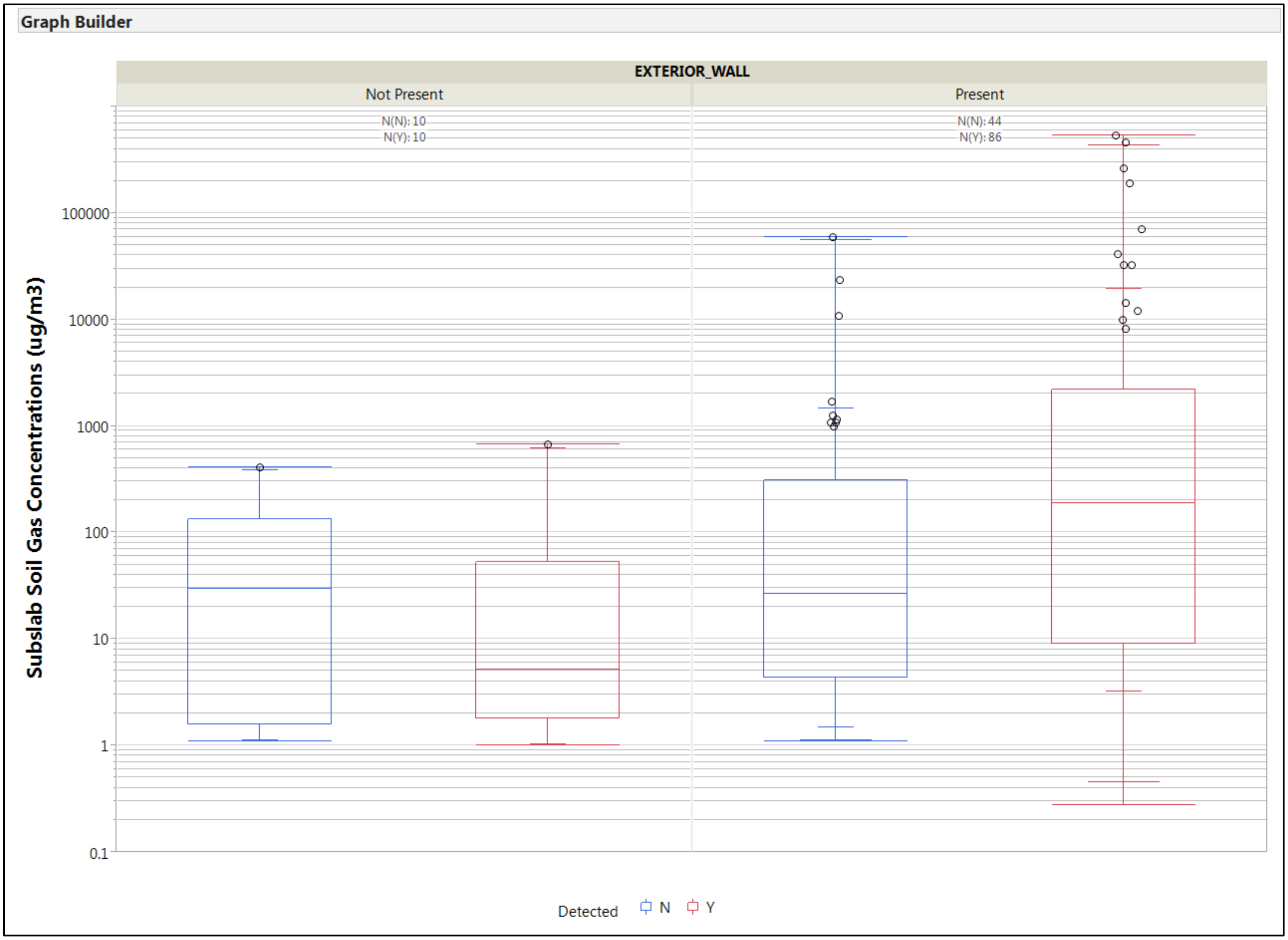


FIGURE E166

1,1,1-TCA Sub-slab Soil Gas Concentration by Exterior Wall Presence

NESDI Project #476

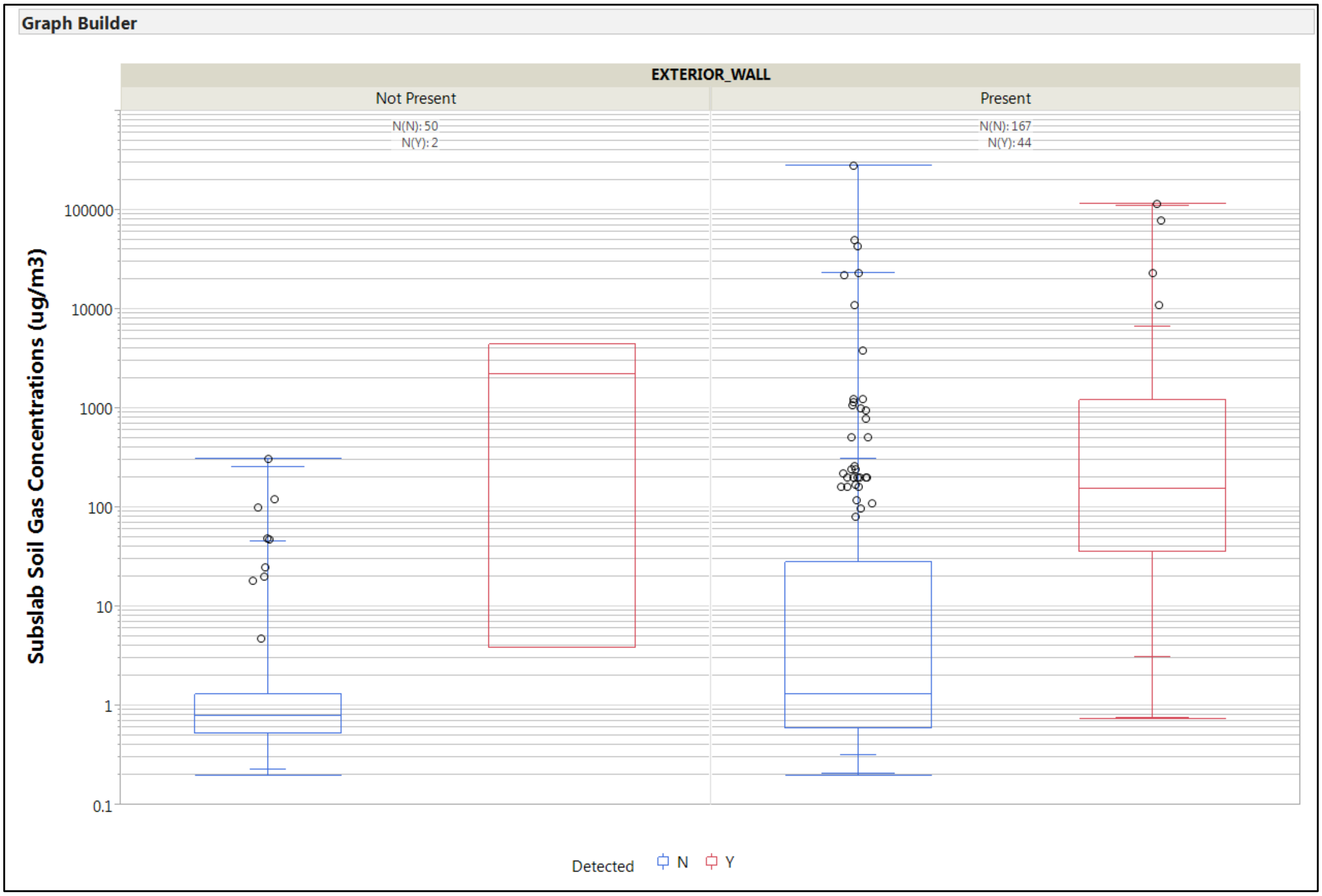


FIGURE E167

1,1-DCE Sub-slab Soil Gas Concentration by Exterior Wall Presence

NESDI Project #476

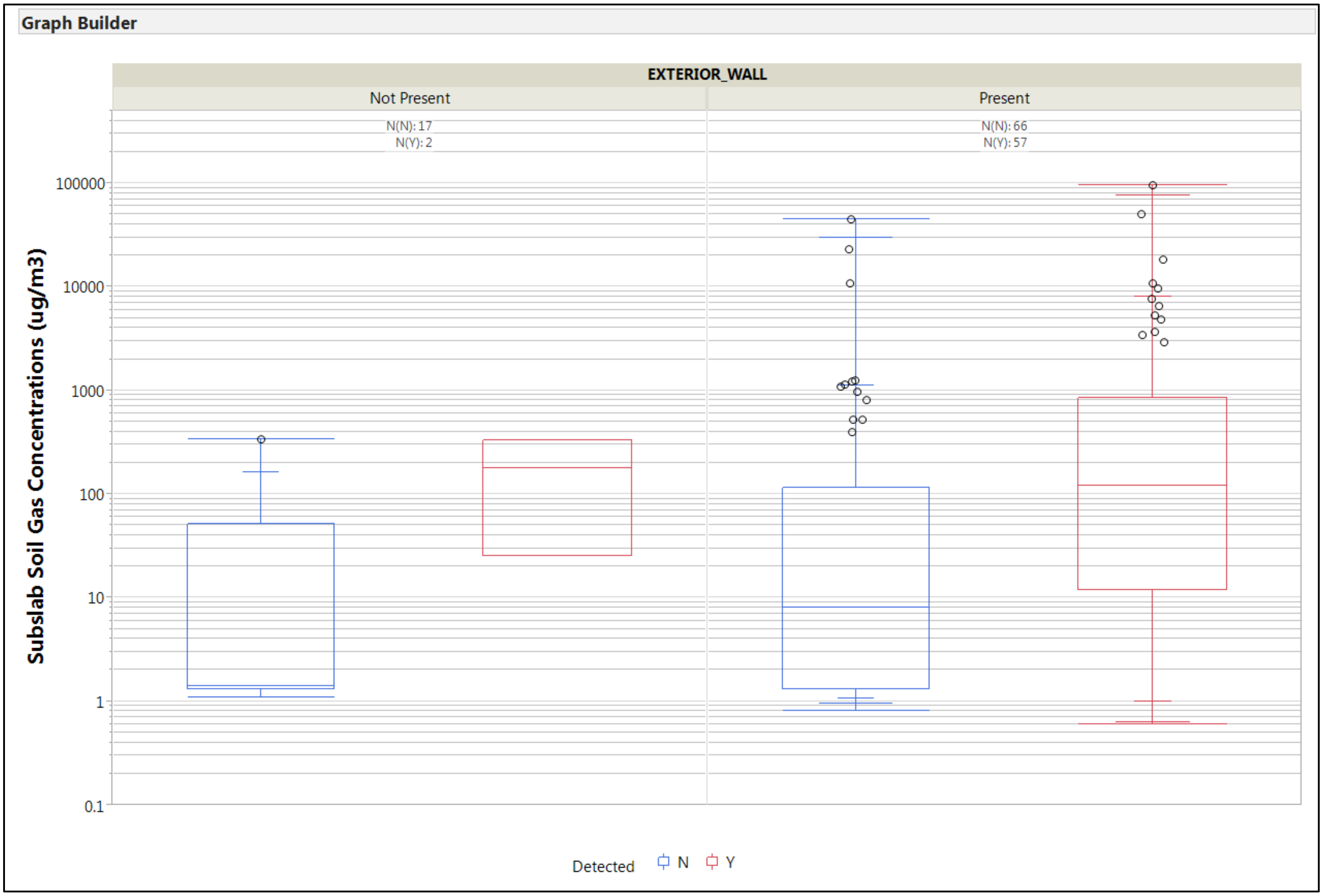


FIGURE E168
1,1,-DCA Sub-slab Soil Gas Concentration by Exterior Wall Presence
NESDI Project #476

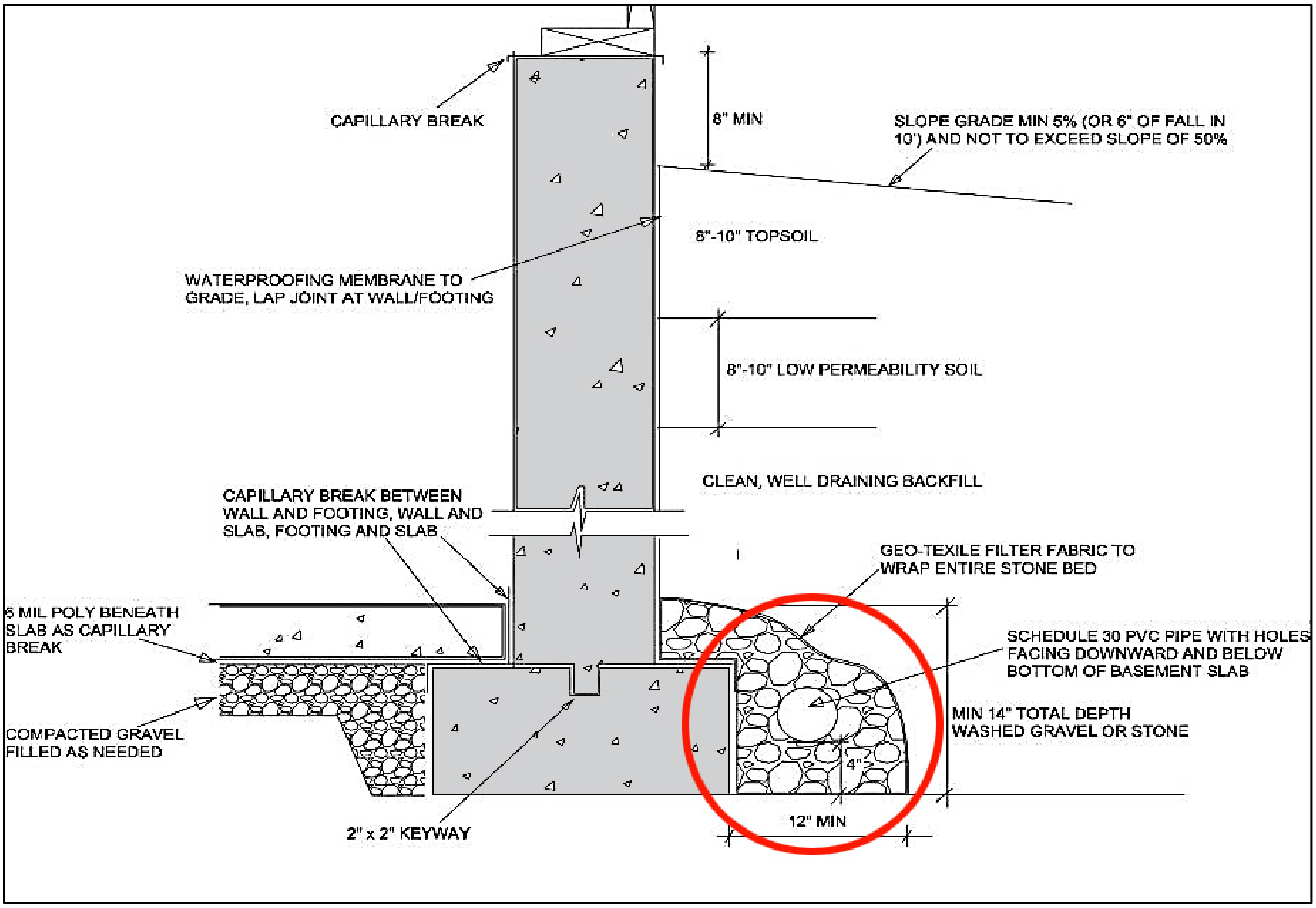


FIGURE E169

Typical Cross-section of Foundation at Exterior Wall, Illustrating Gravel Layer Shape and Capillary Break Between Wall and Footing. Figure from https://basc.pnnl.gov/sites/default/files/images/Drain%20Tile%20Cross-Section.jpg

NESDI Project #476

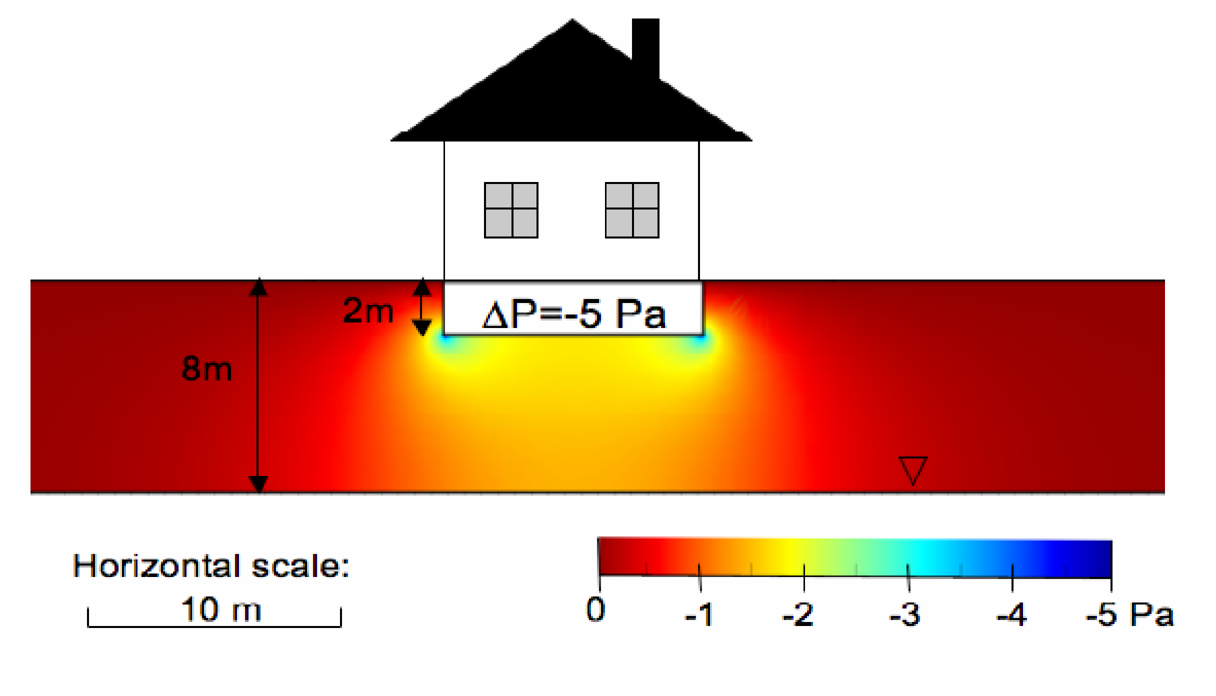


Figure 4.4 Color Pressure Profile for Single Building (Also scenario 1 of chapter 6)

FIGURE E170
Modeling of Pressure Field around Structure, Showing Depressurization Near Edge Crack (Bozkurt, 2009[5])
NESDI Project #476

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[5] Bozkurt, Ozgur, "Investigation of Vapor Intrusion Scenarios Using a 3D Numerical Model", Brown University PhD. Thesis 2009

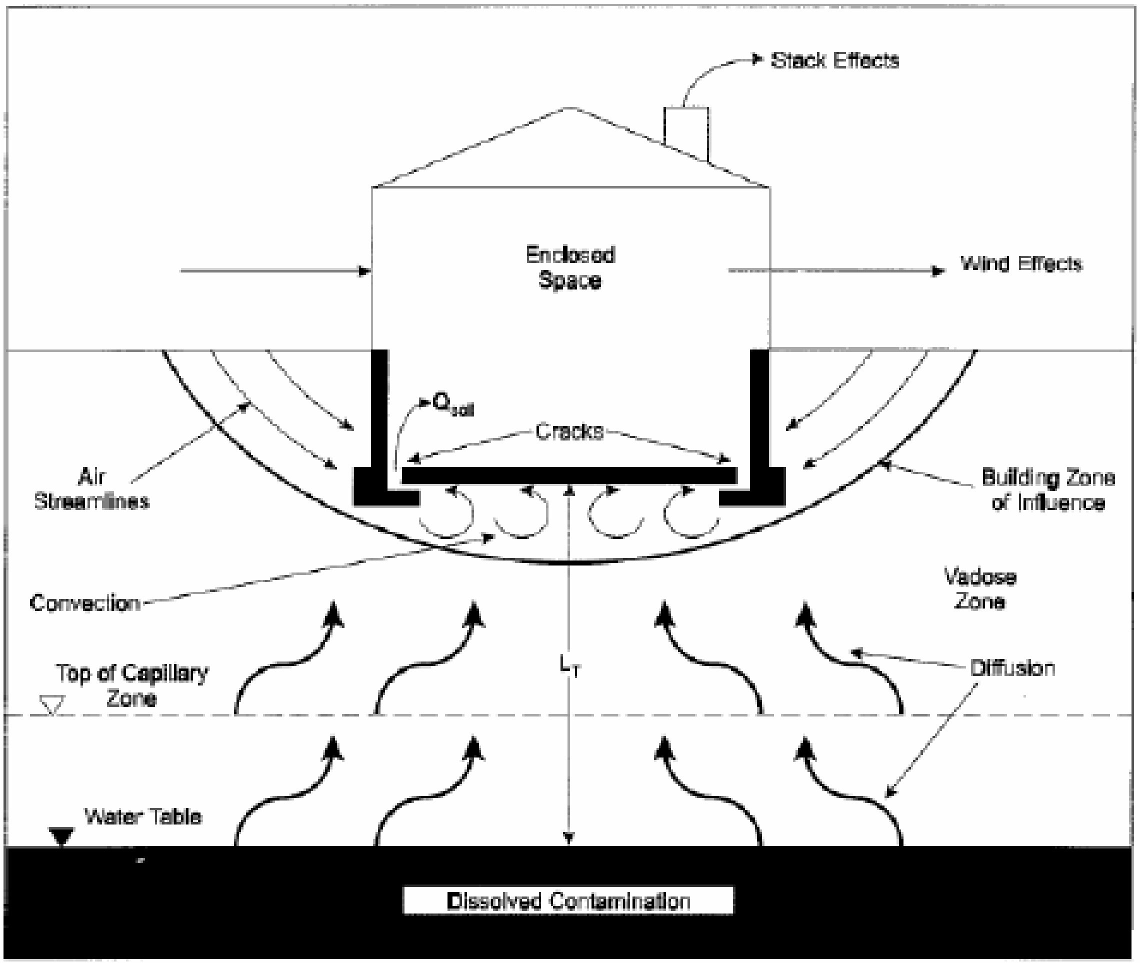

Figure 1.1 General Vapor Intrusion conceptual model (adapted from USEPA 2004).

FIGURE E171

Conceptual Site Model Showing Convection Cells under Slab Bounded by Foundation (Bozkurt, 2009, US EPA 2004[6])

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[6] US EPA 2004 USER'S GUIDE FOR EVALUATING SUBSURFACE VAPOR INTRUSION INTO BUILDINGS

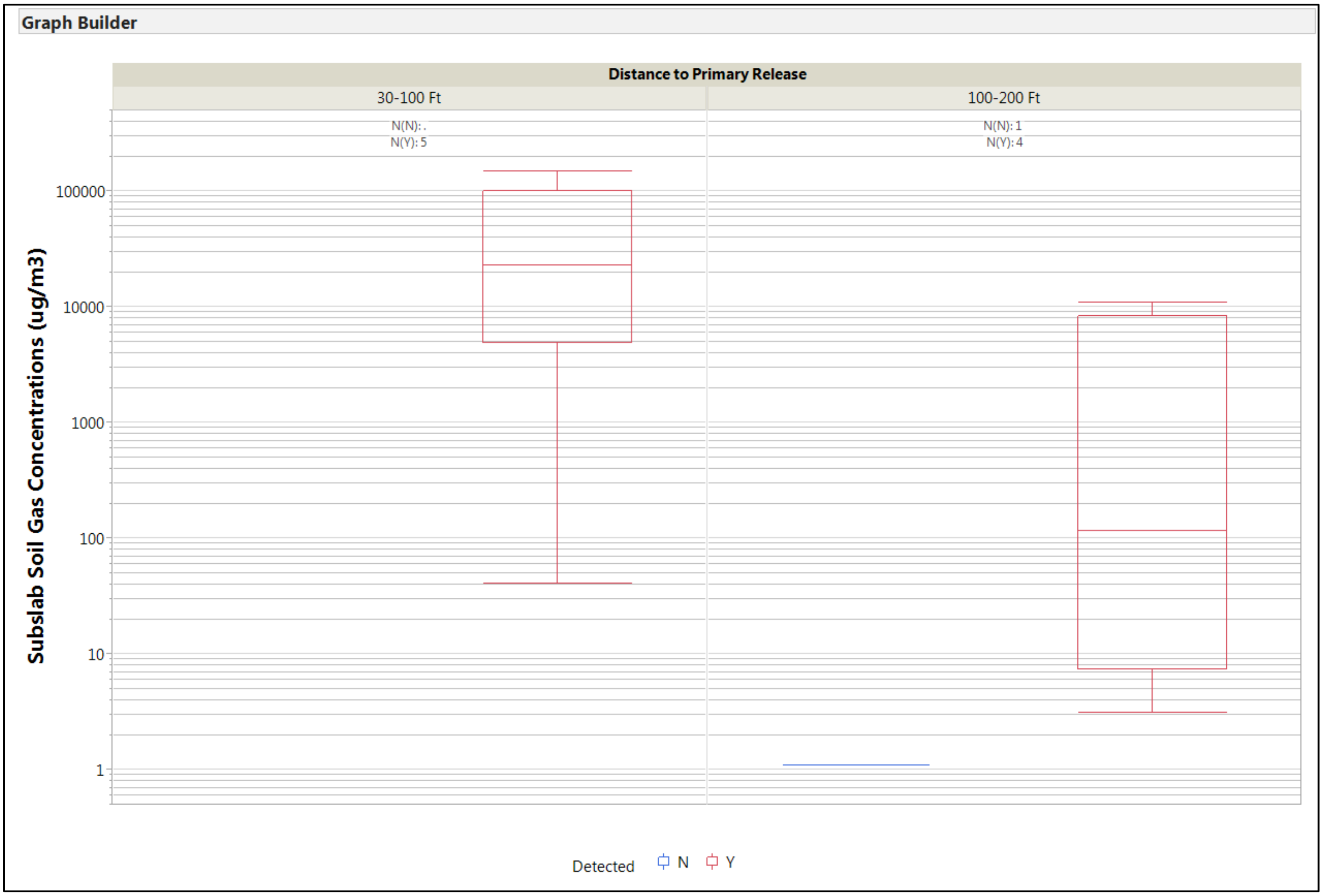

FIGURE E172
Cis-1,2-DCE Sub-slab Soil Gas Concentration by Distance to Primary Release
NESDI Project #476

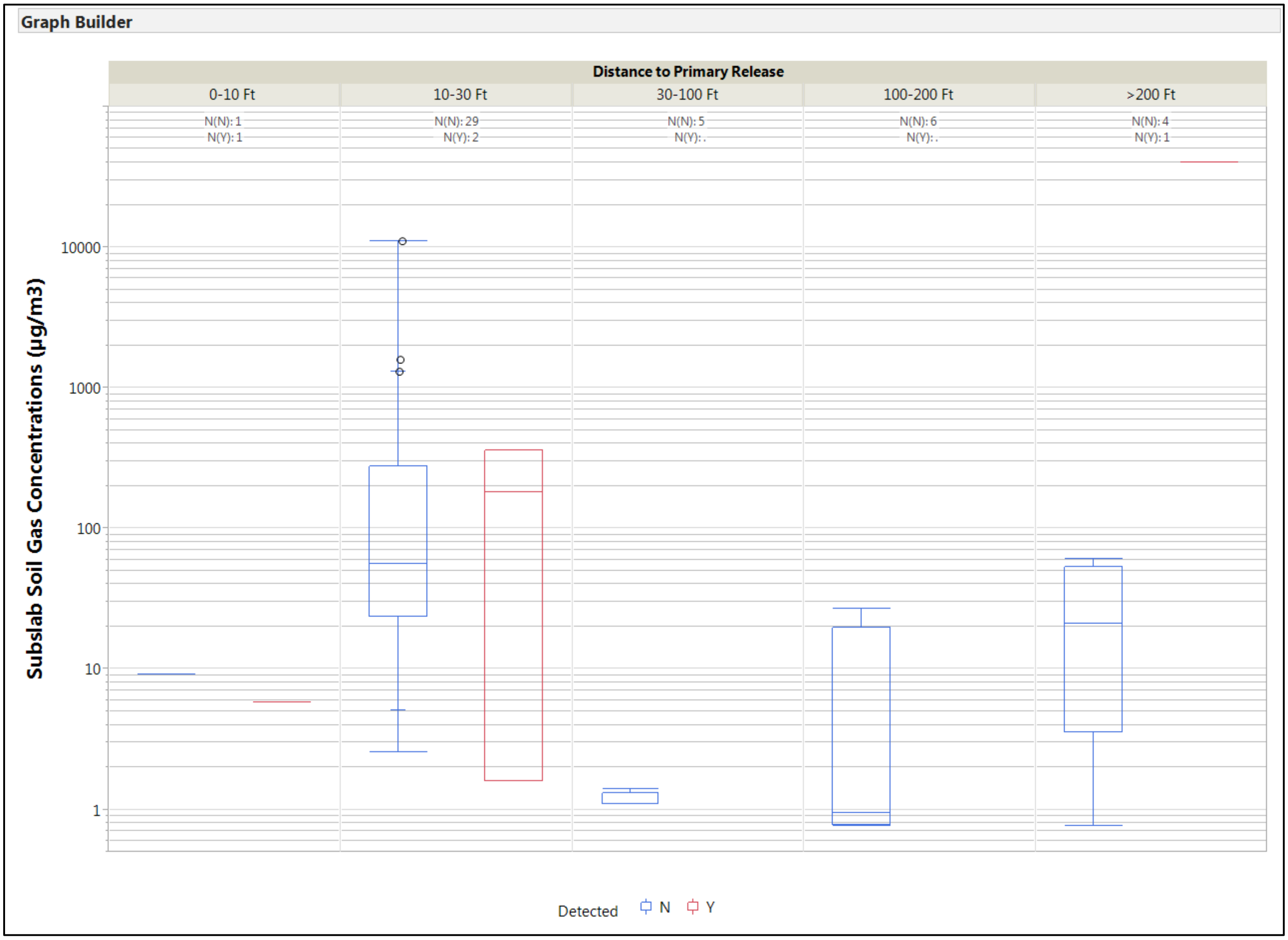

FIGURE E173

Vinyl Chloride Sub-slab Soil Gas Concentration by Distance to Primary Release

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Appendix F – Predictor Variables

Predictor Variables Considered in Full Multivariate Analysis for TCE in Indoor Air as the Outcome Variable

BUILDING_AREA
CEILING_HEIGHT_MIN
CEILING_HEIGHT_MAX
BUILDING_VOLUME_CALC
SAMPLE_ZONE_AREA
SAMPLE_ZONE_HEIGHT_MIN
SAMPLE_ZONE_HEIGHT_MAX
SAMPLE_ZONE_VOLUME_CALC
DEPTH_TO_GROUNDWATER
MinOfSubslab
MaxOfSubslab
Winter Code (Nov through Feb=1)
Groundwater source classification (true=1)
Vadose Zone Source Classification (true=1)
Industrial/Shop Building Use Classification (True = 1)
Engineered HVAC Code (True =1)
Zone Specific HVAC Code (True =1)
Subgrade structure code (True = 1)
Floor Drain Code (True = 1)
Preferential Pathway Code (True=1)
Vault Pit Code (True =1)
Fine soil code (true -1)
Exterior wall code (True=1)
INTERPOLATED_MIN
INTERPOLATED_MAX
MEASURED_MIN
MEASURED_MAX
MEASURED_MAX_DISTANCE
measured max distance (nonzero)
DISTANCE_TO_PRIMARY_RELEASE
measured max/measured max distance
measured max/measured max distance squared
measured max/measured max distance cubed
Interpolated Max/groundwater depth
measured max/groundwater depth

Appendix G – NEDD Recommendations

Appendix G – NEDD Recommendations

Recommendations for a Basic VI NEDD

The fields in the building table of the VI NEDD could include:

- Building Name
- Building Number
- Building Height Maximum
- Building Height Minimum
- Building Construction Date
- Building Footprint Area
- Building Use
- Number of Floors

Definitions for these fields are provided in the data dictionary (**Appendix C**).

Within each building, those planning the study should consider defining one or more sample zones. The sample zone object represents an enclosed location within a building where at least one indoor air sample or sub-slab soil gas sample will be collected. The conceptual idea that best represents sample zone is a box. A sample zone should have limited air mixing with other sample zones. The sample zone characteristics table of the database could include:

- Sample Zone Name
- Sample Zone Number
- Sample Zone Footprint Area
- Sample Zone Interior Ceiling Height Maximum
- Sample Zone Interior Ceiling Height Minimum
- Sample Zone Depth to Groundwater (if information is available)
- Sample Zone Exterior Wall
- Sample Zone HVAC Type
- Sample Zone Preferential Pathway (yes/no with notes)
- Sample Zone Use
- Sample Zone Volume
- Sample Zone Soil Type (if information is available)
- Sample Zone Subgrade Structures (yes/no with notes)
- Sample Zone Background Source
- Floor Drain Present?
- Vault/Pit present?

Those planning a study or the field team would also need to populate the sample zone location table for each sample taken within the sample zone with the location ID (using the NIRIS ID if possible) and sample type.

Those reporting a sub-slab soil gas or indoor air sampling event should also be asked to populate the sample zone groundwater table with the following fields (if available):

- Analyte
- Interpolated Maximum under Sample Zone – determined if possible by interpolation of isoconcentration maps.
- Interpolated Minimum under Sample Zone – determined if possible by interpolation of isoconcentration maps.
- Measured Maximum – Maximum measured (validated analytical result) groundwater concentration of the analyte in groundwater wells within 100 feet of the Sample Zone perimeter in any direction.
- Measured Minimum – Minimum measured (validated analytical result) groundwater concentration of the analyte in groundwater wells within 100 feet of the Sample Zone perimeter in any direction.
- Measured Max Location ID – NIRIS location ID associated with the location where the Measured Maximum was observed.
- Measured Minimum Distance – Shortest distance from the Sample Zone perimeter to the location where the Measured Maximum was observed.

Those reporting a sub-slab soil gas or indoor air sampling event should also be asked to populate the sample zone primary release table with the following fields (if available):

- Distance to Primary Release
- Primary Release Source Name

1.1.1 Recommendations for an Advanced VI NEDD

More extensive information is often developed in the course of vapor intrusion studies, but is not currently recorded in any standard format. Those could be developed as modular tables, examples are provided in the balance of this section.

A HAPSITE GC/MS Building Survey Table with fields such as:

- Sample Number
- Sample Location/description (for example “Headspace of XYZ magic cleaner container at 200 Main Street”)
- Sample Date/Time
- Analyte
- Result
- Units
- Instrument mode (survey, quantitation)

A Differential Pressure Measurement Table with fields such as:

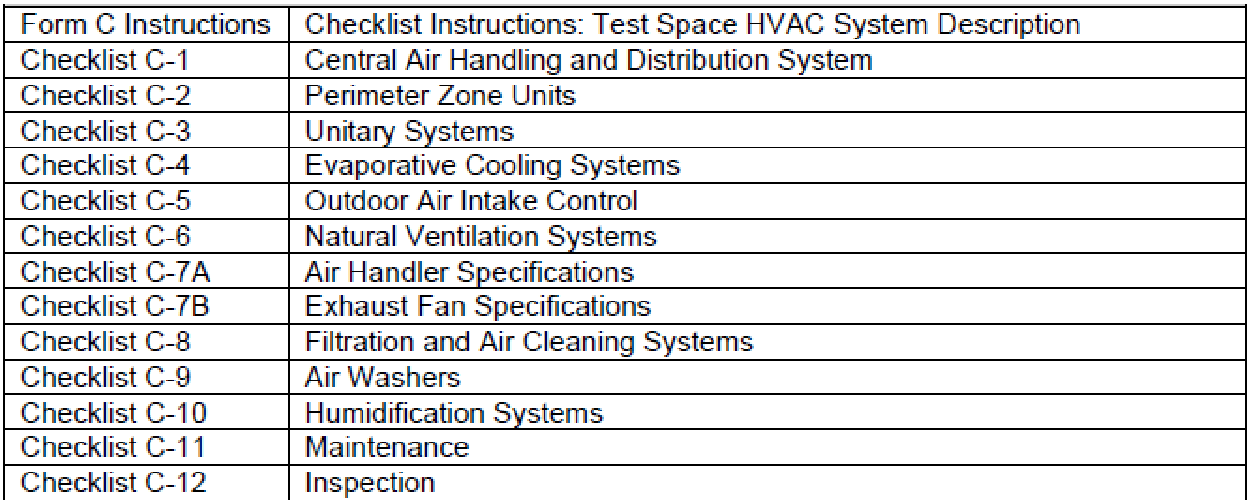
- Location, positive port
- Location, negative port
- Date/time of measurement
- Instrument used
- Averaging time
- Data acquisition frequency
- Building operational conditions during measurement
- Result(s)
- Units

An Airflow Measurement Table with fields such as:

- Location of flow measurement
- Date/time of measurement
- Instrument used
- Averaging time
- Data acquisition frequency
- HVAC settings during measurement
- Building operational conditions during measurement
- Result(s)
- Units

A HVAC System Description Table

This may ultimately be a series of tables. One potential source is the forms provided in USEPA (2003):



Form C Instructions	Checklist Instructions: Test Space HVAC System Description
Checklist C-1	Central Air Handling and Distribution System
Checklist C-2	Perimeter Zone Units
Checklist C-3	Unitary Systems
Checklist C-4	Evaporative Cooling Systems
Checklist C-5	Outdoor Air Intake Control
Checklist C-6	Natural Ventilation Systems
Checklist C-7A	Air Handler Specifications
Checklist C-7B	Exhaust Fan Specifications
Checklist C-8	Filtration and Air Cleaning Systems
Checklist C-9	Air Washers
Checklist C-10	Humidification Systems
Checklist C-11	Maintenance
Checklist C-12	Inspection

An Indoor Source Survey Table with fields such as:

- Method of survey (existing chemical inventory, Safety Data Sheet [SDS] file review, field inspection, instrumental field survey)
- Product name
- Product quantity
- Product Location
- Product use frequency
- VOC concentrations in product by chemical

It is possible that that instead of requiring environmental contractors to prepare an indoor source survey table, similar information could be developed from chemical inventories or purchasing databases.

For example according to the Navy Safety and Occupational Health Program Manual (Chief of Naval Operations, 2011): "*Commanders, Commanding Officers, and Commanding Officers of Installation Tenant Activities shall:…… Develop, implement, and revise as necessary a facility level HM inventory that includes, as a minimum, the identity and quantity (by building) of HM present at the facility, including whether the material is an extremely hazardous substance, hazardous substance, or toxic chemical as defined under EPCRA (see chapter 3 in reference 7-7).*"

Other information relevant to such a tracking program in DoD can be found at:

http://www.public.navy.mil/comnavsafecen/documents/afloat/submarines/medical_hazmat/nstm_670_volume_2_1jun2012.pdf

http://armypubs.army.mil/epubs/pdf/p710_7.pdf

References:

Chief of Naval Operations, NAVY SAFETY AND OCCUPATIONAL HEALTH PROGRAM MANUAL; OPNAVINST 5100.23G CH-1 N09F; 21 Jul 2011

Appendix H- Quantitative Decision Framework – User's Quick Start Guide

Appendix H
Quantitative Decision Framework – User's Quick Start Guide

Overview

The key outcome of this project is a VI decision framework, which is intended to assist DoD project managers in management of VI sites at multiple stages during the project lifecycle and is based on data collected specifically in industrial/commercial buildings at DoD sites. The purpose of this appendix is to bring together in one brief document the basic information needed to apply this quantitative decision framework. The main elements of the decision framework are:

- A flow chart showing the overall process step-by-step and providing "off ramps" for clear-cut cases of very low VI potential and leading to a scorecard for other cases.
- The scorecard allows a more in-depth evaluation of "grey zone" cases using multiple lines of evidence and leading to a "vapor intrusion prioritization score." The range of weights in the scoring system are tailored to emphasize the importance of certain predictor variables identified in the data analysis; sample zone area, average sub-slab concentration, average groundwater concentration, soil type, presence of atypical preferential pathways, and distance to the point at which the chemicals were originally released.
- Graphical keys for the interpretation of the VI prioritization score are provided that can be used at several different stages in site management:
  - In initial site investigations, to prioritize the need for further evaluations, such as determining when indoor air samples are necessary.
  - In site investigations that have progressed to include indoor air sampling, to evaluate if the observed indoor air concentrations are likely the result of VI or background sources.
  - In planning for long-term stewardship of VI sites, if necessary, at current and future buildings.

The factors highlighted in the quantitative decision framework are either those well accepted in the field or were derived from the data analysis efforts in this project. More information about how the factors and weightings were derived is available in **Section 7** of the main body of the report. **Section 6** summarizes the results of the data analysis.

The quantitative decision framework is presented as a series of flowcharts (**Figures 7-1** to **7-2**) that ask basic screening questions to quickly identify atypical preferential pathway cases and very lowest risk cases and then lead to a scorecard (**Figure 7-3**) for the evaluation of the majority of the cases "in the grey area." The scorecard generates two scores:

- A total score indicative of the degree of overall predicted VI potential from a release and its sources
- An uncertainty score that rates the relative amount of information available and thus reliability of the prediction (**Figure 7-3**)

The total VI potential score can then be applied using any of three graphical keys:

- For prioritization decisions for initial investigation (**Figure 7-5**)
- Evaluations of whether indoor air results are reasonably consistent with other lines of evidence (**Figure 7-6**)

- Recommendations on the degree of vigilance needed in long-term stewardship (**Figure 7-7**)

Figure 7-4 shows graphically how **Figures 7-5** through **7-7** are applied throughout the project lifecycle to interpret the scorecard results.

Note that in **Figures 7-5** through **7-7** there is not a strict correspondence of a prioritization score to a recommendation. Rather, recommendations are shown for zones that shade into one another. This reflects the uncertainty of the understanding of VI at this point in time and the need to apply professional judgment to site specific decision making.

It is important to note that this scoring system should not be used indiscriminately – buildings being evaluated for vapor intrusion should be within 100 feet of a release or a subsurface concentration of VOCs (consistent with regulatory and DoD recommendations [Tri-service Environmental Risk Assessment Workgroup, 2009]). Concentrations (sub-slab, indoor air and normalized indoor air) drop rapidly across the first 100 ft.

Using the Flow Charts

Goals for screening industrial buildings for VI potential may vary. Different objectives of various scenarios can be realized while using the flowcharts by application of the following definitions:

Release – (For the definition of a Release, use the scenario below which best describes the situation you are trying to address with your VI screening effort.)

1. Defined contamination (GW plume(s)/soil) from known source(s). Example: A contaminated GW plume originating from historical disposal practices from an industrial operation/building.
2. Defined contamination (GW plume(s)/soil) from unknown source(s) assumed to originate in the general area of the highest concentrations. Example: A contaminated GW plume of unknown source(s) with highest levels of contamination in an industrial area comprised of buildings used in the past for industrial activities and HM/HW storage/usage.
3. Potential undefined contamination (GW plume/soil) emanating from a variety of potential undefined sources.

Source – the past activity which resulted in release(s) of concern that may result in VI.

Single building flowcharts are provided for prioritization in two common cases:

- Groundwater VOC and building characteristics data only available (no sub-slab soil gas data) **(Figure 7-1)**
- Groundwater and sub-slab soil gas VOC data available, along with building characteristics **(Figure 7-2)**

To better describe how to use the flowcharts, the boxes on the flow charts are numbered on the figures:

- **Figure 7-1, Boxes 1 & 4 and Figure 7-2, Boxes 2 &5:** Information about how to identify the unusual building characteristics that could provide atypical preferential pathways later in this section and in **Section 5.2.4.2.** At the current time there is no consensus in the field on how to visually identify preferential pathways, so only lists of types of features that have been observed in specific cases to function as preferential pathways can be provided for guidance.
- **Figure 7-1, Box 2:** To address the question of whether the activities in the building were potentially a source of the release of concern, first determine the appropriate definition of the term "release" from the scenarios listed above. If activities in the building potentially contributed to the release,

identification of any potential vadose zone sources should be considered through evaluation of potential source areas from Preliminary Assessment/Site Inspection reports or Remedial Investigation reports at CERCLA regulated sites. At RCRA regulated sites this information may be in reports such as RCRA Facility Assessments or RCRA Facility Investigations. If contamination is not well characterized and source is unknown, clues indicating potential vadose zone sources can also be provided by the historical name of a building or its known functions. Solvents are often associated with the following DoD site types: underground solvent storage tank, landfill, disposal pit/dry well, drum storage area, fire/crash training area, surface impoundment/lagoon, burn area, waste line, waste treatment plant, sewage treatment plant, oil/water separator, maintenance yard, chemical disposal, plating shop, vapor degreasers and dip tank (EPA, 2004). If necessary, interviews with building managers can provide information on past use or disposal of solvents.

- **Figure 7-1, Box 3:** In order to estimate the groundwater concentration under the building, only analytical data that represent concentrations at or near (10 feet below) the water table should be considered. The approximate groundwater concentration of the analyte under the Sample Zone can be determined by interpolation from isoconcentration maps that are frequently found in remedial investigation, RCRA facility investigation or groundwater monitoring reports. Interpolation of groundwater concentrations under the sample zone will almost always be based on monitoring wells located exterior to the building. Therefore, it would not generally take into account any potential increase of groundwater concentration beneath the building that may occur if there is a capping effect associated with the building (Schumacher et al., 2010) or if the source itself is beneath the building. Groundwater concentrations can then be converted into groundwater vapor concentrations using Henry's law. Henry's law calculators are available as stand alone websites http://www.epa.gov/athens/learn2model/part-two/onsite/esthenry.html or as part of the widely used Johnson & Ettinger model.
- **Figure 7-1, Box 5:** In order to evaluate the significance of vadose zone sources many lines of evidence could be considered:
  - Soil gas sampling results (external to the building) are an excellent source of information. Comparison of soil gas results to the groundwater vapor concentration predicted from groundwater can often suggest whether vadose zone sources are significant.
  - When solvent disposal at the surface of the ground, discharge to sewers or solvent spills to the building floor are known to have occurred, the existence of a vadose zone source near or beneath the building should be presumed. If DNAPL concentrations are observed in groundwater, then the historical mechanism by which the solvents reached the water table should be considered. It is likely that free phase, adsorbed phase, vapor phase or soil moisture phase solvents will be present in the vadose zone unless the disposal was into a deep well (Environment Agency, 2003; Carr, 2011).
  - Results of bulk soil sampling for VOCs are considered a weak line of evidence in part because the subsample size analyzed is tiny compared to the total size of the vadose zone. According to EPA (2013) they "*can be used in a qualitative sense for this purpose. For example, high soil concentrations generally would indicate impacted soil. Unfortunately, the converse is not always true. Non- detect results for soil samples cannot be interpreted to indicate the absence of a subsurface vapor source, because of the large uncertainties associated with measuring concentrations of volatile contaminants introduced during soil sampling, preservation, and chemical analysis.*" Only a very small percentage of the soils in the vadose zone need to have stored VOC mass in order to sustain high soil gas VOC concentrations over a large volume of vadose zone soil.

  - Field screening with PID instruments of soil borings the data for which is typically in the appendices of remedial investigation reports can provide a useful semi-quantitative indicator of potential vadose zone mass storage. However this information must be used with caution because the instruments used are typically sensitive only to part per million concentrations in soil gas, and because the conditions under which the measurement are typically made do not allow these measurements to be related directly to a soil gas concentration.

- **Figure 7-2, Boxes 1& 3:** Subslab concentration information will generally only be available from subslab sampling in vapor intrusion oriented investigation reports. However if bulk soil sampling was performed beneath the building equilibrium soil gas concentrations could be calculated, subject to the cautions about bulk soil sampling discussed above.

Using the Scorecard

This section provides information on how to use the scorecard (**Figure 7-3**).

Selecting Which Sample Zones to Score

In order to use this decision framework, sample zones within the building of interest need to be defined. The Sample Zone object represents an enclosed location within a building where at least one indoor air sample has been collected or could be collected in the future. The sample zone should include at least some regularly occupied spaces within the building. The conceptual idea that best represents Sample Zone is a box. A Sample Zone should have limited air mixing with other Sample Zones. Sample zones should be defined so that air is expected to be reasonably well and rapidly mixed throughout the zone. In order to better understand airflow through buildings, the information on HVAC systems and Airflow in the DoD Vapor Intrusion Handbook, Appendix H, pages 128 -129 should be reviewed (Tri-service Environmental Working Group, 2009). Additional useful information on this subject can be found in Shea (2010).

Some buildings may have an impractically large number of potential sample zones for an initial assessment. The following guidelines can be used in selecting priority sample zones for evaluation:

- At least one sample zone should be selected for each occupied section of the building that was separately constructed. Many DoD buildings have had multiple additions which may have independent foundation systems and are often separated by barriers to airflow. Additions can be identified through a review of building engineering drawing files. Alternately, additions are often apparent in the field based on the external appearance of the building, such as differing foundation styles, building cladding, rooflines etc. An additional aid in identifying additions to a building is a historical sequence of aerial photographs. Often, such a sequence at roughly 5 to 10 year intervals has been assembled and reviewed as part of an initial site assessment.

- The selection of sample zones should include those proximate to expected atypical preferential pathways.

  Examples of Anthropogenic Preferential Pathways include:

  - Subsurface utility conduits (e.g., a sewer line intersecting contaminated groundwater or to which wastes may have been historically discharged)

  - Floor drains (e.g., around the gravel pack of the drain pipe where it enters the building or inside the pipe if contaminated groundwater has entered a sewer line and the trap is not maintained)

  - Building sumps or dry wells

  - Drainage pits

  - Large, unsealed penetrations through otherwise solid concrete floors
  - Unsealed saw-cut expansion joints in concrete floors, or floors where seals have desiccated or deteriorated over time
  - Utility conduits and surrounding granular fill, but only where there is a pressure gradient driving flow or the surrounding soil is too moist to allow appreciable vapor diffusion
  - Unlined crawlspaces, especially where the vadose zone is enough to make pumping important
  - Elevator pits and shafts
  - Open wall cavities connecting to the soil or crawlspace (Florida, 2007) or blocks that allow advective flow (see the discussion of block walls in EPA 2008).
- Sample zones on the lowest occupied level should be prioritized. However in cases with a sparingly occupied or partial basement, sampling in both the basement and on the first floor is advisable.
- The selection of sample zones should include at least one representing each major type of heating and cooling system in use of the building. Ideally one sample zone should be assigned to each HVAC zone within the building and represent the areas likely to be negatively pressurized by the influence of exhaust fans or air returns (Tri-service Environmental Working Group, 2009; Shea, 2010).
- The selection of sample zones should include at least one occupied by each major type of employee who has the building as a routine duty station. For example, buildings with both office workers and industrial workers routinely using solvents in their job duties should be divided into at least two sample zones.
- Sampling zones near the historic locations of contaminant release should be prioritized. This information may be inferred from previous site investigation reports, interviews with long-term workers, or patterns in external soil gas or groundwater data sets.
- The results of this project suggest that small square footage occupied sample zones and those on exterior walls should be prioritized.

Scoring the Sample Zones

The scorecard assumes that some basic information will be available to the user (it is possible to score a sample zone even if several types of information are missing; however, this increases the uncertainty score).

- **Sample Zone Area:** A scaled building floor plan, from which the approximate area of sample zones of interest can be calculated. Sample zones are rooms or spaces with limited air mixing with other areas within the building.
- **Average subslab concentration:** This is the average VOC concentration from sub-slab ports in the sample zone. Sub-slab concentration information will generally only be available from sub-slab sampling in VI investigation reports. However, if bulk soil sampling was performed beneath the building equilibrium soil gas concentrations could be calculated, subject to the cautions about bulk soil sampling discussed in **Section 7**.
- **Average Groundwater Vapor Concentration:** In order to estimate the groundwater concentration under the building only analytical data that represent concentrations at or near (10 feet below) the water table should be considered. The approximate groundwater concentration of the analyte under the Sample Zone can be determined by interpolation from isoconcentration maps that are frequently found in remedial investigation, RCRA facility investigation or groundwater monitoring reports. Interpolation of

groundwater concentrations under the sample zone will almost always be based on monitoring wells located exterior to the building. Therefore, it would not generally take into account any potential increase of groundwater concentration beneath the building that may occur if there is a capping effect associated with the building (Schumacher et al., 2010) or if the source itself is beneath the building. Groundwater concentrations can then be converted into groundwater vapor concentrations using Henry's law. Henry's law calculators are available as stand alone websites http://www.epa.gov/athens/learn2model/part-two/onsite/esthenry.html or as part of the widely used Johnson & Ettinger model.

- **Soil type:** Information describing the predominant shallow soil type between the building slab and the water table is needed. This can normally be determined from nearby site-specific boring logs for monitoring wells, boring logs for geotechnical design purposes, or from soil survey information (available nationally at http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). This information will be used to make a simple classification:
  - If silts or clays are indicated in boring logs or cross sections for the vadose (unsaturated) zone near or beneath the building, the User should consider "Fine" as the soil type. This includes strata containing coarser-grained components such as silty sand, gravelly clay, etc.
  - The "Coarse" soil type should be used in scoring in cases where no fines are indicated or only traces of fines are indicated in the boring logs or soil surveys.
- **Solvent Use/Disposal History:** Evaluation of the contribution to the release of potentially contributing historical solvent activities in a building will vary according to the definition of "release" based on the goals of the screening effort. If activities in the building potentially contributed to the release, identification of any potential vadose zone sources should be considered through evaluation of potential source areas from Preliminary Assessment/Site Inspection reports or Remedial Investigation reports at CERCLA regulated sites. At RCRA regulated sites this information may be in reports such as RCRA Facility Assessments or RCRA Facility Investigations. If contamination is not well characterized and source is unknown, clues indicating potential vadose zone sources can also be provided by the historical name of a building or its known functions. Solvents are often associated with the following DoD site types: underground solvent storage tank, landfill, disposal pit/dry well, drum storage area, fire/crash training area, surface impoundment/lagoon, burn area, waste line, waste treatment plant, sewage treatment plant, oil/water separator, maintenance yard, chemical disposal, plating shop, vapor degreasers and dip tank (EPA, 2004). If necessary, interviews with building managers can provide information on past use or disposal of solvents.
- **Sample zone on exterior wall:** This answer should be yes if the boundary of the sample zone includes the exterior wall of the building along at least one side.
- **Presence of Atypical Preferential Pathways:** Results of a building walk-through or an interview with a person knowledgeable about the building are needed sufficient to determine if an atypical preferential pathway is present (elevator shaft, tunnel, open soil visible beneath pit, or wall, etc.). Examples of Anthropogenic Preferential Pathways are provided in the previous section.
- **Distance to Primary Release Point:** History of building use sufficient to estimate, if possible, the distance between the sample zone and the likely point of the primary release (where the chlorinated solvents likely entered the soil). Many sample zone primary releases will be the locations of surface disposal sites, leaking underground storage tanks, degreasers, solvent spills, disposal pits, and stormwater or sewer conveyance lines.

Using the Flow Charts, Scoring System and Keys in Different Situations

Single Building Prioritization – No Soil Gas or Indoor Air Data Available

The prioritization flowchart for use when only groundwater and building characteristic information is available is shown as **Figure 7-1**. The primary goal of the flowchart is to separate between:

- Cases where impacted groundwater is the only source of VOCs.
- Cases where impacted groundwater is present but a vadose zone source is also likely to be present due to a nearby source of the release.

The flow chart also has a branch suggesting that buildings with no potential for vadose zone sources and low groundwater concentrations have very low VI potential, and do not require consideration of building or sample zone characteristics unless atypical preferential pathways are present. Buildings which contain atypical preferential pathways are recommended for a preferential pathway specific evaluation, with consideration for TCE rapid response if TCE is present.

However, in many cases, the flowchart leads to the need to complete the scorecard and evaluate the results using **Figure 7-5**, which provides recommendations for prioritization among buildings and sample zones. The scorecard also recommends calculating a simple index of the uncertainty of the determination, where each question in the scorecard that could not be definitively answered is assigned one point, and the total number of uncertainty points is interpreted according to **Figure 7-3**. Note that cases without sub-slab soil gas data will always score as at least moderate uncertainty, although a moderate level of uncertainty may well be acceptable if the prioritization score is low.

Single Building Prioritization – with Sub-slab Soil Gas Data Available

The prioritization flowchart for use when sub-slab soil gas, groundwater, and building characteristic information is shown as **Figure 7-2**. In this case, the sub-slab soil gas VOC concentration and atypical preferential pathway information is used to conduct the initial screening. Buildings with sub-slab soil gas concentrations <33x the indoor screening level are considered to have low VI potential, and do not require consideration of building or sample zone characteristics. Buildings with both atypical preferential pathways are recommended for rapid sampling consideration to manage potential acute or short-term exposure.

However, in many cases the flowchart leads to the need to complete the scorecard and evaluate the results using **Figure 7-5**, which provides recommendations for prioritization among buildings and sample zones. The scorecard also recommends calculating a simple index of the uncertainty of the determination, where each question in the scorecard that could not be definitively answered is assigned one point, and the total number of uncertainty points is interpreted according to **Figure 7-3**. Buildings with groundwater, sub-slab soil gas, and building characteristics information available receive a low uncertainty rating.

Single Building Evaluation with Indoor Air Data Available

When indoor air data have already been collected, there is little benefit to using the flowchart, but the scorecard can provide useful information. As the DoD VI handbook states:

> *Measured concentrations of VOCs in indoor air consist of three components:*
>
> *1. VOCs from subsurface VI*
>
> *2. VOCs from indoor air background sources*
>
> *3. VOCs from outdoor air background sources*

> *When determining whether VI is impacting the building at levels of concern, it is important to evaluate the contributions from each of these sources. Therefore, for all direct indoor air measurements, it is recommended that co-located and concurrent groundwater, near-slab or sub-slab soil gas, and outdoor air sampling be performed so that the potential confounding factors (e.g., background concentrations) can be evaluated….. [During sampling] (n)ormal activities may need to be curtailed to avoid adding volatiles to air. Stored chemicals and cleaning supplies may need to be removed from building.* (Tri-Service Environment Risk Assessment Workgroup, 2009)

In practice it is difficult to completely inventory all chemical uses in a large building and it may be impossible to curtail mission critical activities in the building during sampling. Thus, the multiple lines of evidence such as groundwater, sub-slab soil gas, and indoor air concentrations must be weighed together to evaluate the risk. Regulatory agencies frequently seek "concordance" among these lines of evidence but have provided little detail in how the inter-comparison of lines of evidence should be performed. The scoring system presented here can be helpful in evaluating whether observed indoor air concentrations are reasonably attributable to the observed sub-slab soil gas or groundwater concentration. The scoring system (interpreted according to **Figure 7-6**) provides a way to synthesize the experience of 49 other DoD buildings, to put observed indoor air concentrations in a context of what could reasonably be expected maximum concentrations in indoor air as a result of vapor intrusion at a DoD building.

In a case where the scoring system total is quite low but the indoor air concentration is high (represented by the orange box on **Figure 7-6**), it would be advisable to take additional steps to determine if an indoor source may be present. Those additional steps could include:

- Use of a compound specific, field portable, gas chromatography (GC) or gas chromatography/mass spectrometry (GC/MS) instrument to search the building for indoor sources and/or vapor entry points;
- More exhaustive review and verification of chemical inventory information;
- Building pressurization/depressurization tests;
- Analysis of the spatial pattern of compound ratios (i.e., PCE/TCE; PCE/TCA; etc.) in sub-slab soil gas and indoor air; and/or
- Use of tracers (i.e., radon) to determine a building-specific AF.

This comparison should not however be used in reverse direction. As illustrated by many of the figures in **Sections 6.2.2.1** and **6.2.2.2**, there is a wide range of indoor air concentrations experienced in indoor air associated with any given sub-slab soil gas or groundwater concentration. This is expected because DoD buildings vary greatly in factors such as the quality/condition of the slab and amount of air exchange, parameters which were not quantified in this study. Therefore, it would be inappropriate to use a high prioritization score as a reason to discount a properly made observation of low indoor concentrations (blue box on **Figure 7-6**). However, such a dataset might suggest that substantial indoor or building envelope specific evidence may be required to allay concerns about VI. Such evidence might include multiple rounds of indoor air sampling, longer term indoor air sampling, building pressurization/depressurization tests or long term monitoring of sub-slab-indoor differential pressure.

The green box on **Figure 7-6** represents a situation where an indoor concentration above screening levels is found, and that is consistent with a high VI potential score. Under those circumstances, there are three options for next steps:

- Consider confirming exceedances and that they are due to VI (not background indoor sources);
- Decide whether to mitigate; or
- Consider conducting multiple sampling events if averaging over exposure time is allowed.

In evaluating these options consideration can be made of the placement of the situation within the green box. For example, if a concentration in indoor air is observed many orders of magnitude above the screening level with only a moderately high VI potential score, that would suggest that additional effort should be placed on ruling out indoor air sources. Conversely, if an indoor concentration many orders of magnitude above screening levels was observed with a very high VI potential score, less exhaustive efforts to identify potential background sources may be undertaken. In such a situation, the mitigation option may be given higher emphasis.

The purple box in **Figure 7-6** represents the case where low concentration indoor air results are in agreement with expectations from other lines of evidence, which are expressed by a low VI potential score. Situations close to the bottom left corner of the purple box are those with the strongest case for no further VI assessment.

Basewide or National Applications

The flowcharts and scoring systems are designed to be used on a single building level, because the data analysis for this project was conducted on the single building or sample zone level. However, these tools can easily be adapted to be used on a site wide basis, by evaluating buildings individually against the scoring system and collating the results. Alternately, where multiple buildings of an essentially repetitive design and use are present, they can be evaluated as a group. Prioritizing buildings for investigation according to their risk for VI can be useful when it is desirable to evaluate the “worst case” buildings first, to determine whether risks are likely for the site as a whole (USEPA, 2009c). To date, most efforts to identify “worst case” buildings have been based only on plume maps, but this scoring system could allow such choices to take into account both environmental concentrations and building characteristics. The results of this tool can be used to integrate multiple lines of evidence when selecting sampling locations within or between buildings in accordance with USEPA 2012c.

Ultimately, it may be possible to interface this scoring system with NIRIS and with databases of Navy facilities to allow a more automated, nationwide prioritization effort to be pursued.

Applications for Long-Term Stewardship to Avoid Future Vapor Intrusion Risks

This tool can also potentially be useful for determining the type of activities that may be necessary in the future, at locations where multiple lines of evidence analysis indicate that current exposures are less than regulatory targets. Note that this report does not address long-term stewardship requirements for buildings with VI mitigation systems. The potential applications without mitigation are somewhat different for long-term stewardship of existing buildings and for future building construction and thus are described separately in this section although they are shown in one basic figure (**Figure 7-7**).

Long-term Stewardship of Existing Buildings

The USEPA (2009c) Region 3 guidance document states:

> *In situations where the sub-slab source is significant but attenuates greatly so that the indoor air concentrations are low, and if this is confirmed through multiple sampling rounds, the project manager may elect not to take mitigative action at the building itself. However, as long as the significant source remains in the subsurface environment, follow-up monitoring of such a situation is recommended at a minimum…. Alternatively, the project manager may recommend that preventive mitigative action is the best approach*.

Such regulatory recommendations are often made because of concerns about the gradual deterioration of the building slab, the potential for building modifications, or contaminant migration.

It will be assumed here that the release to the environment in question occurred 15 or more years ago, that the plume has been stable or declining for at least 5 years, and, therefore, the soil gas concentrations can be assumed to be at quasi-equilibrium (Carr et al., 2011). A guide to the levels of long-term stewardship activity that may be appropriate with different VI prioritization scores is provided as **Figure 7-6**. Under these circumstances, the greater the VI potential, and the closer to action levels indoor air concentrations are; the greater the frequency of ongoing monitoring that will likely be required. In situations with frequent monitoring requirements cost-benefit analysis can be applied to determine if mitigation for the purpose of reducing monitoring costs is merited. It is generally accepted that in mitigated structures differential pressure monitoring can substitute for some or all of the ongoing indoor air monitoring that may be required. All monitoring plans should include a provision for the eventual cessation of monitoring – for example a period of long term stewardship monitoring may provide sufficient evidence that aging of the building is not increasing the indoor air concentrations.

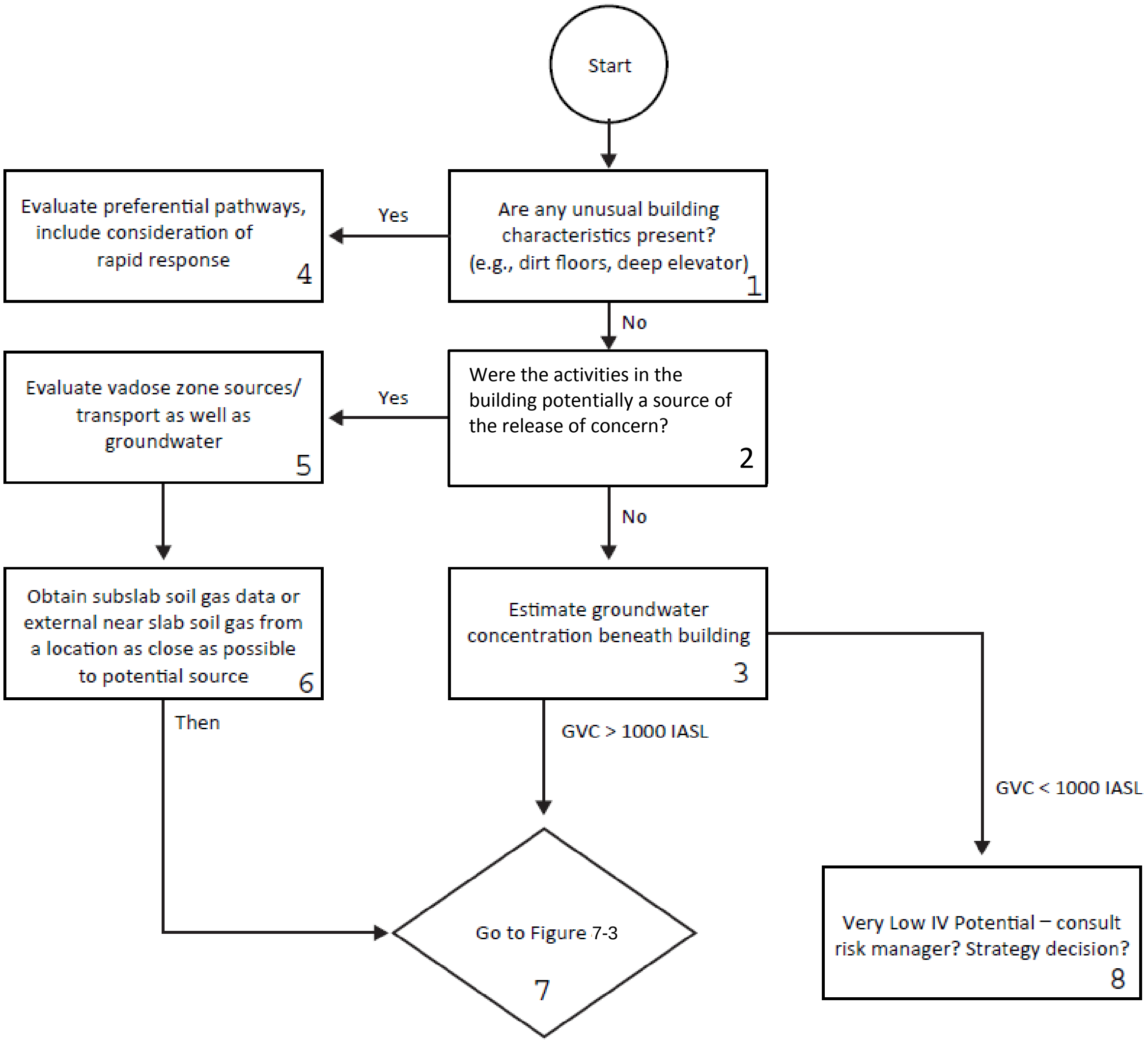
Similarly, the greater the VI potential the more extensive the institutional controls that will be required to prevent building modifications from introducing additional preferential flow pathways, increasing the driving forces from sub-slab to indoor air or reducing the air exchange rate.

Long-Term Stewardship of Future DoD Nonresidential Buildings

USEPA's Vapor Intrusion FAQs state that:

> *Multiple lines of evidence generally should be used to assess the potential for VI in future buildings. Typically, a survey of site history and site conditions, including soil characteristics and subsurface geology, is conducted. Then, information to support a multiple lines of evidence analysis (groundwater data, soil gas data and soil concentrations) should be collected. Another line of evidence that can be used is the Johnson and Ettinger (J&E) model to estimate future conditions using typical building parameters. After appropriate lines of evidence have been obtained, the site manager should then evaluate whether ICs may be needed to complement other response actions (for example, engineered response action components) to limit the potential for VI in future buildings. For future development, the VI assessment may need to be re-evaluated because of changes in site conditions, such as land use, source remediation, or plume migration.* (USEPA, 2012c)

The scorecard developed here can be used for a multiple lines of evidence analysis for future DoD nonresidential construction. A guide to the levels of long-term stewardship activity that may be appropriate with different VI prioritization scores is provided as **Figure 7-6**. New construction provides a unique opportunity for cost effective mitigation. In certain cases of moderate VI potential building features intended for other purposes, such as moisture management, can provide adequate protection against VI (USEPA, 2008). The greater the VI potential, the more monitoring may be required after a new building is constructed. Also, the greater the VI potential, the more institutional controls may be required on future modifications of the new building that might affect its resistance to VI. This scoring system can also be used to help select sites for new construction when a choice of a location that meets other requirements exists.



GVC = Groundwater Vapor Concentration (µg/m^3)
IASL = Indoor Air Screening Level (µg/m^3)

Figure 7-1. Quantitative Decision Framework – Groundwater Data Only
NESDI Project #476

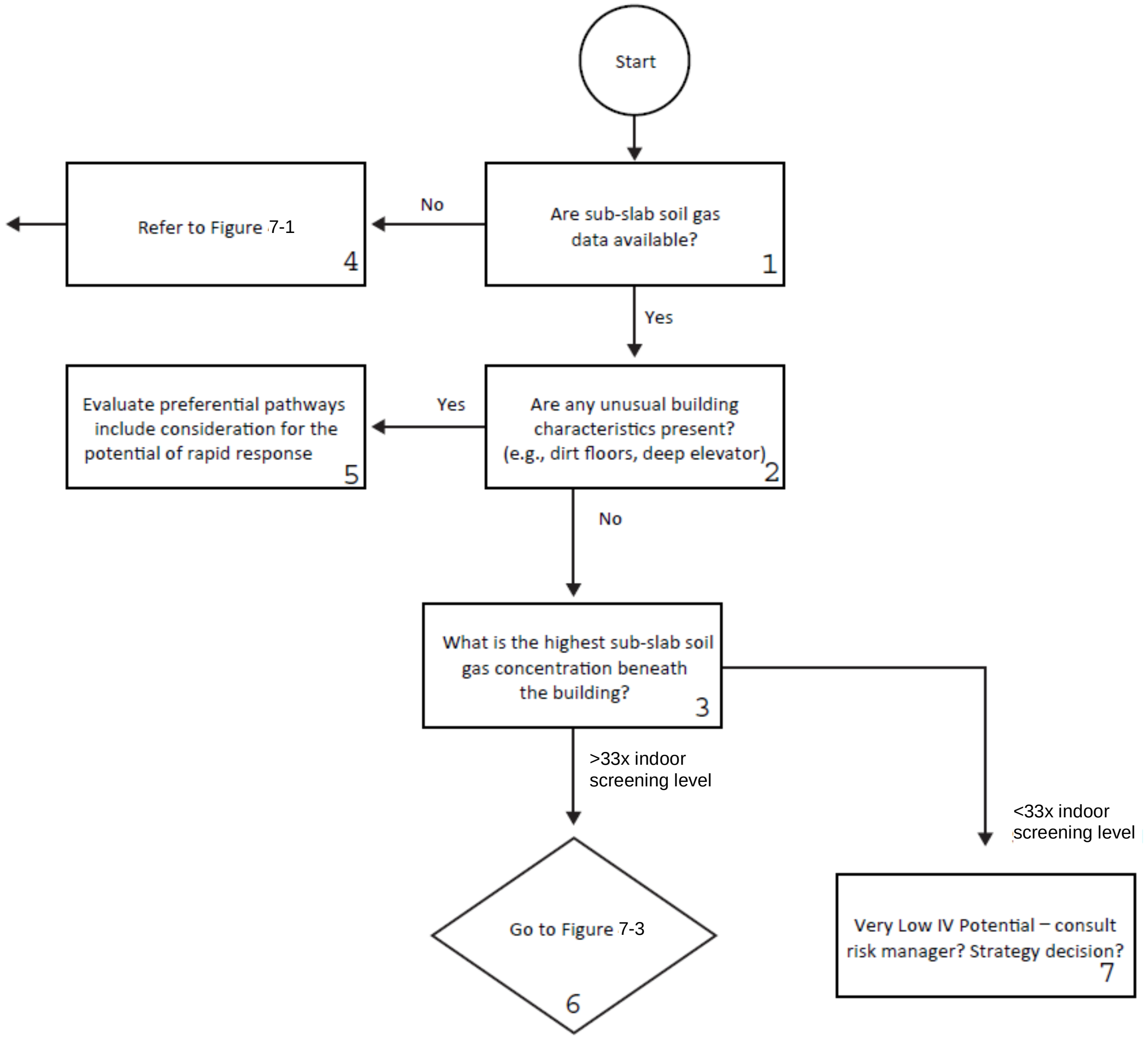
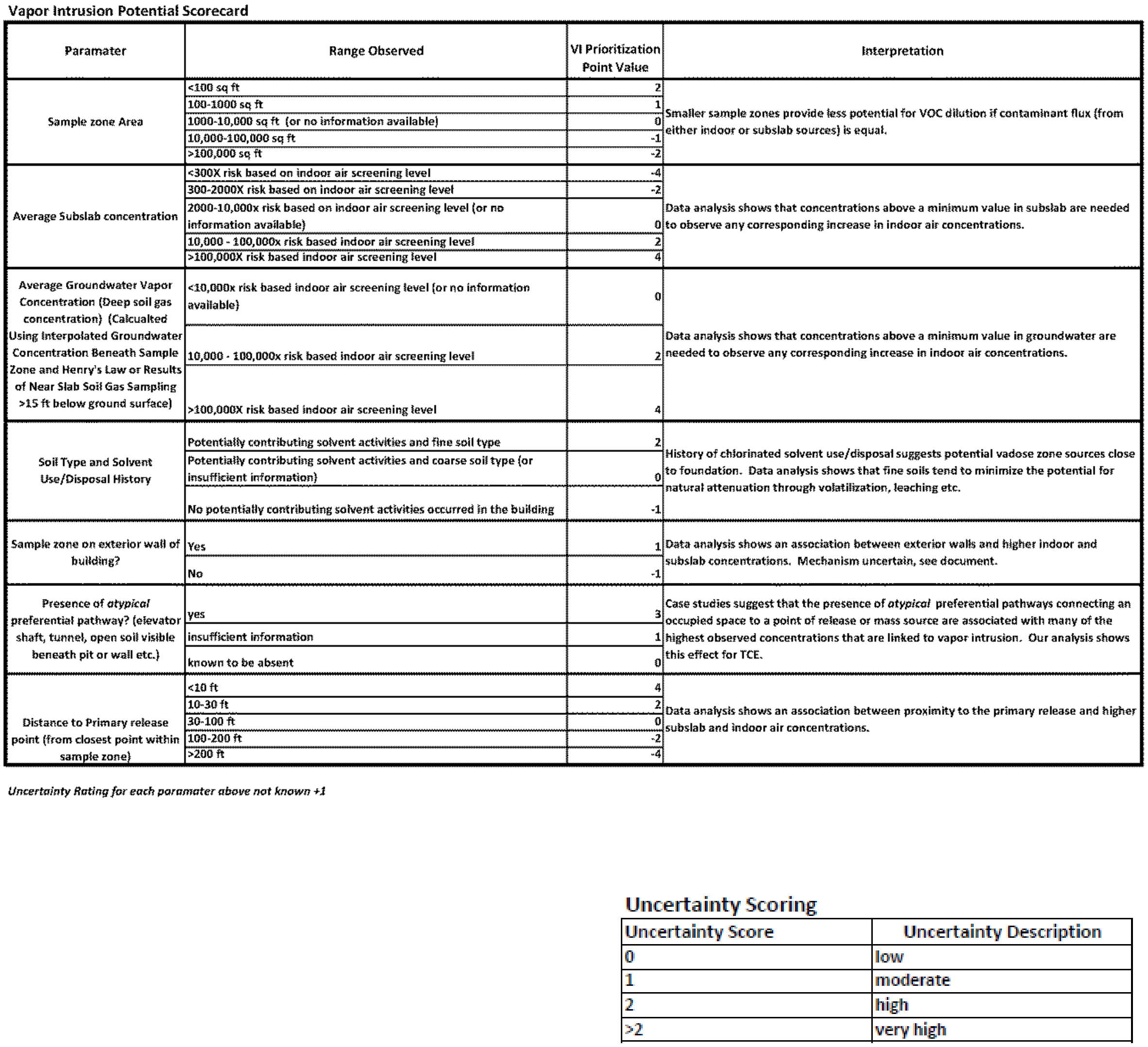


Figure 7-2. Quantitative Decision Framework – Sub-slab Soil Gas Data
NESDI Project #476



Vapor Intrusion Potential Scorecard

Paramater	Range Observed	VI Prioritization Point Value	Interpretation
Sample zone Area	<100 sq ft	2	Smaller sample zones provide less potential for VOC dilution if contaminant flux (from either indoor or subslab sources) is equal.
	100-1000 sq ft	1	
	1000-10,000 sq ft (or no information available)	0	
	10,000-100,000 sq ft	-1	
	>100,000 sq ft	-2	
Average Subslab concentration	<300X risk based on indoor air screening level	-4	Data analysis shows that concentrations above a minimum value in subslab are needed to observe any corresponding increase in indoor air concentrations.
	300-2000X risk based on indoor air screening level	-2	
	2000-10,000x risk based on indoor air screening level (or no information available)	0	
	10,000 - 100,000x risk based indoor air screening level	2	
	>100,000X risk based indoor air screening level	4	
Average Groundwater Vapor Concentration (Deep soil gas concentration) (Calcualted Using Interpolated Groundwater Concentration Beneath Sample Zone and Henry's Law or Results of Near Slab Soil Gas Sampling >15 ft below ground surface)	<10,000x risk based indoor air screening level (or no information available)	0	Data analysis shows that concentrations above a minimum value in groundwater are needed to observe any corresponding increase in indoor air concentrations.
	10,000 - 100,000x risk based indoor air screening level	2	
	>100,000X risk based indoor air screening level	4	
Soil Type and Solvent Use/Disposal History	Potentially contributing solvent activities and fine soil type	2	History of chlorinated solvent use/disposal suggests potential vadose zone sources close to foundation. Data analysis shows that fine soils tend to minimize the potential for natural attenuation through volatilization, leaching etc.
	Potentially contributing solvent activities and coarse soil type (or insufficient information)	0	
	No potentially contributing solvent activities occurred in the building	-1	
Sample zone on exterior wall of building?	Yes	1	Data analysis shows an association between exterior walls and higher indoor and subslab concentrations. Mechanism uncertain, see document.
	No	-1	
Presence of *atypical* preferential pathway? (elevator shaft, tunnel, open soil visible beneath pit or wall etc.)	yes	3	Case studies suggest that the presence of *atypical* preferential pathways connecting an occupied space to a point of release or mass source are associated with many of the highest observed concentrations that are linked to vapor intrusion. Our analysis shows this effect for TCE.
	insufficient information	1	
	known to be absent	0	
Distance to Primary release point (from closest point within sample zone)	<10 ft	4	Data analysis shows an association between proximity to the primary release and higher subslab and indoor air concentrations.
	10-30 ft	2	
	30-100 ft	0	
	100-200 ft	-2	
	>200 ft	-4	

Uncertainty Rating for each paramater above not known +1

Uncertainty Scoring

Uncertainty Score	Uncertainty Description
0	low
1	moderate
2	high
>2	very high

Figure 7-3. Vapor Intrusion Potential Scorecard
NESDI Project #476

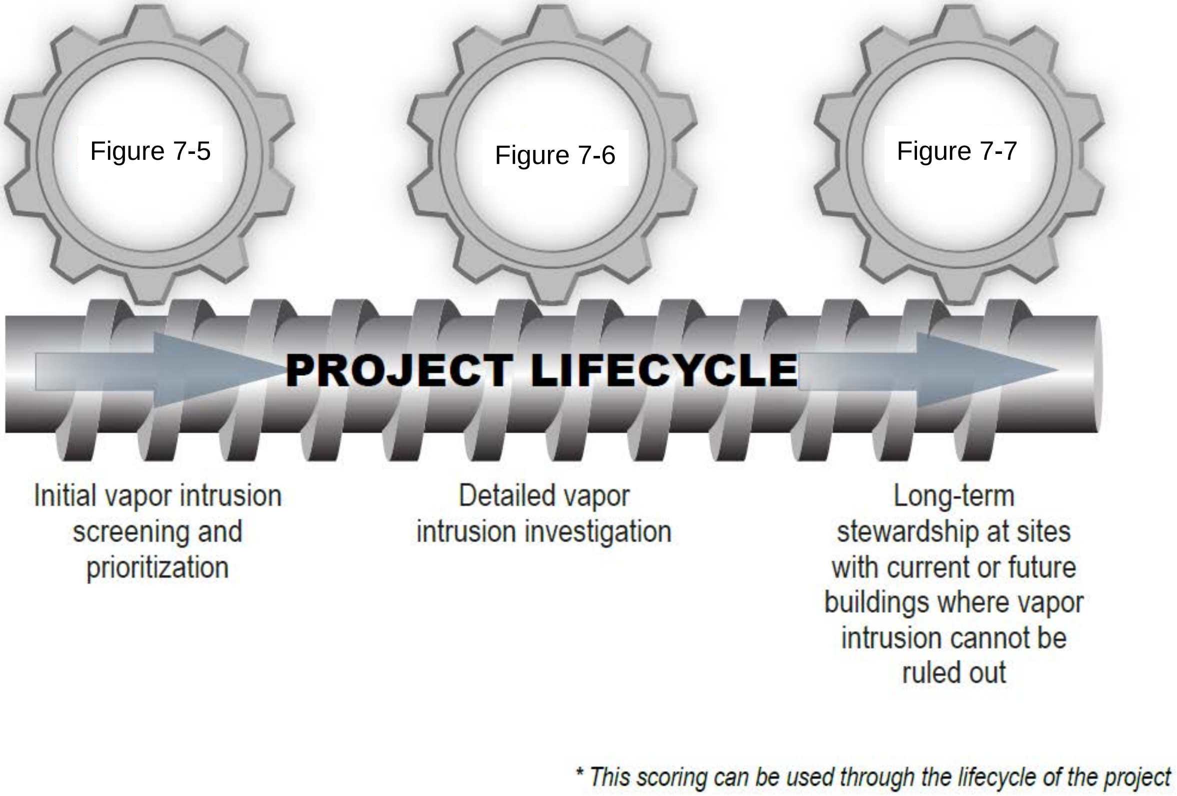


Figure 7-4. Key to Scorecard Interpretation Graphs
NESDI Project #476

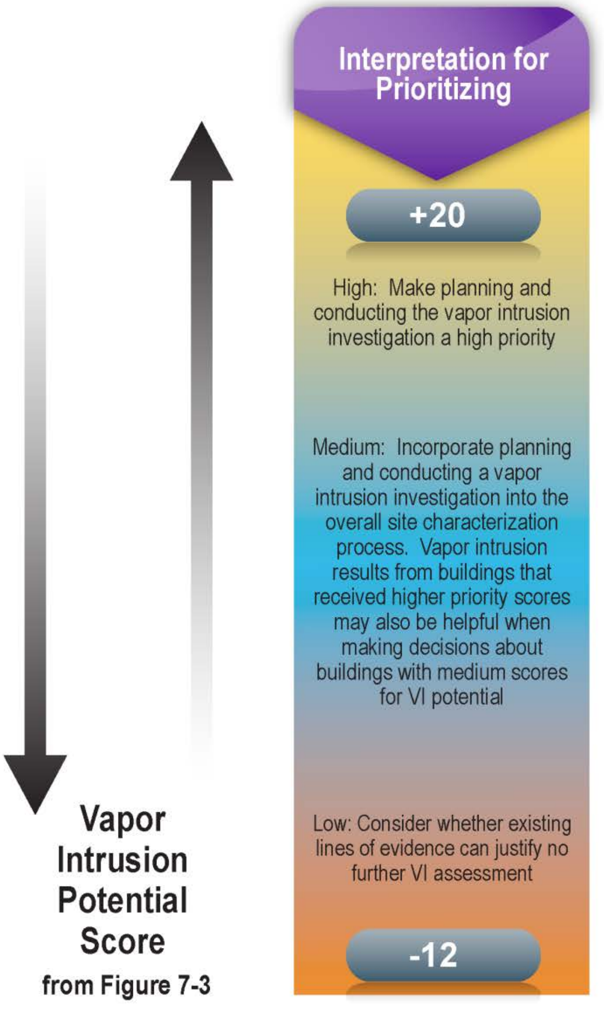
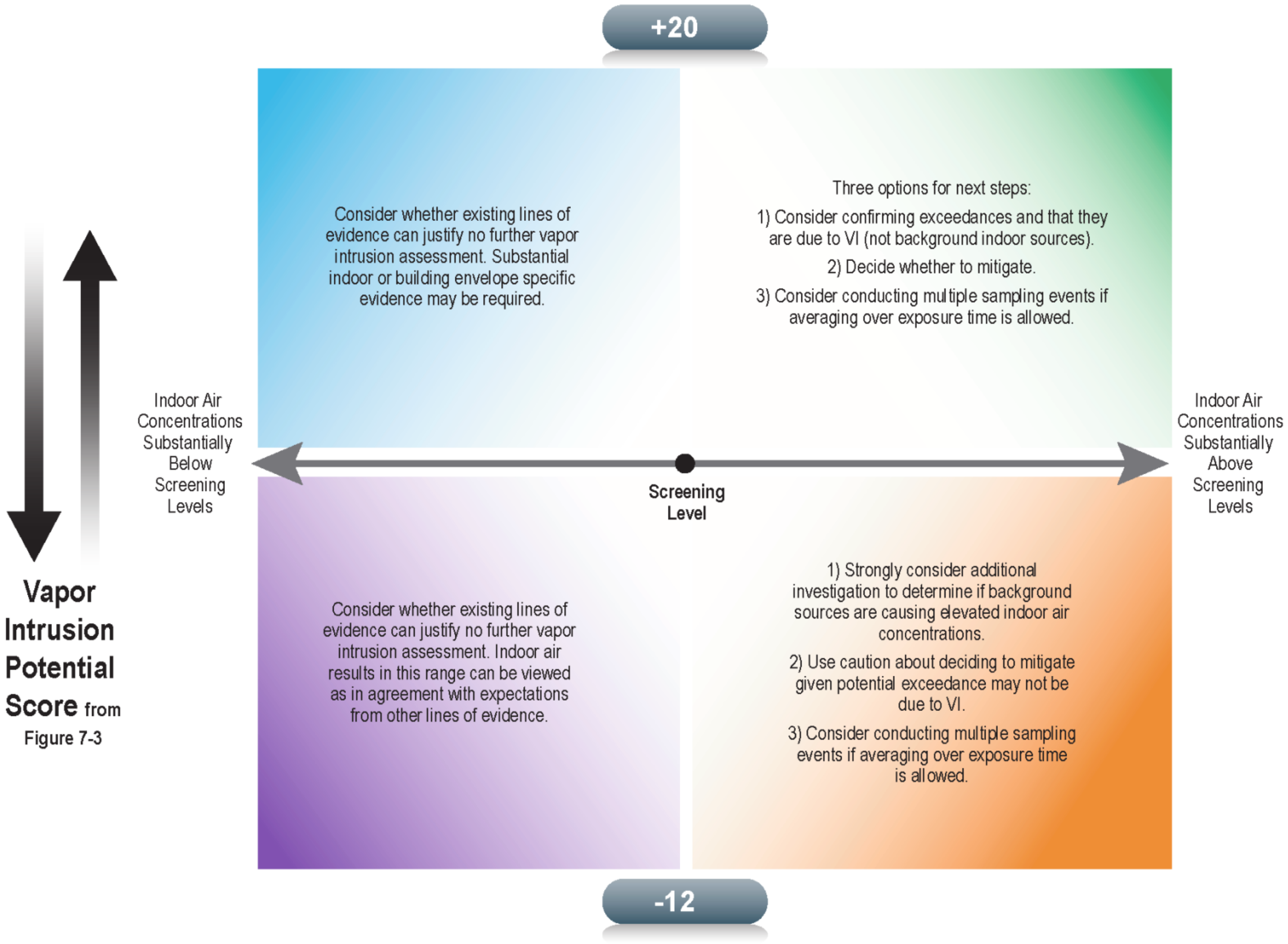


Figure 7-5. Interpretation of Total VI Potential Score for Prioritizing Initial Investigation Efforts
NESDI Project #476



Consider whether existing lines of evidence can justify no further vapor intrusion assessment. Substantial indoor or building envelope specific evidence may be required.

Three options for next steps:

1) Consider confirming exceedances and that they are due to VI (not background indoor sources).

2) Decide whether to mitigate.

3) Consider conducting multiple sampling events if averaging over exposure time is allowed.

Consider whether existing lines of evidence can justify no further vapor intrusion assessment. Indoor air results in this range can be viewed as in agreement with expectations from other lines of evidence.

1) Strongly consider additional investigation to determine if background sources are causing elevated indoor air concentrations.

2) Use caution about deciding to mitigate given potential exceedance may not be due to VI.

3) Consider conducting multiple sampling events if averaging over exposure time is allowed.

Figure 7-6. Interpretation of Scores for VI Potential at Sites with Indoor Air Data
NESDI Project #476

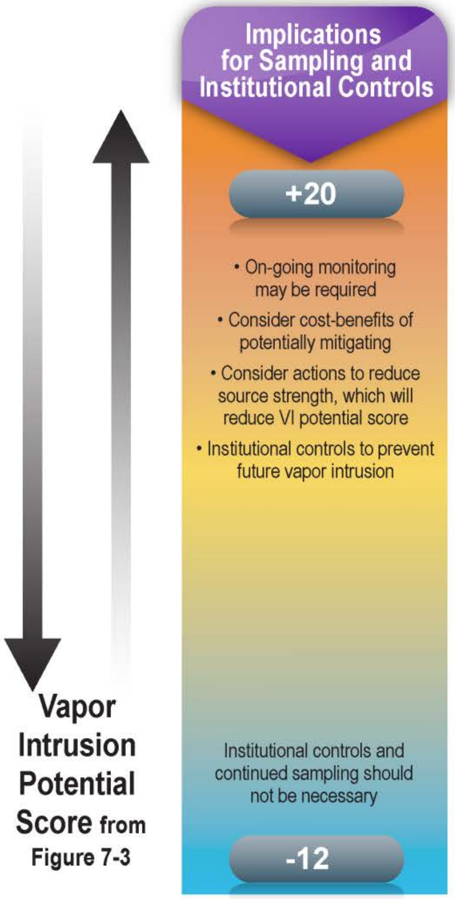


Figure 7-7. Interpretation of Total Score to Design Appropriate Long Term Stewardship
NESDI Project #476

Appendix I – Points of Contact

Appendix I: Points of Contact

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