Sacramento Municipal Utility District

59th Street Corporation Yard

Revised Interim Removal Action Workplan • July 2022

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Revised Interim Removal Action Workplan • July 2022

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PREFACE

This Interim Removal Action Workplan (RAW) was prepared by AECOM Technical Services, Inc. (AECOM) for the Sacramento Municipal Utility District (SMUD) under Master Contract 4600001299, Task Contract 4500121576, Task Number 576-003. The work was initiated by SMUD in accordance with the requirements of the Corrective Action Consent Agreement, Docket Number HWCA P1-13/14-007 between SMUD and the California Department of Toxic Substances Control (DTSC). The work partially relies on information provided by SMUD and information in reports available on the DTSC EnviroStor website. Assumptions based on this data, although believed reasonable and appropriate based on the data provided herein, may not prove to be true in the future as new data are collected.

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List of Acronyms and Abbreviations

°	degree
µg/L	micrograms per liter
µg/m^3	micrograms per cubic meter
’	minute (in the context of latitude and longitude)
#	number
”	second (in the context of latitude and longitude)
AECOM	AECOM Technical Services, Inc.
AF	attenuation factor
AOC	area of concern
APN	Assessor’s Parcel Number
ARAR	applicable or relevant and appropriate requirements
BDCM	bromodichloromethane
bgs	below ground surface
BMP	best management practice
CACA	Corrective Action Consent Agreement
CCR	California Code of Regulations
CEQA	California Environmental Quality Act
CFR	Code of Federal Regulations
COC	chemical of concern
COPC	chemical of potential concern
DBE	dibromoethane
DCE	dichloroethene
DCP	dichloropropane
DTSC	California Department of Toxic Substances Control
e.g.	*exempli gratia*, for example
ELCR	excess lifetime cancer risk
ESA	Environmental Site Assessment
ESL	Environmental Screening Level
HASP	Health and Safety Plan
HAZWOPER	Hazardous Waste Operations and Emergency Response
HERO	Human and Ecological Risk Office
HHRA	Human Health Risk Assessment
HI	hazard index
HSC	Health and Safety Code
I&M	inspection and maintenance
i.e.	*id est*, that is
IC	institutional control
IS/MND	Initial Study and Proposed Mitigated Negative Declaration
Kleinfelder	Kleinfelder, Inc.
LUC	land use control
MCL	Maximum Contaminant Level
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
No.	Number
OSHA	Occupational Safety and Health Administration
OWS	oil/water separator

List of Acronyms and Abbreviations (continued)

Patriot	Patriot Environmental Services, Inc.
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
PG&E	Pacific Gas and Electric
PID	photoionization detector
PPE	personal protective equipment
RAO	removal action objectives
RAP	Remedial Action Plan
RAW	Removal Action Workplan
RCRA	Resource Conservation and Recovery Act
REC	recognized environmental condition
RFI	RCRA Facility Investigation
RSL	Regional Screening Level
RWQCB	Regional Water Quality Control Board
SacRT	Sacramento Regional Transit
Safety-Kleen	Safety-Kleen Systems, Inc.
SCR	Site Characterization Report
Site	59th Street Corporation Yard
SL	screening level
SMAQMD	Sacramento Metropolitan Air Quality Management District
SMUD	Sacramento Municipal Utility District
SNC	Sierra National Construction, Inc.
SPLP	synthetic precipitation leaching procedure
STLC	soluble threshold limit concentration
SVE	soil vapor extraction
SVSL	soil vapor screening level
SWMU	solid waste management unit
SWPPP	Stormwater Pollution Prevention Plan
SWRCB	California State Water Resources Control Board
TBC	To-Be-Considered
TCE	trichloroethene
TCLP	toxicity characteristic leaching procedure
TCP	trichloropropane
TPH	total petroleum hydrocarbons
TPH_d	total petroleum hydrocarbons as diesel
TPH_g	total petroleum hydrocarbons as gasoline
$TPH_{ho/mo}$	total petroleum hydrocarbons as hydraulic oil/motor oil (equivalent carbon number range of C17 – C32 [aromatic high])
U.S.	United States
USA North 811	Underground Service Alert of Northern California and Nevada
USEPA	United States Environmental Protection Agency
UST	underground storage tank
VI	vapor intrusion
VOC	volatile organic compound
XRF	x-ray fluorescence

Executive Summary

This Interim Removal Action Workplan (RAW) was prepared by AECOM Technical Services, Inc. (AECOM) on behalf of the Sacramento Municipal Utility District (SMUD) for the SMUD 59th Street Corporation Yard (Site) in compliance with the *First Amendment to Corrective Action Consent Agreement*, Docket HWCA P1-13/14-007 (California Department of Toxic Substances Control [DTSC], 2018), California Health and Safety Code section 25356.1, the memorandum entitled *Removal Action Workplans (RAWs)* (DTSC, 1998), and the *Proven Technologies and Remedies Guidance - Remediation of Metals in Soil, Appendix C3 Removal Action Workplan Sample* (DTSC, 2008). This Interim RAW presents an evaluation of removal alternatives for soil contamination at the Site, and also describes the recommended removal action alternative and an implementation plan. An interim removal action is being implemented to address arsenic, lead, and total petroleum hydrocarbons as hydraulic oil/motor oil (equivalent carbon number range of C17 – C32 [aromatic high]) ($TPH_{ho/mo}$) contamination in soil and to reduce volatile organic compound (VOC) concentrations in the soil gas contamination source area until soil gas cleanup levels are developed and a final remedy for the Site is selected in a subsequent Remedial Action Plan (RAP) that will address the full extent of soil gas contamination and any residual soil contamination not addressed by the interim remedy.

The Site encompasses 19.74 acres in an area of varied land use. Residential neighborhoods are situated to the west, commercial developments are situated to the north, and United States Highway 50 is located south of the Site. A California Department of Transportation laboratory is located east of the Site. The SMUD headquarters and other buildings of the SMUD campus are located southeast of the Site. The yard is bisected by a Sacramento Regional Transit light rail line and a petroleum product pipeline beneath the light rail right-of-way. Following soil and soil gas remediation, redevelopment plans for the Site include creation of a high-quality mixed-use urban community consisting of a combination of small lot single-family homes, multi-family rental units, and commercial space.

Soil Investigation Results

Several soil, soil gas, sub-slab vapor, and sewer gas investigations were conducted at the Site. This Interim RAW addresses soil contamination at the Site; therefore, the following previous investigation results summary is focused on soil.

Based on previous investigations, arsenic concentrations in soil exceeding the 17.53 milligrams per kilogram (mg/kg) background concentration at a depth of 3 feet below ground surface (bgs) or less was identified in five areas of the Site with an estimated combined area of approximately 1.7 acres. This arsenic background concentration was calculated in the Site Characterization Report (AECOM 2019) that was approved by the DTSC (DTSC, 2020a). The two largest areas of arsenic-impacted soil at a depth of 3 feet bgs or less are located south of the Warehouse Building (approximately 0.9 acre) and in the vicinity of the Salvage Building (approximately 0.6 acre). Three smaller areas of arsenic-impacted soil at a depth of 3 feet bgs or less are located in the vicinity of the Tool Issue Building, west of the Hazardous Material Building, and south of the Garage Building (approximately 0.2 acre combined).

Arsenic concentrations exceeding background in soil at a depth greater than 3 feet bgs were identified in three localized areas: south of the east end of the Warehouse Building (approximately 0.3 acre), south of the Tool Issue Building (approximately 0.03 acre) and west of the Salvage Building (approximately 0.02 acre). In the area south of the east end of the Warehouse Building, the vertical extent of arsenic concentrations exceeding background extends to a depth of at least 10 feet bgs. In the area south of the Tool Issue Building, arsenic concentrations exceeding background extend to a depth between 6 and 11 feet bgs. In the area west of the Salvage Building, the vertical extent of arsenic concentrations exceeding background extend to a depth between 5 and 7.5 feet bgs.

Lead and $TPH_{ho/mo}$ concentrations exceeding their respective 80 and 2,400 mg/kg residential screening levels (SLs) were identified in a localized area within the area of arsenic-impacted soil west of the Salvage Building. The vertical extent of lead and $TPH_{ho/mo}$ concentrations exceeding their residential SLs extend to a depth between 2 and 5 feet bgs.

Removal Action Objectives

Removal action objectives (RAOs) have been established that are protective of human health and the environment and reduce the potential for exposure to the chemicals of concern (COCs) in soil encountered at the Site. Chemicals of potential concern are contaminants suspected of being site-related and were carried through the human health risk assessment's (HHRA's) quantitative risk calculations. Based on the HHRA calculations, contaminants that pose unacceptable carcinogenic risk and/or noncarcinogenic hazard are identified as COCs. The HHRA identified arsenic, lead, and $TPH_{ho/mo}$ as COCs in soil within portions of the Site north of the light rail line (AECOM, 2021a). The following RAOs were developed for soil within the portions of the Site identified by the HHRA as having unacceptable carcinogenic risk and/or noncarcinogenic hazard.

- Prevent direct human contact with, inhalation of, and ingestion of arsenic concentrations in soil exceeding the Site-specific background concentration
- Prevent direct human contact with, inhalation of, and ingestion of lead concentrations in soil corresponding to a 1 microgram per deciliter source-specific incremental change in blood lead levels
- Prevent direct human contact with, inhalation of, and ingestion of $TPH_{ho/mo}$ concentrations in soil corresponding to a hazard index of greater than 1
- Reduce VOC concentrations in the soil gas contamination area by removing VOC mass from the source area identified at the north of the Tool Issue Building

Removal Action Alternatives

The following removal action alternatives were developed for the Site.

- Alternative 1 – No Further Action
- Alternative 2 – Soil Excavation/Off-Site Disposal
- Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

Based on the removal action alternative evaluation, Alternative 2 (Soil Excavation/Off-Site Disposal) was selected as the recommended removal action alternative. Alternative 2 consists of excavating and transporting the impacted soil to appropriate, permitted off-Site facilities for disposal, backfilling the excavations with clean fill, and the continuation of existing land use controls (LUCs) to address any remaining contamination at the Site. Existing LUCs include perimeter fences with security gates, routine security patrols, and construction/maintenance project reviews by SMUD environmental staff.

The impacted soil will be excavated and transported to appropriate, permitted off-Site facilities for disposal. Soil excavated from the Site may be classified as non-hazardous or non-Resource Conservation and Recovery Act (RCRA) hazardous waste based on the potential exceedance of the soluble threshold limit concentration (STLC) for arsenic or lead of 5 milligrams per liter (mg/L). It is not anticipated that the excavated soil will be classified as RCRA-hazardous or need to be treated prior to disposal to comply with land disposal restrictions. Excavation includes using loaders, excavators, and/or other appropriate equipment. Excavation operations will generate dust emissions. Suppressant, water spray, and other forms of dust control may be required during excavation, and workers may be required to use personal protective equipment to reduce exposure to contaminants. Sloping excavation sidewalls may result in increased volume of soil requiring excavation. Confirmation soil sampling and analysis will be conducted to verify that cleanup criteria are met at the excavation bottom and perimeter. Excavation may require soil stockpiling prior to disposal. To achieve the RAOs, the volume of soil to be removed is estimated to be approximately 8,400 bank cubic yards (excluding soil excavated to slope the excavation sidewalls).

Soil samples from the sides and bottom of the completed soil excavation will be collected to assess the COC concentrations to verify that cleanup levels have been met and RAOs for the Site have been achieved. Excavations will be backfilled to existing ground surface. The excavations will be backfilled first with any available clean excavation side slope material that was removed to slope the excavation sidewalls followed by clean imported fill material. Imported backfill material will be compliant with DTSC guidance, *Information Advisory, Clean Imported Fill Material* (DTSC, 2001). After backfilling is completed, the Site surface will be restored to a gravel surface.

1.0 Introduction

This Interim Removal Action Workplan (RAW) was prepared by AECOM Technical Services, Inc. (AECOM) on behalf of the Sacramento Municipal Utility District (SMUD) for the SMUD 59th Street Corporation Yard (Site) in compliance with the *First Amendment to Corrective Action Consent Agreement* (CACA), Docket HWCA P1-13/14-007 (California Department of Toxic Substances Control [DTSC], 2018), California Health and Safety Code (HSC) section 25356.1, the memorandum entitled *Removal Action Workplans (RAWs)* (DTSC, 1998), and the *Proven Technologies and Remedies Guidance - Remediation of Metals in Soil, Appendix C3 Removal Action Workplan Sample* (DTSC, 2008). This Interim RAW presents an evaluation of removal alternatives, and also describes the recommended removal action alternative and an implementation plan. Under the CACA, DTSC is the lead regulatory agency and SMUD is the responsible party for corrective action at the Site. The soil at portions of the Site is impacted with arsenic, lead, and total petroleum hydrocarbons as hydraulic oil/motor oil (equivalent carbon number range of C17 – C32 [aromatic high]) ($TPH_{ho/mo}$). The soil gas is impacted with volatile organic compounds (VOCs), primarily tetrachloroethene (PCE). No contaminants have been detected in groundwater beneath the Site at concentrations exceeding primary Maximum Contaminant Levels (MCLs).

1.1 Removal Action Process

The RAW process, including the regulatory basis and objectives of the RAW, is described in the following subsections.

1.1.1 Regulatory Basis for the RAW

A RAW is one of two remedy selection documents that may be prepared for a hazardous substance release site pursuant to California HSC section 25356.1. In California HSC section 25323.1, a RAW is defined as “a workplan prepared or approved by the DTSC or a California Regional Water Quality Control Board (RWQCB) which is developed to carry out a removal action, in an effective manner, that is protective of the public health and safety and the environment.” A RAW is appropriate when the estimated cost of the removal action is less than $2,000,000. If the estimated capital cost of implementing the chosen action will exceed $2,000,000, a Remedial Action Plan (RAP) should be prepared. The estimated cost of the selected removal alternative recommended in this Interim RAW is estimated to be less than $2,000,000.

1.1.2 Objectives of the Interim RAW

The objectives of this Interim RAW are to:

- Present and evaluate existing Site conditions;
- Establish appropriate removal action objectives (RAOs) for protection of human health and the environment; and
- Evaluate alternatives and identify a final recommendation for an interim remedy at the Site that is protective of human health and the environment.

1.1.3 Elements of the RAW

In order to accomplish the objectives described in Section 1.1.2 and satisfy regulatory requirements, this Interim RAW includes:

- A description of the nature and extent of the chemicals of concern (COCs) at the Site;
- The goals to be achieved by the selected interim remedy;

- An analysis of the alternatives considered and rejected, and the basis for the rejection, including a discussion of effectiveness, implementability, and cost of each alternative; and
- A description of the recommended alternative and an implementation plan.

1.2 Site Description

The following subsections present a description of the Site, including a description of the location, historic use, and current status.

1.2.1 Site Identification and Location

The SMUD 59th Street Corporation Yard is the Site addressed in this Interim RAW. The DTSC EnviroStor website identifies the Site as the SMUD Corporation Yard (EnviroStor Identification Number 34490015). The Site is located at 1708 59th Street in Sacramento, California, approximately 5 miles east of downtown Sacramento (Figure 1-1). The Site is located on the Sacramento East United States (U.S.) Geological Survey Quadrangle Map in Township 8 North, Range 5 East, Section 9 (Mount Diablo Baseline and Meridian). The Site's approximate coordinates are 121 degrees (˚) 26 minutes (') 18 seconds (") West longitude, 38˚ 33' 22" North latitude.

The Site encompasses 19.74 acres in an area of varied land use. Residential neighborhoods are situated to the west, commercial developments are situated to the north, and U.S. Highway 50 is located south of the Site. A California Department of Transportation laboratory is located east of the Site. The SMUD headquarters and other buildings of the SMUD campus are located southeast of the Site. The yard is bisected by the Sacramento Regional Transit (SacRT) light rail Gold Line and a 10-inch diameter petroleum product pipeline beneath the light rail right-of-way (Figure 1-1).

Figure 1-2 presents site features and the land parcels that make up the Site. The main portion of the Site is Assessor's Parcel Number (APN) 008-0010-009-0000 (12.89 acres). The wedge shaped portion of the Site situated south of the light rail line and north of U.S. Highway 50 consists of the following 10 parcels listed west to east: APN 011-0073-001-0000 (0.45 acre), APN 011-0073-002-0000 (1.11 acres), APN 011-0073-003-0000 (0.2 acre), APN 011-0073-004-0000 (0.39 acre), APN 011-0073-006-0000 (0.1 acre), APN 011-0073-008-0000 (1.79 acres), APN 011-0081-001-0000 (0.86 acre), APN 011-0081-002-0000 (0.86 acre), APN 011-0081-003-0000 (0.86 acre), APN 011-0081-008-0000 (0.23 acre). The described wedge-shaped area totals 6.85 acres.

The Site lies approximately 30 feet above mean sea level. The Site is within a reclaimed floodplain and is, therefore, flat and generally lacking in any notable natural landform relief. The majority of the Site is surfaced with a minimum of 4-inch thick asphalt or concrete (SMUD, 1989).

1.2.2 Historic Use and Current Status

SMUD has operated the 59th Street Corporation Yard since 1947, when it was purchased from the Pacific Gas and Electric Company (PG&E). The Corporation Yard served as a central storage area for hazardous and non-hazardous wastes generated on-site and at other off-site SMUD facilities or sites. Historical uses of the yard by SMUD and PG&E appear to have been the same (Ecology and Environment, 1989).

There are eight permanent buildings located on the Site including an Office Building, Inventory Warehouse, Tool Issue Building, Vehicle Maintenance Garage, Workshops Building, Hazardous Materials Storage Building, Salvage Building, and a Pre-fabrication Building. In addition, historical uses at the Site have included designated outdoor areas for the storage of new and refurbished electrical transformers, power poles, power cable, and hazardous wastes.

The SMUD Corporation Yard managed three waste streams. The major waste stream consisted of polychlorinated biphenyls (PCBs) and associated electrical transformers, which accounted for approximately 95 percent of wastes managed on Site. A second waste stream consisted of Resource Conservation and Recovery Act (RCRA)-regulated wastes, which primarily consisted of spent solvents generated by several shops on Site. These wastes were stored on Site for less than 90 days in U.S. Department of Transportation-approved drums prior to shipment to off-site facilities. A third waste stream consisted of wastes generated at SMUD's various off-site locations within the service area that were transferred to the main yard for consolidation and appropriate disposal. These wastes included asbestos used for insulation of underground electric lines, herbicides and pesticides used for right-of-way weed control and pest management, wood products (poles and cross members) treated with pentachlorophenol and creosote, and occasional sulfur wastes from SMUD's geothermal projects.

However, since the relocation of SMUD's equipment yard to their East Campus Operations Center in 2013, the Site was subsequently used for office space and warehouse storage. As of December 2021, the Site has been vacant. Prior to initiation of the removal action, SMUD has scheduled to complete demolition of the Tool Issue Building and the Salvage Building and large portions of paved surfaces at the Site. Following soil and soil gas remediation, redevelopment plans for the Site include creation of a high-quality mixed-use urban community consisting of a combination of small lot single-family homes, multi-family rental units, and commercial space.

1.3 Purpose

Based on the investigation results presented in the Site Characterization Report (SCR) (AECOM, 2019) that was approved by the DTSC (DTSC, 2020a), a Site-specific arsenic background concentration of 17.53 milligrams per kilogram (mg/kg) was calculated. Based on the investigation results presented in the SCR Addendum (AECOM, 2021a), soil at portions of the Site is impacted with arsenic at concentrations exceeding its 17.53 mg/kg Site-specific background concentration, and lead and $TPH_{ho/mo}$ at concentrations exceeding the 80 and 2,400 mg/kg residential screening levels (SLs), respectively. Therefore, further action is required at the Site due to these elevated concentrations of arsenic, lead, and $TPH_{ho/mo}$. Site investigation results also indicate that soil gas is impacted with VOCs; however, further studies are needed to develop soil gas cleanup levels. Until soil gas cleanup levels are developed, SMUD is implementing an interim removal action to address arsenic, lead, and $TPH_{ho/mo}$ contamination in soil and reduce VOC concentrations in the soil gas contamination source area. The final remedy for the Site will be selected in a subsequent RAP that will address the full extent of soil gas contamination and any residual soil contamination not addressed by the interim remedy. The purpose of the remedial options evaluated in this Interim RAW is to mitigate the onsite exposure risk of arsenic, lead, and $TPH_{ho/mo}$ in soil through inhalation, dermal absorption, and ingestion and reduce VOC concentrations in the soil gas contamination source area.

Following completion of the public comment period, DTSC will consider and respond to the comments received. The Interim RAW will be revised, as necessary, in response to the comments received. If significant changes are not required, DTSC will then approve the Interim RAW for implementation. When the remedy has been implemented, a Removal Action Completion Report will be submitted to DTSC for review and certification.

2.0 Site Characterization

The following subsections summarize the environmental setting (including descriptions of the local geology and hydrogeology), previous investigations, nature and extent of contamination, and human health risk assessment.

2.1 Environmental Setting

2.1.1 Geology

The Site lies within the southern portion of the Sacramento Valley, which was formed from sedimentary deposits that were carried as erosion debris from the surrounding mountain ranges. Much of the area near the Site consists of ancient American River deposits. These sedimentary deposits are of Cretaceous to Quaternary age and are quite deep in the general area (SMUD, 1989). The American River is located approximately 1 mile northeast. The American River is confined on the north by steep bluffs, and its ancient course was likely south of its present course, including the area now occupied by the Site (Ecology and Environment, 1989).

Borehole logs from the Phase II Environmental Site Assessment (ESA) (Kleinfelder Inc. [Kleinfelder], 2016) indicate that several layers of clay, silty clay, clayey silt, silt, silty sand, and sand underlie the Site to a depth of at least 37.5 feet below ground surface (bgs).

2.1.2 Hydrogeology

Based on data obtained during the Phase II ESA, the depth to first groundwater beneath the Site is approximately 35 feet bgs and flows in a south to southwesterly direction, at a gradient of approximately 0.001 foot per foot (Kleinfelder, 2016). Municipal drinking water wells draw from depths of approximately 100 to 400 feet bgs. Although many municipal wells are located between 2 and 3 miles from the Site, no active drinking water wells were confirmed to exist within 2 miles of the Site. Several private domestic wells were installed within 2 miles of the Site during the 1950s. Well logs for these installations are generally incomplete. Available information indicates that the wells were completed to depths of approximately 75 to 200 feet. The area where these wells are located is now served by the City of Sacramento, which derives its water from groundwater sources more than 2 miles away from the Site and from surface water from the American River and the Sacramento River. Groundwater generally flows in a south to southwest direction, although it may be affected by the American River. The shallow aquifer has a groundwater flow velocity of approximately 50 to 60 feet per year. The deeper aquifer has a groundwater flow velocity of approximately 10 to 15 feet per year (DTSC, 2012).

The previous investigations and pilot study conducted at the Site are summarized in the Sections 2.1.1 through 2.1.7 and documented in the SCR Addendum (AECOM, 2021a).

2.2 Previous Investigations

2.2.1 Underground Storage Tank Removals

Thirty underground storage tanks (USTs) associated with the Garage Building, Shops Buildings, Tool Issue Building, and a former fueling station between the Garage Building and Shops Building were removed between 1986 and 2014. Some of the older single-walled tanks were replaced with double-walled tanks due to updates in UST regulations. The replacement USTs were later removed when they were no longer needed. The USTs ranged in capacity from 200 to 10,000 gallons and stored leaded and unleaded gasoline, diesel fuel, kerosene, Stoddard solvent, new and used motor oil, hydraulic oil, transmission fluid, and new and used transformer oil. Additionally, there were 12 concrete sumps/lagoons built into the floor of the Garage Building that housed hydraulic rams associated with hydraulic vehicle lifts; the hydraulic rams were removed by SMUD in 2020 and 2021, as detailed in Section 2.2.7. Specific details of the USTs including their former and current locations are presented in the SCR Addendum (AECOM, 2021a).

2.2.2 RCRA Facility Assessment and Investigation

From 2009 to 2012, DTSC conducted a RCRA Facility Assessment to identify and evaluate solid waste management units (SWMUs) and areas of concern (AOCs) at the SMUD Corporation Yard. A SWMU is any discernible waste management unit at a facility from which hazardous waste or hazardous constituents might migrate, irrespective of whether the unit was intended for the management of solid and/or hazardous waste. An AOC is an area that is not a SWMU but which has the potential for hazardous waste or hazardous constituents to be released (DTSC, 2012). DTSC identified the 19 SWMUs and 2 AOCs listed below. Figure 2-1 presents the SWMU and AOC locations.

<u>SWMUs</u>

- SWMU #1: Vehicle Oil/Water Separator (OWS) number (#) 1 at the Garage Building
- SWMU #2: Parts Washer west of the Garage Building
- SWMU #3: Lube Room in the Garage Building
- SWMU #4: Parts Washers in the Garage Building
- SWMU #5: Used Oil Aboveground Storage Tank at the Garage Building
- SWMU #6: Battery Room in the Garage Building
- SWMU #7: Diesel Filter Pulse Cleaner along the southwest side of the Garage Building
- SWMU #8: Former Waste Oil UST near northeast corner of the Garage Building
- SWMU #9: Former Waste Oil UST along the north side of the Garage Building
- SWMU #10: Paint Booth and Paint Storage Room in the Carpenter Shop
- SWMU #11: HazMat Used Battery Storage Area
- SWMU #12: HazMat Building
- SWMU #13: Oil Storage Tanks along the west side of the HazMat Building
- SWMU #14: Drained Transformer Staging Area and Universal Waste Storage Area
- SWMU #15: Former Fuel UST near the southeast corner of the Tool Issue Building
- SWMU #16: Former PCB Storage Area
- SWMU #17: Treated Wood Waste Area and Storage Containers
- SWMU #18: Vehicle OWS #2 near the Treated Wood Waste Area
- SWMU #19: Satellite Accumulation Areas in the Garage Building, Shops Building, and Tool Issue Building

<u>AOCs</u>

- AOC #1: Vehicle Fueling Station
- AOC #2: Utility Pole Storage Area

DTSC recommended that Vehicle OWS #1 at the Garage Building (SWMU #1), Vehicle OWS #2 near the Treated Wood Waste Area (SWMU #18), and the Utility Pole Storage Area (AOC #2) be included in a RCRA Facility Investigation (RFI). DTSC recommended no further RCRA corrective action for the other SWMUs and AOC (DTSC, 2012).

Use of OWS #1 was discontinued in 2013. In February 2014, following issuance of the RCRA Facility Assessment Report, Kleinfelder hydrostatically tested OWS #1 and OWS #2, and no evidence of leakage was identified. SMUD submitted a report describing the hydrostatic test procedures and results to DTSC in March 2014 (Kleinfelder, 2014). Based on the leak testing results, DTSC did not require immediate investigation of the OWSs allowing assessment for potential historical leakage of the two OWSs and ancillary piping to occur at the time of OWS removal. OWS #2 remained in service until just prior to removal in 2020.

In 2015, Kleinfelder performed an RFI for the Utility Pole Storage Area. The RFI assessed whether chemicals applied during wood treatment processes may have migrated from the treated poles to the subsurface. Thirty soil samples were analyzed for total petroleum hydrocarbons (TPH); semi-volatile organic compounds, including polycyclic aromatic hydrocarbons and phthalates; metals; and organochlorine pesticides. The RFI Report (Kleinfelder, 2015) concluded that no further investigation is required at the Utility Pole Storage Area. DTSC concurred with the conclusion (DTSC, 2016).

In 2020, OWS #1 and OWS #2 were removed and a ground cavity assessment was performed by SMUD with support from Patriot Environmental Services, Inc. (Patriot), Safety-Kleen Systems, Inc. (Safety-Kleen), Sierra National Construction, Inc. (SNC), and AECOM. In preparation for the OWS removals, Patriot removed residual oil, water, and sludge from both OWSs and pressure-washed the OWS interior sidewalls and bottom. The non-RCRA hazardous waste was transported by Safety-Kleen to their facility in Davis, California. Following cleanout, SMUD inspected the interiors of both OWSs, which were observed to be in good condition with no visible cracks. After SNC removed both OWSs, the resulting ground cavities were inspected by SMUD and soil from the ground cavity sidewalls and bottom was screened by AECOM using a photoionization detector (PID) capable of detecting VOCs in the parts per billion concentration range. Limited soil staining and odors were observed around where the inlet pipe had entered OWS #1, and the PID detected VOCs in soil from this northern portion of the ground cavity. With DTSC present to observe, SNC continued to excavate soil from the north end of the OWS #1 ground cavity until VOCs were no longer detected using the PID and DTSC indicated the cavity could be backfilled. At OWS #2, no evidence of contamination (i.e., no staining or odors) was observed and no VOCs were detected in soil from the ground cavity sidewalls and bottom. SMUD concluded no further investigation is warranted and requested closure of OWS # 1 and OWS #2 (SMUD, 2021), which was approved by DTSC (DTSC, 2021).

2.2.3 Phase II Environmental Site Assessment

In 2015, Kleinfelder performed a Phase II ESA to evaluate areas of the SMUD Corporation Yard where past and/or current activities may have chemically-impacted soil gas, soil, or groundwater, in preparation for possible property redevelopment (Kleinfelder, 2016). Investigation activities included passive soil gas, active soil gas, soil, and groundwater sampling and analysis. PCE was detected in soil gas at concentrations exceeding the 210 and 2,100 micrograms per cubic meter (µg/m^3) residential and commercial/industrial Environmental Screening Levels (ESLs) (California State Water Resources Control Board [SWRCB], 2013), respectively, in effect at the time. Arsenic was detected in soil at concentrations ranging from 14 to 110 mg/kg, which exceeded the 0.39 and 1.6 mg/kg residential and commercial/industrial direct contact ESLs, respectively, in effect at the time. Three VOCs (bromodichloromethane [BDCM], chloroform, and PCE) and petroleum hydrocarbons (TPH as diesel [TPH_d], TPH as gasoline [TPH_g], and TPH as motor oil) were detected in groundwater at concentrations that did not exceed their respective primary MCLs, if established. Metals including cobalt, copper, nickel, silver, and vanadium were detected in groundwater at concentrations that did not exceed their respective primary MCLs, if established.

2.2.4 2018-2019 Soil Gas, Soil, and Groundwater Investigation

From December 2018 to March 2019, AECOM conducted Site investigation activities to further characterize the lateral and vertical extent of PCE in soil gas, soil, and groundwater and arsenic in soil as detailed in the SCR (AECOM, 2019). The lateral extent of PCE in soil gas was delineated using soil gas data collected from 5.5 feet bgs and the 460 and 2,000 µg/m^3 residential and commercial/industrial soil vapor screening levels (SVSLs), respectively, derived using the 0.001 attenuation factor (AF) recommended by DTSC guidance (DTSC, 2011) at the time for existing commercial and future residential buildings. The areal extent of PCE concentrations in soil gas exceeding the residential and commercial/industrial SVSLs were 0.9 and 0.2 acre, respectively, and were partially underlying the Tool Issue Building. PCE was detected in two soil samples at a maximum concentration of 0.0048 mg/kg, which did not exceed its 0.59 and 2.7 mg/kg residential and commercial/industrial SLs, respectively. PCE was detected in groundwater at a maximum concentration of 0.73 microgram per liter (µg/L), which did not exceed its 5 µg/L primary MCL.

The arsenic concentrations detected in soil during the 2018 soil investigation and earlier investigations were used to derive a Site-specific arsenic background concentration of 17.53 mg/kg that was calculated in the SCR (AECOM, 2019) which was approved by the DTSC (DTSC, 2020a). The arsenic concentrations detected in soil above background were primarily limited to the southern portion of the North Corporation Yard. Within this area, the arsenic concentrations exceeding background in soil at a depth of 3 feet bgs or less encompassed approximately 2.4 acres in the vicinity of the Tool Issue and Salvage Buildings (0.8 acre) and the south side of the Warehouse Building (1.6 acres); however, the full extent of these areas was not fully defined. There were also two smaller areas encompassing approximately 0.2 acre combined beneath the parking lots to the west of the Hazardous Material Building and south of the Garage Building. Arsenic concentrations exceeding background in soil between a depth of greater than 3 feet to 6 feet bgs occurred in two localized areas: in the vicinity of the Tool Issue Building (approximately 0.2 acre) and in the vicinity of the eastern end of the Warehouse Building, including the area between the building and the SacRT light rail line (approximately 0.3 acre). In the vicinity of the Tool Issue Building, the vertical extent of arsenic concentrations exceeding background appeared to extend to a depth of at least 6 feet bgs but did not exceed 11 feet bgs. In the vicinity of the eastern end of the Warehouse Building, the vertical extent of arsenic concentrations exceeding background also extended to a depth of at least 6 feet bgs, but the total depth was unknown. Additional soil characterization was necessary to refine the lateral and vertical extent of arsenic-impacted soil to support the remedy selection and design, which prompted an additional soil investigation in 2021.

2.2.5 Phase I Environmental Assessment

In 2020, AECOM performed a Phase I ESA of the Site to evaluate potential environmental liabilities resulting from past or current uses (AECOM, 2020). The Phase I ESA identified five recognized environmental conditions (RECs) associated with the Site. These RECs include the following.

1. The presence of potentially uncharacterized environmental impacts associated with 11 vehicle hydraulic lifts and related hydraulic oil reservoirs in the Garage Building, Vehicle OWS #1 at the Garage Building, and Vehicle OWS #2 near the Treated Wood Waste Area. These features have since been removed and investigated as discussed in Sections 2.2.1 and 2.2.7.
2. Lack of information or documentation regarding the removal of Tool Issue Building USTs 2 and 3. Removal documentation for these USTs was later found and documented in the SCR Addendum (AECOM, 2021a).
3. The presence of PCBs in building materials with concentrations greater than 50 mg/kg. For demolition and disposal purposes, building materials with PCB concentrations greater than or equal to 50 mg/kg are considered PCB bulk product waste under Title 40, Code of Federal Regulations Part 761 and are classified as hazardous waste by DTSC. Any PCB-related work at the Site (e.g., inspection, removal, or clean-up) must be performed by individuals trained and qualified to do so. PCB abatement has since been completed in the Hazmat Building.
4. The presence of potentially uncharacterized PCE in soil gas and the potential for vapor encroachment for buildings within 100 feet of PCE-impacted areas. Additional soil gas characterization for PCE and other VOCs was performed as part of the 2021 investigation and the results are presented in Section 2.2.8.
5. The presence of potentially uncharacterized arsenic in soil. Additional soil characterization for arsenic was performed as part of the 2021 investigation and the results are presented in Sections 2.2.8 (AECOM, 2021a).

2.2.6 Soil Vapor Extraction Pilot Study

In 2020, AECOM initiated a pilot study in the vicinity of the Tool Issue Building to determine whether soil vapor extraction (SVE) would be an effective technology to address VOC contamination in soil gas (AECOM, 2021b). The pilot study was conducted in two phases. In May 2020, an initial 5-day pilot test (Phase I) was performed using five SVE wells and a portable SVE unit to evaluate vapor recovery rates obtainable at various applied vacuum pressures and estimate the area of influence and efficiency of a given well or combination of wells. In August 2020, long-term pilot test operation of the SVE system (Phase II) began using information learned from the 5-day pilot test. The SVE pilot study ended in April 2022 when the associated piping and equipment were decommissioned. The associated SVE wells were destroyed in June 2022 prior to implementing the Interim RAW. Quarterly system monitoring included collection and analysis of soil gas samples from SVE wells SVE-1 through SVE-5 and vapor monitoring wells SVM-1 through SVM-3. Analytical data for soil gas samples collected from vapor monitoring wells SVM-1 through SVM-3 in July 2021 were incorporated into the most recent 2021 investigation soil gas data set (AECOM, 2021d).

2.2.7 Garage Building Hydraulic Lift Removal

In 2020, SMUD removed the hydraulic vehicle lifts in the Garage Building. Prior to removal of the lifts, the hydraulic oil was removed. During removal, several of the subsurface hydraulic rams were found to have leaked hydraulic oil. Limited soil excavation was performed to remove contaminated soil. Subsequently, a soil investigation was performed to determine if any additional soil contamination was present. Soil samples were analyzed for TPH, PCBs, and California Administrative Manual 17 metals. PCBs and metals were not detected in soil above their respective SLs, except for arsenic; however, the detected arsenic concentration did not exceed the Site-specific background concentration. TPH_d and $TPH_{ho/mo}$ were detected in soil above their respective SLs. The TPH_d detections are likely associated with weathered hydraulic oil in the TPH_d carbon range because diesel was not used in the hydraulic lifts. Additional soil excavation was performed until confirmation soil sample analytical results indicated TPH_d and $TPH_{ho/mo}$ concentrations were below their SLs as documented in the *Building F Removal and Soil Investigation Summary Report* (AECOM, 2021c). DTSC concurred with the report’s no further action recommendation (DTSC, 2022).

2.2.8 2020-2021 Soil Gas and Soil Investigations

From June 2020 to March 2021, AECOM conducted Site investigation activities to (1) further characterize the lateral and vertical extent of arsenic in soil, (2) further characterize the lateral and vertical extent of VOCs in soil gas based on the residential and commercial/industrial SVSLs derived using a more conservative AF of 0.03 proposed by DTSC (California Environmental Protection Agency, 2020), and (3) determine if any of the 19 VOCs that previously had elevated method detection limits and naphthalene, which was previously not analyzed for, are present in soil gas at concentrations exceeding commercial/industrial and/or residential SVSLs (AECOM, 2021a). From July to August 2021, AECOM conducted Site investigation activities to further characterize the lateral and vertical extent of VOCs in soil gas, evaluate seasonal and temporal variations in soil gas concentrations, utilize sub-slab vapor data to further develop lines of evidence regarding soil vapor attenuation at the Site, and utilize sewer gas data to assess sewer lines as a potential preferential pathway for vapor intrusion (VI) (AECOM, 2021c).

Soil. Based on previous and 2020-2021 investigations, arsenic concentrations in soil exceeding the 17.53 mg/kg background concentration at a depth of 3 feet bgs or less was identified in five areas of the Site with an estimated combined area of approximately 1.7 acres: in the vicinity of the Tool Issue Building, west of the Hazardous Material Building, and south of the Garage Building (approximately 0.2 acre combined); south of the Warehouse Building (approximately 0.9 acre); and in the vicinity of the Salvage Building (approximately 0.6 acre).

Arsenic concentrations exceeding background in soil at a depth greater than 3 feet bgs were identified in three localized areas: south of the east end of the Warehouse Building (approximately 0.3 acre extending to a depth of at least 10 feet bgs), south of the Tool Issue Building (approximately 0.03 acre extending to a depth between 6 and 11 feet bgs), and west of the Salvage Building (approximately 0.02 acre extending to a depth between 5 and 7.5 feet bgs).

Although the primary focus of the 2020-2021 investigation was to further refine the lateral and vertical extent of arsenic-impacted soil to support remedy selection and design, lead and $TPH_{ho/mo}$ concentrations exceeding their respective 80 and 2,400 mg/kg residential SLs were identified in a localized area within an area of arsenic-impacted soil west of the

Salvage Building. The vertical extent of lead and $TPH_{ho/mo}$ concentrations exceeding their residential SLs extend to a depth between 2 and 5 feet bgs.

Soil Gas. Eighteen analytes (benzene, benzyl chloride, BDCM, chloroform, 1,2-dibromoethane [DBE], 1,2-dichloroethane, *cis*-1,2-dichloroethene [DCE], 1,2-dichloropropane [DCP], 1,4-dioxane, ethylbenzene, n-heptane, hexane, naphthalene, PCE, toluene, trichloroethene (TCE), 1,2,3-trichloropropane [TCP], and TPH_g) were detected at concentrations exceeding commercial/industrial and/or residential SVSLs derived using the 0.03 AF. In comparison, only eight of these analytes (benzene, chloroform, 1,2-DBE, *cis*-1,2-DCE, 1,2-DCP, PCE, TCE, and 1,2,3-TCP) were detected at concentrations exceeding commercial/industrial and/or residential SVSLs derived using the 0.001 AF.

PCE in soil gas was previously identified as a COC at the Site because of the potential for unacceptable human health risk if soil gas migrates into indoor air (i.e., the VI pathway). Based on the 2020-2021 investigations and a 0.001 vapor AF, *cis*-1,2-DCE, chloroform, and TCE were identified as additional COCs in soil gas. 1,2-DBE and naphthalene, which were previously identified during the fall/winter 2020/2021 sampling event as COCs in soil gas, were not detected in shallow soil gas during the summer 2021 sampling event. When a more conservative 0.03 AF was applied, benzene, BDCM, ethylbenzene, were also identified as COCs in soil gas. 1,2-DBE, naphthalene, and toluene detected during the fall/winter 2020/2021 sampling event were not confirmed to be COCs in soil gas based on the summer 2021 sampling results.

The extent of soil gas contamination was greater based on fall/winter 2020/2021 sampling results when compared to the summer 2021 sampling results. The lateral extent of VOC concentrations in shallow soil gas exceeding the SVSLs derived using a 0.03 AF extend beneath approximately 9.2 acres based on fall/winter 2020/2021 data compared to 8.4 acres based on the summer 2021 data. The lateral extent of fall/winter 2020/2021 VOC concentrations in shallow soil gas exceeding the SVSLs derived using a 0.001 AF is limited to two localized areas comprising approximately 0.65 acre. In comparison, the lateral extent of summer 2021 VOC concentrations in shallow soil gas exceeding the SVSLs derived using a 0.001 AF is limited to three localized areas comprising approximately 0.36 acre.

Sub-Slab Vapor. The SCR Addendum (AECOM, 2021a) recommended sub-slab vapor sampling beneath existing buildings overlying areas where soil gas COCs were detected at concentrations exceeding their SVSLs to evaluate soil vapor conditions beneath the buildings to further develop lines of evidence regarding soil vapor attenuation at the Site. Therefore, vapor samples were collected and analyzed from immediately beneath the concrete slab foundations of the Garage Building, Shops Building, Hazardous Material Building, Salvage Building, and Tool Issue Building.

PCE was detected in sub-slab vapor beneath the Tool Issue Building at a concentration exceeding the residential SVSL derived using a 0.001 AF. No VOCs were detected in sub-slab vapor at concentrations exceeding the commercial/industrial SVSL derived using a 0.001 AF. When a more conservative 0.03 AF was applied, PCE was detected in sub-slab vapor beneath the Garage Building, Shops Building, Hazardous Material Building, Tool Issue Building, and Salvage Building at concentrations exceeding the residential SVSL. The PCE concentrations detected in sub-slab vapor beneath the Shops Building, Hazardous Material Building, and Tool Issue Building also exceeded the commercial/industrial SVSL. Additionally, TCE was detected in sub-slab vapor beneath the Tool Issue Building at a concentration exceeding the residential SVSL. TCE is a degradation product of PCE and can form where PCE is present. Therefore, PCE and TCE are considered sub-slab vapor COCs for the existing buildings at the Site.

Sewer Gas. The SCR Addendum recommended ambient air sampling of onsite subsurface pipe networks (e.g., sewers) in areas where detected VOC concentrations in soil gas exceed their SVSLs to assess preferential pathway VI potential from subsurface pipes entering buildings. Therefore, ambient air (sewer gas) samples were collected and analyzed from sewer line cleanouts within or immediately adjacent to buildings in areas where VOCs were previously detected in soil gas at concentrations exceeding their SVSLs.

No VOCs were detected in sewer gas at concentrations exceeding the SLs derived using a 0.001 AF. When a more conservative 0.03 AF was applied, benzene was detected in sewer gas associated with the Garage Building and Salvage Building at concentrations above the residential SL. Additionally, chloroform was detected in sewer gas associated with the Salvage Building at a concentration above the residential SL. Both of these buildings were previously used for equipment repair or dismantling, and the presence of benzene and chloroform in sewer gas may be attributable to Site use. Therefore, benzene is considered a sewer gas COC for the Garage Building and benzene and chloroform are considered sewer gas COCs for the Salvage Building.

2.3 Background Arsenic Concentrations

Laboratory analytical results for soil samples collected from the Site during previous investigations were used to derive a Site-specific arsenic background concentration (AECOM, 2019). The laboratory analytical data were obtained from 135 soil samples collected from 71 locations.

Site-specific arsenic background concentrations in soil were derived for the Site using the methods described in *Arsenic Strategies, Determination of Arsenic Remediation, Development of Arsenic Cleanup Goals* (DTSC, 2009). Although intended for clean-up goals, the guidance states: “The incremental cancer risk difference between background levels and proposed cleanup goals will be very small or insignificant in most cases.” This suggests that the methods for deriving clean-up levels also serves for background levels when conservatively evaluated. The methods used in this evaluation results in a range of prospective background concentrations and the selection is based on graphical assessment, statistical interpretation, Site knowledge, and professional judgement. Both the graphical and statistical methods were used to calculate the Site-specific arsenic background concentration. An optional step of comparing the graphical results (e.g., inflection point) with the statistical results was also performed. Although the Site soil appears to be heterogeneous both laterally and vertically, three data sets were evaluated, which included a combined data set consisting of all the soil types together and separate data sets for the coarse and fine grain soil types.

The graphical evaluation involved plotting the data and using visual cues, specifically a gap or shift in the slope of the primary line group close to the origin, to identify the background concentration. The statistical evaluation assesses the characteristics of the data set, identifies outliers and then re-assesses the data set without the outliers. An upper confidence limit is calculated to determine the background concentration. The proposed Site-specific arsenic background concentration is supported by conservative interpretations of these lines of evidence.

The Graphical Evaluation results showed relative consistency between the three data sets for both the non-transformed and transformed data. The non-transformed data sets suggest a range of 7.3 to 29 mg/kg. The transformed data sets suggest a range of 7.5 to 16 mg/kg. An inflection point concentration of 10 mg/kg was observed in the non-transformed and transformed data sets for both the All and Fine Soil types.

The Statistical Evaluation is more precise and calculates a mathematical result. The transformed data sets showed 17.53 mg/kg for the All Soil, 12.98 mg/kg for the Coarse Soil, and 20.62 mg/kg for the Fine Soil data sets. The Statistical Evaluation results generally corroborate the observations of the Graphical Evaluation. Given the range of prospective values and the mixed distribution of coarse- and fine-grained soil throughout the Site, the All Soil value of 17.53 mg/kg from the Statistical Evaluation was selected and proposed for the arsenic background concentration at the Site in the SCR (AECOM, 2019), which was approved by DTSC (DTSC, 2020a).

2.4 Nature, Source, and Extent of Contamination

2.4.1 Type, Source, and Location of Contaminants

Soil

Based on previous investigations, arsenic concentrations in soil exceeding the 17.53 mg/kg background concentration at a depth of 3 feet bgs or less was identified in five areas of the Site with an estimated combined area of approximately 1.7 acres (Figure 2-2 and Table 2-1). The two largest areas of arsenic-impacted soil at a depth of 3 feet bgs or less are located south of the Warehouse Building (approximately 0.9 acre) and in the vicinity of the Salvage Building (approximately 0.6 acre). Three smaller areas of arsenic-impacted soil at a depth of 3 feet bgs or less are located in the vicinity of the Tool Issue Building, west of the Hazardous Material Building, and south of the Garage Building (approximately 0.2 acre combined).

Arsenic concentrations exceeding background in soil at a depth greater than 3 feet bgs were identified in three localized areas: south of the east end of the Warehouse Building (approximately 0.3 acre), south of the Tool Issue Building (approximately 0.03 acre) and west of the Salvage Building (approximately 0.02 acre). In the area south of the east end of the Warehouse Building, the vertical extent of arsenic concentrations exceeding background extends to a depth of at least 10 feet bgs in select sampling locations. In the area south of the Tool Issue Building, arsenic concentrations exceeding background extend to a depth between 6 and 11 feet bgs. In the area west of the Salvage Building, the vertical extent of arsenic concentrations exceeding background extend to a depth between 5 and 7.5 feet bgs.

Lead and $TPH_{ho/mo}$ concentrations exceeding their respective 80 and 2,400 mg/kg residential SLs were identified in a localized area within an area of arsenic-impacted soil west of the Salvage Building. The vertical extent of lead and $TPH_{ho/mo}$ concentrations exceeding their residential SLs extend to a depth between 2 and 5 feet bgs. Furthermore, lead and $TPH_{ho/mo}$ were identified as additional COCs in soil in the vicinity of borehole VW35.

Soil Gas

PCE in soil gas was previously identified as a COC at the Site because of the potential for unacceptable human health risk if soil gas migrates into indoor air (i.e., the VI pathway). Based on the 2020-2021 investigations and a 0.001 vapor AF, the following VOCs were identified as COCs in soil gas:

- Chloroform (detected in soil gas at concentrations up to 1,500 $\mu g/m^3$)
- 1,2-DBE (detected in soil gas at concentrations up to 24 $\mu g/m^3$)
- *cis*-1,2-DCE (detected in soil gas at concentrations up to 53,000 $\mu g/m^3$)
- PCE (detected in soil gas at concentrations up to 1,200,000 $\mu g/m^3$)
- TCE (detected in soil gas at concentrations up to 18,000 $\mu g/m^3$)

When a more conservative 0.03 vapor AF was used, the following VOCs were identified as additional COCs in soil gas:

- Benzene (detected in soil gas at concentrations up to 2,500 $\mu g/m^3$)
- BDCM (detected in soil gas at concentrations up to 60 $\mu g/m^3$)
- 1,2-DCP (detected in soil gas at concentrations up to 820 $\mu g/m^3$)
- Ethylbenzene (detected in soil gas at concentrations up to 220 $\mu g/m^3$)
- Naphthalene (detected in soil gas at concentrations up to 70 $\mu g/m^3$)
- Toluene (detected in soil gas at concentrations up to 11,000 $\mu g/m^3$)

Additionally, total petroleum hydrocarbons as gasoline (TPH_g) were detected in soil gas at concentrations up to 1,900,000 $\mu g/m^3$.

The lateral extents of VOC concentrations in soil gas exceeding their respective residential and commercial/ industrial SVSLs based on summer 2021 shallow soil gas data (i.e., from 4 to 5.5 feet bgs) are shown on Figures 2-3 and 2-4 (AECOM, 2021d) for primary soil gas COCs PCE, TCE, *cis*-1,2-DCE, BDCM, and chloroform. The lateral extent of summer 2021 VOC concentrations in shallow soil gas exceeding the SVSLs derived using a 0.001 AF is limited to three localized areas: in the vicinity of vapor monitoring wells SVM-1, SVM-3, and VW14 at the north side of the Tool Issue Building; an area encompassing vapor monitoring wells VW30, VW61, and VW64 south of the Garage Building; and an area encompassing vapor monitoring wells VW17 and VW18 along the northern property boundary. These three areas comprise approximately 0.36 acre.

The maximum summer 2021 concentrations of six soil gas COCs (BDCM, chloroform, 1,2-DCP, PCE, TCE, and *cis*-1,2-DCE) were detected in shallow soil gas samples collected from 4 to 5.5 feet bgs.

2.4.2 Extent of Soil Contamination

The estimated lateral extent of elevated arsenic is shown on Figure 2-2. As shown on Figure 2-2, lead and $TPH_{ho/mo}$ concentrations exceeding the 80- and 2,400-mg/kg residential SLs, respectively, were detected within the areas of arsenic-impacted soil within the property boundary.

2.4.3 Health Effects of Contaminants

Potential exposures to the COCs could result from dermal contact and direct ingestion of the affected soil, as well as inhalation of airborne dust particulates. Inhalation of high levels of arsenic can cause a sore throat or irritated lungs. Ingesting very high levels can result in death. Exposure to lower levels of arsenic can cause nausea and vomiting, decreased production of red and white blood cells, abnormal heart rhythm, damage to blood vessels, and a sensation of “pins and needles” in hands and feet. Low level exposures can also cause a darkening of the skin and the appearance of small corns or warts on the palms, soles, and torso. Several studies have shown that ingestion of inorganic arsenic can increase the risk of skin cancer and cancer in the lungs, bladder, liver, kidney, and prostate; inhalation can increase the risk of lung cancer.

Lead is a bio-accumulative substance and a reproductive and developmental toxin. Lead poisoning is one of the most commonly reported occupational diseases among adults due to inhalation of dust or fumes. Lead can impair the nervous system, affecting hearing, vision, and muscle control. It is toxic to lungs, kidneys, blood, and heart. Possible exposure pathways include ingestion and inhalation. Symptoms develop more quickly through inhalation exposure than ingestion since absorption takes place through the respiratory tract rather quickly. Acute lead poisoning is most common in children with history of pica; symptoms include anorexia, vomiting, malaise, and convulsions due to increased intracranial pressure, which may lead to permanent brain damage. Exposure in children can cause irreversible learning deficits, mental retardation, weight loss, weakness, anemia, cognitive dysfunction, and delayed neurological and physical development. Lead is considered a teratogen but is not a suspected carcinogen.

VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. Possible exposure pathways include inhalation of vapors, dermal contact, and ingestion. Health effects may include symptoms such as eye, nose and throat irritation, headaches, loss of coordination and nausea, and damage to liver, kidney, and central nervous system. Some VOCs are suspected or known carcinogens.

2.5 Human Health Risk Assessment

This section summarizes the risk evaluation results from the SCR Addendum (AECOM, 2021a). No additional risk evaluation for future conditions is necessary for conducting this interim removal action. As described in Section 7.0, a Site-specific health and safety plan (HASP) will identify chemical and physical hazards to remediation workers associated with the planned activities and will specify minimum levels of training, protection, and safe operating guidelines for workers in compliance with Hazardous Waste Operations and Emergency Response (HAZWOPER) and California Occupational Safety and Health Administration (OSHA) regulations.

A preliminary human health exposure assessment was performed for soil and groundwater (AECOM, 2021a). A focused baseline Human Health Risk Assessment (HHRA) was performed for the VI exposure pathway. An ecological risk evaluation was not conducted as the Site does not provide suitable habitat for ecological receptors and thus ecological exposure pathways are considered incomplete.

2.5.1 Identification of Chemicals of Concern

Based on the HHRA calculations, contaminants that pose unacceptable carcinogenic risk and/or noncarcinogenic hazard are identified as COCs.

Soil

Based on soil sampling performed at the Site, the primary risk driver from soil exposure is arsenic. The low toxicity criterion for arsenic suggests that even at background levels there is substantial risk. Potential exposure routes for soil include inhalation of soil particulates and direct contact via incidental ingestion and dermal contact. The majority of the Site is covered with buildings and pavement; therefore, under current conditions Site workers are unlikely to be exposed to soil at the Site unless they are involved in landscape maintenance in unpaved areas or construction activities involving excavation, trenching, or pavement removal. Site personnel engaging in activities that could result in inhalation of soil particulates or direct soil contact can minimize their potential risk by reducing dust generation, wearing personal protective equipment (PPE), and following good sanitation practices.

Groundwater

Based on groundwater sampling performed at the Site, the primary risk driver from groundwater exposure is PCE. Potential groundwater exposure routes include direct contact via ingestion and dermal contact. Groundwater is located greater than 35 feet bgs and there are no water wells located on Site; therefore, these exposure pathways are currently incomplete for Site workers. Additionally, PCE concentrations detected in groundwater are below the 5.0 µg/L primary MCL; therefore, the PCE concentrations in groundwater are within acceptable limits for potable use should the groundwater be extracted for such use in the future.

Indoor Air

The Site was used for limited commercial and industrial purposes as all activities formerly conducted at the Site have either been transferred to other SMUD facilities or are no longer conducted by SMUD as of December 2021. Following soil and soil gas remediation, the potential future Site redevelopment includes a mix of residential and commercial/industrial uses.

For the current commercial/industrial worker exposure scenario evaluated in the HHRA, the inhalation of vapors in indoor air was considered a complete pathway. To address potential risk to building occupants, SMUD conducted indoor air sampling within the Tool Issue Building in December 2016 and April 2019 (AECOM, 2019). The Tool Issue Building was selected for indoor air sampling because it represented the worst-case scenario in terms of the building's proximity to the highest VOC concentrations detected in soil gas at the Site. Based on the indoor air sampling results, it was concluded that VI was not an immediate concern. Therefore, additional indoor air sampling was not performed, and potential indoor air risk for current receptors was not calculated in the HHRA.

Inhalation of vapors in indoor air is considered a potentially complete pathway for potential future residents and commercial/industrial workers. Future redevelopment of the Site may expose construction workers to VOCs migrating from the subsurface to outdoor air while working in an excavation trench. Exposure to volatiles is expected to be *de minimus* due to mixing with outdoor air. Thus, this potentially complete, yet insignificant, exposure pathway was not quantitatively evaluated in the HHRA.

Soil vapor data collected in November and December 2020 from 5.5 feet bgs at 42 vapor monitoring wells (VW16A through VW57A) and March 2021 from 5.5 feet bgs at six vapor monitoring wells (VW24A, VW30A, VW42A, VW45A, VW48A, VW49A) and from 4.0 or 5.0 feet bgs at three SVE system vapor monitoring wells (SVM-1 through SVM-3) were used to evaluate soil vapor risk for potential future residents and commercial/industrial workers. When more than one result was available for a particular sample location, the highest detected analyte concentration was used in the risk evaluation for that location. Chemicals of potential concern (COPCs) are the contaminants suspected of being site-related and are the analytes carried through the HHRA's quantitative risk calculations. A chemical was identified as a COPC if its maximum detected concentration exceeded its SVSL. Additionally, chemicals detected at concentrations below their respective SVSLs were conservatively carried through the HHRA's quantitative risk calculations.

The risk characterization is the presentation of the quantitative risk results with supporting definitions, context, and site applicability. Per U.S. Environmental Protection Agency (USEPA) (USEPA, 1991), an excess lifetime cancer risk (ELCR) of $1x10^{-6}$ or less is considered *de minimis* risk. A noncancer hazard index (HI) of less than 1 is also acceptable because the concentrations are cumulatively below harmful levels. USEPA (1991) uses the ELCR range of 10^{-4} to 10^{-6} as a "target risk management range." Risks in this range may be acceptable for risk management decisions. Consistent with the screening-level evaluation described in Section 2.4.2, two AFs (0.03 and 0.001) were utilized in the HHRA for the VI pathway.

2.5.2 Cumulative Risk and Hazard Evaluation

The risk characterization from the SCR Addendum (AECOM, 2021a) for residential and commercial/industrial worker receptors using SVSLs derived from AFs of 0.03 and 0.001 is summarized below.

- Using an AF of 0.03, the future resident ELCR from exposure to soil vapor is $2x10^{-2}$, which is greater than the risk management range. The primary cancer risk driver is PCE ($2.1x10^{-2}$), with decreasing contributions from TCE ($9.4x10^{-4}$), chloroform ($3.4x10^{-4}$), 1,2-DBE ($3.3x10^{-5}$), naphthalene ($2.5x10^{-5}$), 1,2-DCP ($2.4x10^{-5}$), benzene ($1x10^{-5}$), BDCM ($9.5x10^{-6}$), and ethylbenzene ($1.8x10^{-6}$). The noncancer HI for soil vapor exposure is 578, which is greater than the safe dose threshold of 1. The primary hazard driver is PCE (229), with decreasing contributions from TCE (215), *cis*-1,2-DCE (127), 1,2-DCP (4.3), and toluene (0.92).
- Using an AF of 0.001, the future resident ELCR from exposure to soil vapor is $7x10^{-4}$, which is greater than the risk management range. The primary cancer risk driver is PCE ($7.0x10^{-4}$), with decreasing contributions from TCE ($3.1x10^{-5}$), chloroform ($1.1x10^{-5}$), and 1,2-DBE ($1x10^{-6}$). The noncancer HI for soil vapor exposure is 19, which is greater than the safe dose threshold of 1. The primary hazard driver is PCE (7.6), with decreasing contributions from TCE (7.2), and *cis*-1,2-DCE (4.2).
- Using an AF of 0.03, the future commercial/industrial worker ELCR from exposure to soil vapor is $5x10^{-3}$, which is greater than the risk management range. The primary cancer risk driver is PCE ($4.8x10^{-3}$), with decreasing contributions from TCE ($1.5x10^{-4}$), chloroform ($7.8x10^{-5}$), 1,2-DBE ($7.6x10^{-6}$), naphthalene ($5.8x10^{-6}$), 1,2-DCP ($5.5x10^{-6}$), benzene ($2.8x10^{-6}$), and BDCM ($2.2x10^{-6}$). The noncancer HI for soil vapor exposure is 136, which is greater than the safe dose threshold of 1. The primary hazard driver is PCE (53.3), with decreasing contributions from TCE (51.7), *cis*-1,2-DCE (29.2), and 1,2-DCP (1.0).
- Using an AF of 0.001, the future commercial/industrial worker ELCR from exposure to soil vapor is $2x10^{-4}$, which is within the risk management range. The primary cancer risk driver is chloroform, with decreasing contributions from PCE and 1,2-DBE. The noncancer HI for soil vapor exposure is 5, which is greater than the safe dose threshold of 1. The primary hazard driver is PCE (1.8), with decreasing contributions from TCE (1.7), and *cis*-1,2-DCE (1.0).

COCs are contaminants that pose unacceptable risk. Based on the HHRA, the soil gas COCs are listed below by receptor and the applicable AF.

- Future resident soil vapor exposure scenario (0.03 AF) – benzene, BDCM, chloroform, 1,2-DBE, *cis*-1,2-DCE, ethylbenzene, naphthalene, PCE, toluene, and TCE.
- Future resident soil vapor exposure scenario (0.001 AF) – chloroform, 1,2-DBE, *cis*-1,2-DCE, PCE, and TCE.
- The future commercial/industrial worker soil vapor exposure scenario (0.03 AF) – benzene, BDCM, chloroform, 1,2-DBE, *cis*-1,2-DCE, 1,2-DCP, naphthalene, PCE, and TCE.
- The future commercial/industrial worker soil vapor exposure scenario (0.001 AF) – chloroform, PCE, and TCE.

2.5.3 Point Risk and Hazard Evaluation

In order to limit uncertainty associated with such a large site, point risk estimates were developed for the future resident and commercial/industrial worker scenarios using the 0.03 and 0.001 AFs to evaluate if portions of the Site exhibit unacceptable risks and/or hazards.

To calculate the cumulative ELCR and HI for each receptor, the individual chemical risks and hazards were summed at each sample location. Non-detect results were not included in point risk estimates. Details of the point risk estimates are presented in the SCR Addendum (AECOM, 2021a).

For the future resident scenario based on a 0.03 AF, potentially unacceptable risks and/or hazards were calculated for the majority of sample locations distributed across the Site. The majority of unacceptable risks and hazards were driven by the presence of benzene, chloroform, 1,2-DBE, PCE, TCE, toluene, and naphthalene. Acceptable risks were limited to locations VW37, VW42, VW43, VW46, VW47, and SVM-2. In comparison, based on a 0.001 AF, potentially unacceptable risks and/or hazards were limited to locations VW19 (cancer risk), VW24 (cancer risk), VW30 (cancer risk), VW48 (cancer risk), and SVM-1 (cancer risk and noncancer hazard), which were driven by the presence of PCE, TCE, and chloroform.

For the future commercial/industrial worker scenario based on a 0.03 AF, potentially unacceptable risks and/or hazards were calculated for locations in the northern portion of the North Corporation Yard (VW16 through VW19, VW21 through VW27, VW29, VW30, VW44, VW45, VW52, and VW54). In the southern portion of the North Corporation Yard, potentially unacceptable risks and/or hazards were limited to VW34 through VW36, VW48, and SVM-1. Potentially unacceptable risks and hazards were driven by the presence of benzene, chloroform, 1,2-DBE, PCE, TCE, and naphthalene. In comparison, potentially unacceptable risks and/or hazards based on a 0.001 AF were calculated for only two locations (SVM-1 and VW30). Potentially unacceptable risks and hazards were driven by the presence of chloroform, PCE, and TCE.

2.5.4 Potential Exposure to Human and Ecological Receptors

Residential neighborhoods are located adjacent to the Site on the western boundary, north of Folsom Boulevard north of the Site, and south of U.S. Highway 50 south of the Site. Seven schools are located within approximately 0.5 mile from the Site (DTSC, 2012). Surface runoff from the Site is collected by storm drains and transported by the sewer system for off-site treatment. The Site is not open to public access, so exposure to contaminated media on Site would be restricted to SMUD personnel. The Site is considered to be unsuitable habitat for ecological receptors due to its highly developed nature.

Based on soil sampling performed at the Site, the primary risk driver from soil exposure is arsenic. Potential exposure routes for soil include inhalation of soil particulates and direct contact via incidental ingestion and dermal contact. To mitigate against potential exposure routes, current land use controls (LUCs) implemented at the Site include perimeter fences with security gates, routine security patrols, and construction/maintenance project reviews by SMUD environmental staff. Additionally, the majority of the Site is covered with buildings and pavement; therefore, under current conditions Site workers are unlikely to be exposed to soil at the Site unless they are involved in landscape maintenance in unpaved areas or construction activities involving excavation, trenching, or pavement removal. Site personnel engaging in activities that could result in inhalation of soil particulates or direct soil contact can minimize their potential risk by reducing dust generation, wearing PPE, and following good sanitation practices.

Based on groundwater sampling performed at the Site, the primary risk driver from groundwater exposure is PCE. Potential groundwater exposure routes include direct contact via ingestion and dermal contact. Groundwater is located at approximately 35 feet bgs and there are no water wells located on Site; therefore, these exposure pathways are currently incomplete. Additionally, PCE concentrations detected in groundwater are below the 5.0 µg/L primary MCL; therefore, the PCE concentrations in groundwater are within acceptable limits for potable use should the groundwater be extracted for such use in the future.

Building occupants may be exposed to volatile chemicals through the VI pathway. In December 2016, SMUD performed an indoor air quality assessment at the Tool Issue Building for VOCs, mold, and dust. PCE was not detected in the indoor air samples collected from the Tool Issue Building. SMUD proceeded with collection of additional indoor air samples from the Tool Issue Building in April 2019 following review of the 2018 soil gas investigation findings to determine if there is unacceptable indoor air risk to building occupants from PCE and its associated degradation products. PCE was detected in 2 of 6 indoor air samples collected; however, the detected concentrations were less than the 0.46 µg/m^3 residential ambient air SL (DTSC, 2020b). *Cis*-1,2- DCE was the only PCE degradation product detected. *Cis*-1,2-DCE was detected in 1 of 6 indoor air samples collected, and the detected concentration was less than the 8.3 µg/m^3 residential ambient air SL (DTSC, 2020b).

3.0 Removal Action Requirements, Objectives, and Cleanup Goals

The following subsections describe the applicable or relevant and appropriate requirements (ARARs), RAOs, and cleanup goals for Site soil. Site soil vapor will be addressed in a separate RAP.

3.1 Applicable or Relevant and Appropriate Requirements

ARARs are federal and state environmental statutes, regulations, and standards. Applicable requirements are federal or state laws or regulations that specifically address a hazardous substance, pollutant, contaminant, removal action, or location. Relevant and appropriate requirements that, while not "applicable," address problems or situations sufficiently similar to those encountered that their use is well suited to the particular site. State requirements are ARARs only if they are more stringent than federal requirements.

In addition to ARARs, this analysis includes an evaluation of To-Be-Considered (TBC) criteria. TBCs are advisories, criteria, or guidance that may be considered for a particular action or specific issue, as appropriate. TBCs are not ARARs because they are neither promulgated nor enforceable.

The ARARs or TBCs may be: 1) chemical; 2) location; or 3) activity specific. Chemical specific ARARs or TBCs are usually health- or risk-based numerical values or methodologies used to determine acceptable concentrations of chemicals that may be found in, or discharged to, the environment. Location-specific ARARs or TBCs restrict actions or contaminant concentrations in certain environmentally sensitive areas.

Examples of areas regulated under various federal laws include locations where endangered species or historically significant resources are present. Action-specific ARARs or TBCs are usually technology- or activity-based requirements or limitations on actions or conditions involving specific chemicals of concern. A list of the potential ARARs and TBCs for the Site is presented in Appendix A.

3.2 Removal Action Objectives

RAOs have been established that are protective of human health and the environment and reduce the potential for exposure to the COCs in soil encountered at the Site. COPCs are contaminants suspected of being site-related and were carried through the HHRA's quantitative risk calculations. Based on the HHRA calculations, contaminants that pose unacceptable carcinogenic risk and/or noncarcinogenic hazard are identified as COCs. The HHRA identified arsenic, lead, and $TPH_{ho/mo}$ as COCs in soil within portions of the Site north of the light rail line (AECOM, 2021a). The following RAOs were developed for soil within the portions of the Site identified by the HHRA as having unacceptable carcinogenic risk and/or noncarcinogenic hazard.

- Prevent direct human contact with, inhalation of, and ingestion of arsenic concentrations in soil exceeding the site-specific background concentration.
- Prevent direct human contact with, inhalation of, and ingestion of lead concentrations in soil corresponding to a 1 microgram per deciliter source-specific incremental change in blood lead levels.
- Prevent direct human contact with, inhalation of, and ingestion of $TPH_{ho/mo}$ concentrations in soil corresponding to a hazard index of greater than 1.
- Reduce VOC concentrations in the soil gas contamination area by removing VOC mass from the source area identified at the north of the Tool Issue Building.

3.3 Removal Action Cleanup Goals

Arsenic was identified in the risk assessment as the chemical posing the greatest risk to human health. The cleanup goal for arsenic in Areas #1 through #8 is based upon its background concentration in soil and is set at 17.53 mg/kg consistent with the Site-specific background concentration calculated in the SCR (AECOM, 2019). For Areas #1 through #8, the cleanup goals for lead and $TPH_{ho/mo}$ are set at 80 mg/kg and 2,400 mg/kg respectively, which are the residential SLs (DTSC, 2020b) for these contaminants. For Area #9, the cleanup goals for soil vapor will be addressed in a future RAP.

4.0 Removal Action Alternative Evaluation

This section identifies and screens possible removal action alternatives for soil that may best achieve the RAOs identified in Section 3.2. Remedial actions for soil vapor will be addressed in a separate RAP. The removal action alternatives for soil were screened and evaluated based on their effectiveness, implementability, and cost.

4.1 Identification of Soil Removal Action Alternatives

The response actions to address COCs in soil include excavation and off-Site disposal, on-Site containment/capping in-place, and land use controls. These response actions were assembled into candidate removal alternatives for the Site. Screening of several technology types using the above criteria was conducted to select removal actions for further evaluation. Based on this screening, the three removal action alternatives identified and developed are:

- Alternative 1 – No Further Action
- Alternative 2 – Soil Excavation/Off-Site Disposal
- Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

4.1.1 Alternative 1 – No Further Action

As required by DTSC, the No Further Action alternative has been included to provide a baseline for comparisons among other removal alternatives. The No Further Action alternative would not require implementing any measures at the Site, and no costs would be incurred. Future development of the Site is not part of the remedy; therefore, any future construction costs (e.g., asphalt removal/resurfacing) are not included in Alternative 1 or the other remedial alternatives. Alternative 1 includes no new LUCs, no maintenance of existing LUCs, no soil excavation, and no monitoring.

4.1.2 Alternative 2 – Soil Excavation/Off-Site Disposal

Under Alternative 2, excavation and off-Site disposal of on-Site contaminated soil outside of the existing building footprints would be performed to prevent human exposure to COCs in soil and protect groundwater (Figure 4-1). Alternative 2 includes implementation of LUCs to prevent contact with soil contaminants until after excavation is completed, cleanup goals are achieved, and LUCs can be removed.

Alternative 2 consists of excavating and transporting impacted on-Site soil to appropriate, permitted off-Site facilities for disposal; backfilling the excavation with clean imported fill (Class II aggregate base); and restoring the Site with gravel surface after excavation. The Salvage Building and the Tool Issue Building, which are located within three of the proposed soil excavation areas, will be demolished prior to implementing the removal action. Excavation includes using loaders, excavators, and/or other appropriate equipment. Based upon arsenic and lead soil concentrations, most of the soil excavated from the Site is assumed to be classified as non-hazardous waste. For the purposes of evaluating Alternative 2, it is assumed that 95 percent of the excavated soil will be non-hazardous waste and 5 percent will be non-RCRA hazardous waste based on the potential exceedance of the soluble threshold limit concentration (STLC) of 5 milligrams per liter (mg/L) for arsenic or lead. It is not anticipated that the non-RCRA hazardous waste will need to be treated prior to disposal to comply with land disposal restrictions.

Excavation operations will generate dust emissions. Suppressant, water spray, and other forms of dust control may be required during excavation, and workers may be required to use PPE to reduce exposure to contaminants. Sloping excavation sidewalls may result in increased volume of soil requiring excavation. Confirmation soil sampling and analysis would be conducted to verify that cleanup criteria are met at the excavation bottom and perimeter. Excavation may require soil stockpiling prior to disposal. To achieve the RAOs, soil across the Site requires removal to a depth of approximately 3 feet in most locations and to a depth of greater than 10 feet bgs in the southeast corner of the Site near the Warehouse Building. Any residual soil contamination not addressed by this interim remedy would be addressed by the final remedy that will be selected in the final remedy RAP.

As shown in Table 4-1, the volume of soil to be excavated would be approximately 8,400 bank cubic yards (excluding soil excavated to slope the excavation sidewalls).

Soil samples from the sides and bottom of the completed soil excavation would be collected to assess the COCs concentrations to verify that cleanup levels have been met and RAOs for the Site have been achieved. Confirmation samples will also be used to determine whether arsenic-impacted soil extends off-Site and beneath the Warehouse Building. If arsenic-impacted soil extends off-Site and beneath the Warehouse Building, this soil would be addressed in the final remedy RAP. Excavations would be backfilled to existing ground surface. The excavations would be backfilled first with any available clean excavation side slope material that was removed to slope the excavation sidewalls followed by clean imported fill material (Class II aggregate base). Imported backfill material will be compliant with DTSC guidance, *Information Advisory, Clean Imported Fill Material* (DTSC, 2001). After backfilling is completed, the Site surface would be restored to a gravel surface.

4.1.3 Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

Alternative 3 consists of removing and transporting impacted soil from limited areas of the Site to appropriate, permitted off-Site facilities for disposal, capping the surface of the remaining on-Site impacted areas outside of existing building footprints with asphalt pavement, and implementing LUCs (Figure 4-2). The Warehouse Building/loading dock would function as a cap for arsenic-impacted soil beneath the Warehouse Building/loading dock.

Alternative 3 consists of excavating and transporting limited areas of impacted on-Site soil (Area #1, #4, #5, #6, and #9) to appropriate, permitted off-Site facilities for disposal; backfilling the excavation with clean imported fill (Class II aggregate base); and restoring the Site with gravel surface after excavation. The Salvage and Tool Issue Building will be demolished prior to implementing the removal action. Excavation includes using loaders, excavators, and/or other appropriate equipment. Based upon arsenic and lead soil concentrations, the majority of soil excavated from the Site is assumed to be classified as non-hazardous waste.

Excavation operations will generate dust emissions. Suppressant, water spray, and other forms of dust control may be required during excavation, and workers may be required to use PPE to reduce exposure to contaminants. Sloping excavation sidewalls may result in increased volume of soil requiring excavation. Confirmation soil sampling and analysis would be conducted to verify that cleanup criteria are met at the excavation bottom and perimeter. Excavation may require soil stockpiling prior to disposal. To achieve the RAOs, soil from the limited areas requires removal to a depth of 3 feet or less in most locations. As shown in Table 4-2, the volume of soil to be excavated would be approximately 1,900 bank cubic yards (excluding soil excavated to slope the excavation sidewalls).

Soil samples from the sides and bottom of the completed soil excavation would be collected to assess the COCs concentrations to verify that cleanup levels have been met and RAOs for the Site have been achieved. Confirmation samples will also be used to determine whether arsenic-impacted soil extends off-Site and beneath the Warehouse Building. If arsenic-impacted soil extends off-Site and beneath the Warehouse Building, this soil would be addressed in the final remedy RAP.

Excavations would be backfilled to existing ground surface. The excavations would be backfilled first with any available clean excavation side slope material that was removed to slope the excavation sidewalls followed by clean imported fill material (Class II aggregate base). Imported backfill material will be compliant with DTSC guidance, *Information*

Advisory, Clean Imported Fill Material (DTSC, 2001). After backfilling is completed, the Site surface would be restored to a gravel surface.

Asphalt caps would cover the remaining impacted areas (Area #2, #3, #7, and #8) (Figure 4-2). Capping would achieve the RAOs by preventing direct contact via incidental ingestion and dermal contact, inhalation of soil particulates, and infiltration of water that could mobilize COCs in soil to underlying groundwater. A security fence with signage would protect the integrity of the cap by minimizing the potential for trespass. A land use restriction would be executed between DTSC and the property owner and recorded as a land use covenant on the property deed to ensure that the caps are inspected and maintained, and that future uses of the property are consistent with the inspection and maintenance (I&M) of the cap. An I&M plan would be submitted and approved by DTSC. SMUD would enter into an I&M agreement with DTSC that would specify the I&M requirements and provide financial assurance for future I&M of the cap. The I&M plan would specify periodic inspections of the cap, inspection procedures, and reporting to DTSC. The I&M plan would also specify that work that could disturb the cap must be coordinated with and approved by DTSC, and a copy of a maintenance/repair record completed after an asphalt cap repair is sent to DTSC.

Land use/access restrictions (i.e., LUCs) will also be used to protect human health by preventing contact with contaminated soil. Land use/access restrictions are intended to eliminate exposure to site contaminants through site controls such as perimeter fences with security gates, routine security patrols, and construction/maintenance project reviews by SMUD environmental staff. Following implementation of Alternative 3, LUCs for the Site would be attached to the property deed in the form of deed restrictions for contamination remaining under the asphalt containment cap.

4.2 Evaluation Criteria

Each removal action alternative was independently analyzed without consideration to the other alternatives. Each of the removal action alternatives is screened based on effectiveness, implementability, and cost.

4.2.1 Effectiveness

In the effectiveness evaluation, the following factors are considered:

- *Overall Protection of Human Health and the Environment* – This criterion evaluates whether the removal alternative provides adequate protection to human health and the environment and is able to meet the Site’s RAOs.
- *Compliance with ARARs/TBCs* - This criterion evaluates the ability of the removal alternative to comply with ARARs and TBCs.
- *Short-Term Effectiveness* - This criterion evaluates the effects of the removal alternative during the construction and implementation phase until removal objectives are met. It accounts for the protection of workers and the community during removal activities and environmental impacts from implementing the removal action.
- *Long-Term Effectiveness and Permanence* - This criterion addresses issues related to the management of residual risk remaining on Site after a removal action has been performed and has met its objectives. The primary focus is on the controls that may be required to manage risk posed by treatment residuals and/or untreated wastes.
- *Reduction of Toxicity, Mobility, or Volume* - This criterion evaluates whether the removal technology employed results in significant reduction in toxicity, mobility, or volume of the hazardous substances.

4.2.2 Implementability

This criterion evaluates the technical and administrative feasibility of implementing the alternative, as well as the availability of the necessary equipment and services. This includes the ability to design and perform a removal alternative, ability to obtain services and equipment, ability to monitor the performance and effectiveness of technologies, and the ability to obtain necessary permits and approvals from agencies, and acceptance by the State and the community. DTSC reviewed the Draft Interim RAW and their comments are provided in Appendix F.

4.2.3 Cost

This criterion assesses the relative cost of each technology based on estimated fixed capital for construction or initial implementation and ongoing operational and maintenance costs. The actual costs will depend on true labor and material cost, competitive market conditions, final project scope, and the implementation schedule.

4.3 Evaluation of Removal Action Alternatives

Each alternative is discussed in the following sections.

4.3.1 Alternative 1 – No Further Action

The No Further Action alternative would not require implementing any measures at the Site, and no costs would be incurred. Consequently, there would be no activities that would disturb site soil, and therefore, no short-term risks to site workers or the community as a result of implementing this alternative.

However, under the No Further Action alternative, the impacts due to the presence of COCs in soil would not be addressed and there would be no reduction in the potential risks. This alternative, therefore, does not meet the effectiveness criterion. As a result, acceptance by the State and the community would be unobtainable.

4.3.2 Alternative 2 – Soil Excavation/Off-site Disposal

4.3.2.1 Effectiveness

Alternative 2 would involve excavation of impacted soil. Potential short-term risks to onsite workers, public health, and the environment could result from dust or particulates that may be generated during excavation and soil handling activities. These risks could be mitigated using PPE for onsite workers and engineering controls, such as dust suppression and additional traffic and equipment operating safety procedures, for protection of the surrounding community and to meet all ARARs. Excavation and disposal would remove the COCs from the Site, and therefore, eliminates the long-term risks and accomplishes the RAOs. Although the COCs will be removed from the Site, excavation and off-Site land disposal does not result in the reduction of toxicity or volume of the COCs. By placing the impacted soil in an engineered landfill suitable for receiving the concentrations of COCs, the mobility of the COCs will be reduced.

4.3.2.2 Implementability

Excavation/off-site disposal is a well-proven, readily implementable technology that is a common method for cleaning up contaminated sites. It is a relatively simple process, with proven results. Equipment and labor required to implement this alternative are uncomplicated and readily available. The depths of the identified contamination make excavation implementable. It is anticipated that regulatory approval would be granted since it is a proven and permanent technology. Acceptance by the State and the community for this alternative is considered high.

4.3.2.3 Cost

The estimated present value cost for excavation, transportation, and disposal of the impacted soils is approximately $1,800,000 as presented in Appendix B. This estimate includes permitting, excavation/removal, transportation, and disposal at approved off-Site disposal facilities.

4.3.3 Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

4.3.3.1 Effectiveness

Alternative 3 would involve excavation of a portion of the impacted soil. Potential short-term risks to onsite workers, public health, and the environment could result from dust or particulates that may be generated during excavation and soil handling activities. These risks could be mitigated using PPE for onsite workers and engineering controls, such as dust suppression and additional traffic and equipment operating safety procedures, for protection of the surrounding community and to meet all ARARs. Excavation and disposal would remove the COCs from a portion of the Site, and therefore, eliminates the long-term risks and accomplishes the RAOs in those areas of the Site. Although the COCs will be removed from the Site, excavation and off-Site land disposal does not result in the reduction of toxicity or volume of the COCs. By placing the impacted soil in an engineered landfill suitable for receiving the concentrations of COCs, the mobility of the COCs will be reduced.

Containment/capping-in-place would involve little to no disturbance of the impacted soil that will be capped. Therefore, there would be very little exposure to the COCs and the short-term risks would be low. The installation of a surface cap would require long-term inspection and maintenance to meet ARARs and provide long-term effectiveness. Periodic inspections would be required to check for settlement, cracking, ponding of liquids, erosion, and naturally occurring invasion by deep-rooted vegetation. Additionally, precautions would have to be taken to ensure that the integrity of the cap is not compromised by land use activities. Containment through surface capping would not lessen toxicity or volume of the COCs, but would limit mobility, specifically the prevention of surface water infiltration and thus, the potential downward migration of contaminants.

4.3.3.2 Implementability

Excavation/off-site disposal is a well-proven, readily implementable technology that is a common method for cleaning up contaminated sites. It is a relatively simple process, with proven results. Equipment and labor required to implement this alternative are uncomplicated and readily available. The depths of the identified contamination make excavation implementable. Containment is a relatively simple technology that is easily implemented and can be quickly installed. As COCs would remain onsite, obtaining permits and regulatory approval can be difficult. In addition, community acceptance for this alternative may be more difficult since the COCs would remain onsite.

4.3.3.3 Cost

The estimated present value cost for the implementation of Alternative 3 for 30 years is approximately $1,500,000 as presented in Appendix B.

4.4 Comparative Analysis of Removal Action Alternatives

A comparative analysis was conducted to identify the advantages and disadvantages of each removal alternative. The comparative analysis of the removal alternatives was conducted to address the criteria listed in Section 4.2.

4.4.1 Effectiveness

Under the No Further Action alternative, the impacts associated with the Site-specific COCs would not be addressed. Consequently, there would be no reduction in the potential risks and the RAOs would not be achieved. Alternative 2 (Excavation/Off-Site Disposal) will require removing, handling, and transporting the impacted soil, resulting in higher short-term exposure risks. Alternative 3 (Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs) involves activities that would disturb some impacted soil during excavation and grading. Therefore, there would be some short-term risks to onsite workers or the community as a result of implementing this alternative. However, it is expected that these risks for both alternatives can be sufficiently mitigated through site control measures.

Alternatives 2 and 3 reduce or eliminate potential exposure to COCs, and therefore, accomplish the RAOs. The Alternative 2 (Excavation/Off-Site Disposal) would remove the COCs from the Site and would not require any further management or site controls. Once implemented, Alternative 3 that includes containment/capping-in-place would require long-term monitoring to ensure its effectiveness. In addition, future changes in land use could disturb the soil.

Based upon this evaluation, Alternative 2 is favored under this criterion.

4.4.2 Implementability

No measures would be implemented for the No Further Action alternative. Containment/capping-in-place and excavation/off-site disposal are both well-proven, readily implementable technologies. However, Alternative 3 is less implementable due to land use control implementation that includes long-term cap monitoring and maintenance. Acceptance by the State and the community for Alternative 2 is considered higher than for Alternative 3 because the COCs will be removed from the Site under Alternative 2. Accordingly, Alternative 2 is favored by this criterion.

4.4.3 Cost Effectiveness

The estimated costs to implement the proposed alternatives is presented in Appendix B. The Alternative 2 cost of $1,800,000 is slightly greater than the Alternative 3 cost of $1,500,000.

4.5 Recommended Removal Action Alternative

Based on the comparative analysis described in Section 4.4, Alternative 2 (Soil Excavation/Off-Site Disposal) is the preferred and recommended removal action alternative for addressing the Site. This alternative was selected because Alternative 2 accomplishes the RAOs by reducing or eliminating potential exposure to COCs and is more implementable than Alternative 3. Although the costs for Alternative 2 are slightly greater than Alternative 3, Alternative 2 provides added benefits with regards to future use of the property.

The preferred remedy removes soil containing COCs above Site cleanup goals to eliminate direct exposure and enable redevelopment of the Site. The primary factors which supported the selection of Alternative 2 (soil excavation /off-site disposal) are: (1) this alternative is protective of human health and the environment, is cost effective, and is technically feasible; (2) it will not limit redevelopment of the Site with permanent LUCs; and (3) it will help minimize the potential for contaminants to migrate to groundwater. Furthermore, it was moderate in cost and hence the most cost effective of the alternatives that meets the threshold criteria requirements.

5.0 Removal Action Implementation

Implementation of the remedy consists of a series of separate tasks. The following sections discuss each task and the associated activities: Permitting (Section 5.1), Utility Clearance (Section 5.2), Site Preparation (Section 5.3), Soil Excavation Extent and Methodology (Section 5.4), Control Measures (Section 5.5), Air Monitoring During Soil Excavation (Section 5.6), Institutional Controls (Section 5.7), and Field Variances (Section 5.8).

5.1 Permitting

The following permits may be required for excavation operations.

- A grading permit from the City of Sacramento.
- A Sacramento Metropolitan Air Quality Management District (SMAQMD) Authority to Construct/Permit to Operate (soil excavation) may be required.
- SMUD has a USEPA Identification number as the generator of the waste.
- Coverage under the State's General Permit for Storm Water Discharges Associated with Construction and Land Disturbance Activities is anticipated because construction activity that results in a land disturbance will be more than 1 acre. However, the project land disturbance is anticipated to be less than 5 acres and may qualify for an Erosivity Waiver depending on the R factor calculated for the project that is partly based on the time of year and duration of construction activity.

The excavation and soil handling will be conducted by a qualified, HAZWOPER-trained, contractor using conventional earthwork equipment. The contractor will prepare a Site-specific HASP, which will address identification of hazards, hazard mitigation, safe work practices and emergency response procedures for the project. The Site-specific HASP will be prepared to comply with Title 29 Code of Federal Regulations (CFR) Section 1910.120 and Title 8 California Code of Regulations (CCR) Section 5192.

5.2 Utility Clearance

Prior to commencing excavation activities, Underground Service Alert of Northern California and Nevada (USA North 811) will be contacted at least 48 hours in advance to identify the location of utilities that enter the property. All proposed excavation areas will be clearly marked with white paint or surveyors flagging as required by North 811. North 811 will contact all utility owners of record within the site vicinity and notify them of the intent to excavate. All utility owners of record will be expected to clearly mark the position of their utilities on the ground surface throughout the designated area.

In addition, prior to any excavation, an independent utility location will be performed using geophysical methods. A licensed geophysical contractor will perform a survey with ground penetrating radar, electromagnetic, and magnetometer equipment to locate buried utility cables and other obstructions. After the areas are surveyed, any obstructions discovered will be clearly marked with paint and/or flagging.

Overhead utilities located within the limits of work for the planned excavation will be noted and marked with signage, as appropriate. Careful planning and appropriate measures will be taken to ensure equipment and trucks traveling to and from the Site stay clear of off-site overhead utilities. Sufficient offset distances (as specified in the HASP) between equipment and electric transmitting lines will be maintained if overhead utilities are encountered on site.

5.3 Site Preparation

5.3.1 Work Zone Delineation

Before any soil-disturbing activities are conducted at the Site, the work area will be secured to limit access to only authorized personnel. Work zones will be established using barriers and signage. The work area will be delineated with construction fencing (e.g., 6-foot high chain-link fencing), cones, barricades, and/or flagging, as appropriate for the work area and the work being conducted. A decontamination area will be identified and constructed at the Site, allowing for decontamination of construction equipment and capture of associated debris and decontamination water. Onsite workers will be briefed on the work zones and the procedures for entrance and egress to and from these areas. Personnel exiting the work areas will decontaminate and remove PPE at the personnel decontamination stations established adjacent to the work areas. Personnel will follow the decontamination procedures described in the forthcoming approved HASP. Decontamination fluids will be transferred to onsite water storage tanks for testing and disposal. Used PPE will be discarded and placed in containers for disposal.

5.3.2 Surveying

The post-excavation soil limits will be surveyed by a California-licensed surveyor. Survey data will be recorded and documented in the Removal Action Completion Report.

5.3.3 Demolition

Prior to initiation of the removal action, SMUD has scheduled to complete demolition of the Tool Issue Building, Salvage Building, and Garage Building and surrounding pavement. Additional demolition is not anticipated; however, if any site features remain, conventional construction equipment, such as an excavator, will be used to remove any surface features such as asphalt or concrete and any utilities at the excavation areas. Utilities present within the excavation area will remain in-place if feasible, otherwise, utilities will be capped and removed as necessary. Asphalt, concrete, and/or piping will be segregated and disposed of appropriately.

Vapor monitoring wells within the planned excavation areas and immediate vicinity were destroyed June 2022 in accordance with Sacramento County requirements. The vapor monitoring well destruction effort will be documented in the Removal Action Completion Report.

5.4 Soil Excavation Extent and Methodology

The soil from the excavation areas will be removed to minimize the potential for direct exposure to COCs in soils (Figure 5-1). Excavation areas will be sloped or benched as deemed appropriate by the California OSHA-competent person (29 CFR 1926.32(f)) to provide appropriate slope stability protection in accordance with OSHA regulations. The OSHA-competent person will be a licensed Civil Engineer when:

- excavation slope or bench, support, shield, or other protective system is designed per 29 CFR 1926.652(b)(3) or (b)(4), (c)(3) or (c)(4), and
- excavations in the vicinity of structures to determine if the structure is sufficiently removed from the excavation so as to be unaffected by the excavation activity or to design support systems to ensure the safety of employees and the stability of the structure.

If shoring becomes necessary, it will be installed in accordance with approved engineered designs to be provided by the shoring subcontractor. If needed, a ramp leading into the excavation will be sloped at a minimum of 3:1 to allow for safe excavator access. It is estimated that the total in-place volume of impacted soil for excavation is approximately 8,400 bank cubic yards. The excavation in the southeast corner of the Site near the Warehouse Building will extend to deeper than 10 feet bgs in the vicinity of sample WB10. However, excavation is not anticipated to reach the groundwater table, which is at approximately 35 feet bgs. A licensed Civil Engineer will determine if the Warehouse Building is sufficiently removed from the excavation so as to be unaffected by the excavation activity and, if necessary, will design support systems to ensure the safety of workers and the stability of the structure. Soil excavation and backfill activities (including mobilization and site restoration) are expected to take approximately 8 to 12 weeks to complete. Work would be conducted between 7 a.m. and 4 p.m., Monday through Friday.

The soil will be removed using standard earthmoving equipment (e.g., excavator, front end loader). Excavated soil will be segregated based on previous sampling data and other evidence, such as x-ray fluorescence (XRF) soil analyzer results, into three separate stockpiles: (1) potentially reusable fill stockpile (e.g., soil from excavation side slopes); (2) soil potentially requiring disposal as non-hazardous waste at a Class II or III landfill; and (3) soil potentially requiring disposal as California (non-RCRA)-hazardous waste at a Class I landfill. The selected XRF soil analyzer will be able to detect arsenic in soils below the arsenic background value of 17.53 mg/kg or parts per million. Stockpiling and segregation activities onsite will be limited by space constraints and excavation timeframes. If not directly loaded into trucks, the excavated soil will either be stockpiled or placed in covered soil bins until characterization and disposal arrangements are completed. Non-RCRA hazardous stockpiled soil will be placed on plastic sheeting and covered with plastic sheeting when not actively being worked on and at the end of each workday in compliance with the requirements of staging piles in 40 CFR 264.554 and remediation waste staging in California Health and Safety Code 25123.3 (a) (2) described below. Sandbags, or other weights, will be used to keep the plastic cover in place. The stockpiled soil will be placed within the property boundaries. If the excavation areas are not pre-characterized, soil samples will be collected from the stockpiles and submitted for chemical analyses to characterize the soil for disposal at a frequency of at least one four-point composite sample analyzed per 250 cubic yards. Waste characterization sampling procedures are further described in Section 6.2. Soil excavated from the Site may be classified as non-RCRA hazardous waste based on the potential exceedance of the STLC for lead or arsenic. It is not anticipated that the excavated soil will be classified as RCRA-hazardous or need to be treated prior to disposal to comply with land disposal restrictions. Soil will be disposed at appropriate landfills under appropriate documentation and in accordance with applicable federal, state, and local regulations.

Soil samples from the sides and bottom of the completed soil excavation will be collected to assess the COCs concentrations to verify that cleanup levels have been met and RAOs for the Site have been achieved as described in Section 6.1. Upon completion of excavation, final excavation shape and dimensions will be surveyed and documented. In excavations where the entry of personnel is not feasible, confirmation surveys will be collected remotely. Survey meters will be mounted on poles or other devices to allow them to be lowered into the excavations for surveying.

5.4.1 Staging Piles

Federal staging pile regulations in 40 CFR 264.554 and remediation waste staging in California Health and Safety Code 25123.3 (a) (2) were identified as ARARs in Appendix A. Remediation waste soil piles classified as hazardous waste will be removed from the Site and disposed within an off-site landfill within 90 days. The standards and design criteria for the remediation waste soil piles will comply with the requirements of staging piles in 40 CFR 264.554.

The remediation waste soil will be placed in roll-off bins or stockpiled within a perimeter fence that will have signage and be secured by using locked gates.

The remediation waste soil piles will be designed to prevent or minimize the releases of hazardous waste and hazardous constituents to the environment and minimize cross-media transfer by using best management practices (BMPs) such as liners, covers, and run-off/run-on controls. No waste-containing liquids will be placed in the hazardous waste soil piles. Unclassified soils or soils classified as hazardous waste will be placed on a high-density polyethylene plastic liner (20-mil for paved areas and 60-mil for unpaved areas). The remediation waste soil piles will be covered with 10-mil polyethylene sheeting and anchored by gravel or sand-filled bags. A linear sediment barrier (sandbag berm, asphalt curbing, or similar method) will be installed around the perimeter of the hazardous waste soil piles. The hazardous waste soil piles will be inspected weekly, and before, during (daily), and after storms during business hours. In addition, stockpile erosion, windblown dispersion, and run-on/run-off will be minimized using standard BMPs to avoid migration of sediment into the storm drain or water surfaces.

5.4.2 Area #9 Investigation Excavation

Soil at Area #9 will be excavated to approximately 15 feet bgs as part of a remedial investigation to determine the source of VOCs at that location. The presence of VOC contamination in the excavation sidewall soils will be evaluated using PID readings. If a PID reading of an excavation sidewall exceeds 5 parts per million, the excavation will be expanded to remove additional VOC-impacted soil. The contaminated soil will be excavated until PID readings indicate the contaminated soil has been removed or to the extent practicable.

5.4.3 Backfill and Site Restoration

5.4.3.1 Backfill Procedures

Excavations will be backfilled to at or near pre-excavation grade. The excavations will be backfilled first with any available clean excavation side slope material (Section 5.4) that was removed to slope the excavation sidewalls followed by clean imported fill material (Class II aggregate base). The clean backfill material will be moisturized as needed by hose or water truck prior to placement, or else mixed as the fill material is being placed. All backfill material will be placed in uniform horizontal layers not greater than 8 inches in loose thickness and thoroughly compacted in place with suitable equipment such as a roller. The backfilling process will continue until the desired site grade is reached.

5.4.3.2 Backfill Sampling

Excavation side slope material that was removed to slope the excavation sidewalls and can potentially be used for backfill material will be sampled at a frequency up to one four-point composite sample per 250 cubic yards of material. Samples will be analyzed for arsenic by USEPA Method SW6020 in accordance with DTSC guidance, *Information Advisory, Clean Imported Fill Material* (DTSC, 2001). Excavation side slope material removed from Area #3 will additionally be analyzed for lead by USEPA Method SW6020 and $\text{TPH}_{\text{ho/mo}}$ by USEPA Method SW8015.

Virgin Class II aggregate base used to backfill the excavation will be screened to ensure that contamination is not inadvertently brought onto the Site. Recycled aggregate base shall not be used. Aggregate base will be sourced from rock quarries. After the backfill source is selected, one four-point composite sample will be collected from the aggregate base source in accordance with DTSC guidance, *Information Advisory, Clean Imported Fill Material* (DTSC, 2001). These samples will be analyzed for asbestos by OSHA Method ID-191, and Title 22 metals by USEPA Methods SW6020 and SW7471.

The analytical results will be compared to California DTSC Human and Ecological Risk Office (HERO) HHRA Note 3 residential SLs (DTSC, 2020b), USEPA residential Regional Screening Levels (RSLs) (USEPA, 2021), and San Francisco Bay RWQCB groundwater protection ESLs (RWQCB, 2019). If results indicate that the analyte concentrations are below California DTSC HERO HHRA Note 3 residential SLs, USEPA residential RSLs, San Francisco Bay RWQCB groundwater protection ESLs, and an arsenic concentration of 17.53 mg/kg for side slope material or an arsenic concentration of 11 mg/kg for Virgin Class II aggregate base (Duvergé, 2011), the material can be used as backfill.

The source of the clean backfill material, certification that the fill is clean, and supporting analytical data will be obtained from the excavation subcontractor and submitted to DTSC approximately 5 working days before beginning excavation activities at the Site. The source of the fill material cannot be included at this time because the excavation subcontractor and the specific fill material source have not been identified.

5.4.3.3 Site Restoration

The Site will be graded to promote positive drainage and prevent excessive ponding. The Site surface will be restored to a compacted Class II aggregate surface. Temporary fencing and work zone delineation will be removed, all construction-related trash and debris will be picked up and disposed of appropriately, and all equipment and personnel will be demobilized.

5.5 Control Measures

Control measures will be implemented during remedy implementation to mitigate against fugitive dust emissions, provide best management practices related to stormwater, mitigate against construction noise, and ensure proper decontamination of equipment leaving the Site as described in the sections below.

5.5.1 Dust Control Measures

During excavation activities, depending on soil conditions, there is potential to generate airborne dust. Dust emissions will be managed and controlled during all phases of the project in accordance with the Dust Control and Air Monitoring Plan in Appendix D. Air and meteorological monitoring strategies and methodologies will be implemented during remedy implementation to achieve the following:

- Identify and measure the air contaminants generated during the soil removal and decontamination activities to assign the appropriate PPE and safety measures specified for those activities.
- Provide feedback to Site personnel regarding potential hazards from exposure to hazardous air contaminants generated through excavation activities.
- Identify and measure air contaminants at points outside of the soil removal and decontamination exclusion zones. Air monitoring will be conducted during work activities to measure potential exposure of sensitive receptors to Site COCs as a result of removal activities and to monitor the dust control measures implemented.

Dust control measures will comply with SMAQMD Rules 401, 402, and 403 to protect onsite and off-site receptors from chemicals in soil and nuisance dust. Dust suppression will be performed by lightly spraying or misting the work areas (such as the excavation, soil handling areas and haul roads) with water, BioSolve®, or a similar surfactant if water is not sufficient to reduce the potential for dust generation. Vapor and odor control will be utilized during field activities, as needed, by lightly spraying or misting BioSolve®, or similar vapor and odor suppressant. Misting may also be used on soil placed in the transport trucks. Efforts will be made to minimize the soil drop height from the excavator's bucket onto the soil pile or into the transport trucks. The excavator will be positioned so as to load or stockpile soil from the leeward side. After the soil is loaded into the transport trucks, the soil will be covered to prevent soil from spilling out of the truck during transport to the disposal facility. Additionally, soil stockpiles and truck beds containing soil will be covered to minimize the potential for dust generation.

Low-visibility with low-permeability windscreen will be attached to the temporary and permanent fencing prior to commencement of onsite activities. While on the property, all vehicles will maintain slow speeds (e.g., less than 5 miles per hour) for safety purposes and for dust control measures. Before exiting the job site, the vehicle's tires will be inspected and brushed, if necessary, to ensure that impacted soil remains onsite. This cleanup/ decontamination area will be established as close to the excavation and/or loading areas as possible to minimize spreading the impacted soil.

5.5.2 Stormwater Control Measures

If the project does not qualify for a Erosivity Waiver, a Stormwater Pollution Prevention Plan (SWPPP) will be prepared prior to the start of excavation work that includes use of best management practices to manage and control stormwater. The SWPPP will be submitted to the Regional Board for review and approval before beginning work.

5.5.3 Noise Control Measures

To mitigate against the potential community impacts of construction noise, work would be conducted between 7 a.m. and 4 p.m., Monday through Friday.

5.5.4 Decontamination

An area will be set up for decontaminating construction equipment and vehicles prior to leaving the Site. To the extent possible, equipment will be decontaminated by dry methods. Dried mud and soil will be removed using standard brushes, aided when necessary with a flat scraper or spatula. High-pressure water will be applied only if dry methods are not successful in removing contamination from the equipment.

All debris and liquids generated during decontamination will be captured, stockpiled or placed in drums or other appropriate storage vessels, and processed appropriately as hazardous or non-hazardous construction waste. Upon completion, the decontamination area will be cleaned.

5.6 Air Monitoring During Soil Excavation

Air monitoring activities will be conducted in the work zone and in the Site perimeter by the Site Safety Officer during excavation. This section describes the perimeter air monitoring program that will be implemented at the Site. Work zone air monitoring is described in the Dust Control Plan and Air Monitoring Plan (Appendix D) and addressed in the HASP (see Section 7.0). The air monitoring procedures at the Site during earthwork are consistent with the *DTSC Community Air Monitoring Plan (CAMP) Guidance*. Airborne particulate monitoring will be conducted to verify and document the effectiveness of dust suppression measures. To mitigate off-Site dust migration impacts to neighboring properties, watering of the active excavation areas will be conducted throughout the removal action. Factors considered in providing fugitive dust, vapor, and odor control measures will include wind direction, wind speed, and available dust control and dust suppression methods (see Section 5.5.1). Air monitoring for particulates will be performed during the excavation activities at the perimeter of the property. The limit on dust concentrations at the property boundaries is presented in the HASP (see Section 7.0). These measurements for particulates will also be taken near and around the property boundary at breathing height level using a portable handheld dust monitor. Measurements for VOCs will be taken using a direct reading PID during excavation and soil handling activities as specified in the HASP.

5.7 Institutional Controls

Institutional controls (ICs) are required for sites that contain residual contamination to prevent inappropriate uses, which would pose a threat under certain exposure scenarios. LUCs at the Site are currently implemented including perimeter fences with security gates, routine security patrols, and construction/maintenance project reviews by SMUD environmental staff. The removal action includes continued implementation of LUCs to prevent contact with soil contaminants until after soil removal action cleanup goals are achieved and LUCs can be removed at Areas #1 through #8. LUCs would remain at Area #9 until the cleanup goals that will be established in the future RAP are established and achieved.

Periodic monitoring of compliance with the LUC restrictions at the Site will be required until the removal action goals are achieved. Inspections and maintenance of any physical and administrative controls such as the Site perimeter fence and appropriate safety/risk management protocols will be conducted as described in the LUCs.

5.8 Field Variances

Variances from the work plan will be discussed with DTSC prior to any action being taken except for emergencies (when an immediate response is required). DTSC will be notified if an emergency response is implemented. The field variances will be documented in the Removal Action Completion Report prepared for the project.

6.0 Sampling and Analysis

The proposed remedy will require the collection and analysis of samples to confirm the removal of the impacted soil and to determine the proper waste classification of excavated soils for disposal purposes. Further details of the confirmation sampling and waste classification approach, laboratory analysis, data quality assurance and quality control, and data management are provided in the Sampling and Analysis Plan in Appendix E.

6.1 Confirmation Sampling of Excavated Areas

Soil samples from the sides and bottom of the completed soil excavation will be collected to assess the COCs concentrations to verify that cleanup levels have been met and RAOs for the Site have been achieved. XRF data will be used as a screening tool to guide excavation extents. A field-portable XRF unit will be used to measure total arsenic concentrations in soil collected from the excavation. Confirmation samples will be collected when excavation work has been completed to the depth and extent defined in this RAW. Additional excavation will be performed until the cleanup goals are attained.

Confirmation sampling for excavations less than 2,500 square feet will be conducted at an approximate frequency of one sample per sidewall (4 sidewall samples total) and excavation bottom. Confirmation sampling for excavations greater than 2,500 but less than 5,000 square feet will be conducted at an approximate frequency of two samples per sidewall (8 sidewall samples total) and excavation bottom (two bottom samples total). Confirmation sampling for excavations greater than 5,000 square feet will be conducted at an approximate frequency of one sample per 50 linear feet of sidewall and 2,500 square feet of excavation bottom. The sidewall samples will be collected at a depth halfway between the top and bottom of the sidewall. The proposed bottom and sidewall confirmation sample locations are shown on Figure 5-2. If a soil sample exceeds the cleanup criteria, soil surrounding the soil sample will be further excavated. A confirmation sample will be collected from the new excavation limit. The exact confirmation sample locations will be verified in the field in consultation with DTSC, as required. Sample locations and the number of samples collected may be adjusted in the field if necessary. Additional excavation and confirmation sampling will be performed until the cleanup goals are attained.

For excavations deeper than 5 feet that are not shored or sloped, the confirmation soil samples will be collected utilizing hand augers with extensions or by using the excavator bucket, so personnel are not required to enter the excavation. Soil samples collected from the hand auger or excavator bucket will be placed into laboratory-supplied, glass sample jars. If reusable sample equipment will be used, equipment blanks will be collected at a minimum of one equipment blank at the beginning of the event for each sample equipment type. Co-located field duplicate samples will also be collected at a frequency of 10 percent in the same manner as the corresponding original samples. The samples will be labeled with the following information: sample identification number, date and time of sample collection, analysis required, and preservation, and sampler initials. Samples will be delivered to the off-site analytical laboratory under chain-of-custody protocol. The confirmation samples for Area #1, #2, #4, #5, #6, #7, and #8 will be analyzed for arsenic by USEPA Method SW6020. Confirmation samples for Area #3 will be analyzed for arsenic and lead by USEPA Method SW6020, lead by synthetic precipitation leaching procedure (SPLP) by USEPA Method 1312, and $TPH_{ho/mo}$ by USEPA Method SW8015M. The potential for migration of lead from soil to groundwater will be evaluated by comparing the SPLP data against a cleanup standard of 5 mg/L. The Area #9 excavation bottom and sidewall will be evaluated using PID readings as described in Section 5.4.2.

6.2 Waste Characterization Sampling

Prior to excavation activities, a minimum of one pre-design waste characterization sample may be collected for every 250 cubic yards of proposed excavated soil. Alternatively, a minimum of one four-point composite waste characterization sample for every 250 cubic yards of excavated soil may be collected from soil stockpiled after excavation. The waste characterization samples will be analyzed for the following.

- Title 22 metals by USEPA Methods SW6020 and SW7471,
- Toxicity characteristic leaching procedure (TCLP) arsenic and lead by SW-846 Method 1311 (as necessary),
- Waste Extraction Test arsenic, lead, and VOCs by CCR Title 22 (as necessary),
- VOCs by USEPA Method SW8260B,
- Semi-volatile organic compounds by USEPA Method SW8270C,
- Organochlorine pesticides by USEPA Method SW8081A,
- Chlorinated herbicides by USEPA Method SW8151A,
- PCBs by USEPA Method SW8082, and
- Oil-, diesel-, and gasoline-range organics by USEPA Methods SW8015M.

Additional waste characterization samples, analytes or methodologies may be required to be collected depending on landfill acceptance criteria. The waste characterization samples will be collected by scooping the soil directly into laboratory-supplied, glass sample jars. The samples will be labeled with the following information: sample identification number, date and time of sample collection, analysis required, and preservation, and sampler initials. Samples will be delivered to the off-site analytical laboratory under chain-of-custody protocol.

Some soil excavated from the Site may be classified as non-RCRA hazardous waste based on the potential exceedance of the STLC or RCRA-hazardous if the TCLP arsenic or lead concentration exceeds 5 mg/L. Most of the soil is assumed to be classified as non-hazardous. It is not anticipated that the excavated soil will be classified as RCRA-hazardous or need to be treated prior to disposal to comply with land disposal restrictions. The excavated soil will be transported to appropriate, permitted off-Site facilities for disposal in accordance with the Transportation Plan in Appendix C.

6.3 Backfill Sampling

The backfill samples, as described in Section 5.4.3.2, will be collected by scooping the soil directly into laboratory-supplied, glass sample jars. The samples will be labeled with the following information: sample identification number, date and time of sample collection, analyses required, and preservation, and sampler initials. Samples will be delivered to the off-site analytical laboratories under chain-of-custody protocol. The samples will be analyzed for the constituents listed in Section 5.4.3.2. If results indicate that the analyte concentrations are below California DTSC HERO HHRA Note 3 residential SLs (DTSC, 2020b), USEPA residential RSLs (USEPA, 2021), San Francisco Bay RWQCB groundwater protection ESLs (RWQCB, 2019), and an arsenic concentration of 17.53 mg/kg for side slope material or an arsenic concentration of 11 mg/kg for Virgin Class II aggregate base (Duvergé, 2011), the material can be used as backfill.

7.0 Health and Safety

All contractors will be responsible for operating in accordance with the most current requirements of State and Federal Standards for Hazardous Waste Operations and Emergency Response (8 CCR Section 5192 and 29 CFR Section 1910.120). Onsite personnel are responsible for operating in accordance with all applicable regulations of OSHA outlined in the State General Industry and Construction Safety Orders (8 CCR) and Federal Construction Industry Standards (29 CFR 1910 and 29 CFR 1926), as well as other applicable federal, state and local laws and regulations. All personnel shall operate in compliance with all California OSHA requirements.

A site-specific HASP will be prepared prior to initiation of field work. The HASP provides direction regarding the minimum levels of protection and safe operating guidelines expected of each employee or subcontractor involved in the performance of the field activities described in this RAW. The HASP also identifies anticipated chemical and physical hazards associated with the planned activities. The provisions of the HASP are mandatory for all personnel and contractors at the Site. The contractor and its subcontractors doing fieldwork in associated with this RAW will either adopt and abide by the HASP or shall develop their own safety plans which, at a minimum, meet the requirements of the HASP. All onsite personnel shall read the HASP and sign the acknowledgement page before starting Site activities. HASP supplements will be generated as necessary to address additional activities or changes in Site conditions that may occur during field operations. Once generated, each supplement will be inserted as an attachment to the HASP and reviewed/acknowledged by field personnel prior to start of applicable work activities.

8.0 Public Participation

The public participation requirements for the RAW process include:

- The development of a community profile,
- Publishing a notice of the availability of the RAW for public review and comment,
- Making the RAW and other supporting documents available at DTSC's office and on DTSC's publicly-accessible EnviroStor database,
- Responding to public comments received on the RAW.

In accordance with the Community Profile prepared for this Site, the following additional activities will be conducted.

- A fact sheet will be sent out to the site mailing list describing the Site and the proposed removal action.
- A public review and comment period of 30 days will be provided.
- A public meeting or workshop will be held if there is sufficient community interest.

Once the public comment period is completed, DTSC and SMUD will review and respond to the comments received. The RAW will be revised, as necessary, to address the comments received. If significant changes to the RAW are required, the RAW will be revised and be resubmitted for public review and comment. If significant changes are not required to the RAW, the RAW will be modified and DTSC will approved the modified RAW for implementation.

9.0 California Environmental Quality Act Documentation

The California Environmental Quality Act (CEQA), modeled after the National Environmental Policy Act of 1969, was enacted in 1970 as a system of checks and balances for land-use development and management decisions in California. It is an administrative procedure to ensure comprehensive environmental review of cumulative impacts prior to approval. It has no agency enforcement tool but allows challenge in courts.

A CEQA project is a project that has a potential for resulting in a direct physical change in the environment. CEQA applies to all discretionary projects proposed to be carried out or approved by California public agencies, unless an exemption applies.

In accordance with CEQA, SMUD, in coordination with DTSC, prepared a Final Initial Study and Proposed Mitigated Negative Declaration (IS/MND) for the 59th Street Remediation and Demolition Project, which includes the soil removal proposed in this Interim RAW and the building and pavement demolition necessary to support implementation of the selected removal action. The IS/MND was made available for public review on 18 January 2022, and a public meeting took place on 3 February 2022 in support of the CEQA public review process. The IS/MND was finalized on 4 April 2022 (Ascent Environmental, 2022).

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Tables

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND(a)
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Location ID	Sample Date	Sample Depth (feet bgs)(b)	Arsenic
			mg/kg
			17.53
2015 Investigation (c)			
KA-1	6/1/2015	21	**2.2**
KA-2	5/29/2015	6	**7.4**
		16	**3.0**
KA-3	6/1/2015	6	**7.0**
		11	**3.8**
KA-4	6/1/2015	6	**5.8**
		16	**1.9**
KA-5	5/28/2015	6	**7.5**
		36	**1.5**
		46	**2.5**
KA-6	5/21/2015	6	**7.2**
		36	**1.5**
		46	**1.7**
KA-7	5/29/2015	6	**5.8**
		36	**2.2**
		46	**1.4**
KA-8	6/3/2015	2	**4.1** **4.3**(d)
KA-9	5/22/2015	6	**6.3**
		36	**1.0**
		51	**1.7**
KA-10	5/19/2015	1.5	**29**
		4.5	**2.6**
KA-11	5/19/2015	1.5	**5.9**
KA-13	6/1/2015	6	**4.8**
		11	**7.2**
KA-14	6/2/2015	6	**3.2** **5.2**(d)
		16	**2.5** **3.5**(d)
KA-15	5/26/2015	6	**4.2**
		36	**2.5**
	5/27/2015	46	**2.6**
KA-16	5/18/2015	1.5	**3.9**
KA-17	5/18/2015	1.5	**100**
		5	**2.2**
KA-18	6/2/2015	6	**23** **22**(d)
		11	**7.2** **6.5**(d)

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND(a)
(Page 2 of 7)

Location ID	Sample Date	Sample Depth (feet bgs)(b)	Arsenic mg/kg 17.53
2015 Investigation(c) (continued)			
KA-19	6/2/2015	6	**10** **14**(d)
		16	**5.7** **5.0**(d)
KA-20	5/19/2015	1.5	**4.9**
KA-21	5/19/2015	1.5	**3.6**
KA-22	5/19/2015	2	**5.3**
KA-23	6/2/2015	6	**1.7** **5.4**(d)
		11	**7.1** **8.6**(d)
KA-24	6/2/2015	6	**2.5** **4.7**(d)
		11	**2.3** **4.8**(d)
KA-25	6/1/2015	6	**5.2**
		16	**1.7**
KA-26	5/26/2015	6	**3.7**
		36	**0.79 J**
		51	**3.3**
KA-27	5/22/2015	6	**6.7**
		36	**0.97 J**
		46	**3.9**
KA-28	5/20/2015	1	**5.2**
KA-29	5/20/2015	1	**5.8**
KA-30	5/20/2015	1	**5.1**
KA-31	5/20/2015	1	**6.9**
KA-32	5/20/2015	1	**5.0**
KA-33	5/19/2015	1	**10**
KA-34	5/20/2015	2	**4.7**
KA-35	6/2/2015	6	**4.7** **5.2**(d)
		16	**2.3** **2.5**(d)
KA-36	6/3/2015	6	**7.9** **8.3**(d)
		16	**5.1** **6.1**(d)

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND[(a)]
(Page 3 of 7)

Location ID	Sample Date	Sample Depth (feet bgs)(b)	Arsenic mg/kg 17.53
2015 Investigation (c) (continued)			
KA-37	6/3/2015	6	**7.6** **7.7**(d)
		11	**5.0** **5.6**(d)
KA-38	6/3/2015	6	**6.0** **6.2**(d)
		11	**3.7** **3.7**(d)
KA-40	6/3/2015	6	**7.0** **6.9**(d)
		16	**2.0** **1.9**(d)
KA-41	5/27/2015	6	**4.4**
		26	**2.0**
		36	**1.2**
KA-42	5/27/2015	6	**5.5**
		26	**0.65 J**
		36	**2.4**
KA-43	5/18/2015	1	**4.9**
KA-44	5/18/2015	1.5	**30**
		5	**2.5**
KA-45	5/18/2015	1.5	**7.4**
KA-46	5/18/2015	1.5	**6.5**
KA-47	5/18/2015	1.5	**4.0**
KA-48	5/19/2015	2	**60**
KA-49	5/19/2015	1.5	**15**
KA-50	5/19/2015	3	**110**
		5	**6.8**
SCR Investigation (f)			
B01	12/4/2018	1.5-2.0	**6.4**
B02	12/5/2018	1.5-2.0	**6.3**
B03	12/5/2018	1.5-2.0	**8.2**
B04	12/6/2018	1.67-2.17	**16**
		5.17-5.67	**3.3**
B05	12/6/2018	1.67-2.17	**3.7**
	12/7/2018	4.67-5.17	**3.5**
B06	12/3/2018	1.67-2.17	**3.6**
	12/4/2018	4.67-5.17	**5.1**
B07	12/4/2018	1.33-1.83	**2.7**
	12/5/2018	4.83-5.33	**4.9**

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND(a)
(Page 4 of 7)

Location ID	Sample Date	Sample Depth (feet bgs)(b)	Arsenic mg/kg 17.53
SCR Investigation (continued)			
B08	12/5/2018	1.5-2.0	**67**
		5.0-5.5	**4.4**
B09	12/3/2018	1.67-2.17	**3.4**
	12/4/2018	4.67-5.17	**5.2**
B10	12/5/2018	1.5-2.0	**240**
		5.0-5.33	**9.1**
B11	12/6/2018	1.21-1.71	**260**
		3.71-4.21	**190**
B12	12/6/2018	1.67-2.17	**13**
	12/31/2018	4.67-5.17	**7.3**
B13	12/4/2018	1.5-2.0	**8.7**
	12/5/2018	4.5-5.0	**3.9**
B14	12/4/2018	1.5-2.0	**13**
		5.0-5.33	**4.4**
B15	12/5/2018	1.5-2.0	**140**
		5.0-5.33	**6.3**
B16	12/5/2018	1.5-2.0	**280**
		5.0-5.33	**3.8** **3.4**(e)
B17	12/5/2018	1.5-2.0	**45**
		5.0-5.5	**270** **330**(e)
Borehole B08 Step-Outs(g)			
B08-E	6/29/2020	1.5	**29**
B08-E	6/29/2020	3.0	**40**
B08-N	6/29/2020	1.5	**28**
B08-N	6/29/2020	1.5	**29**(e)
B08-N	6/29/2020	3.0	**5.7**
B08-S	6/29/2020	1.5	**54**
B08-S	6/29/2020	3.0	**9.1**
B08-W	6/29/2020	1.5	**19**
B08-W	6/29/2020	3.0	**12**
B08-EE	7/20/2020	1.5	**99**
B08-EE	7/20/2020	3.0	**13**
B08-NN	7/20/2020	1.5	**30**
B08-SS	7/20/2020	1.5	**24**
B08-3-E	8/7/2020	1.5	**9.1**
B08-3-N	8/7/2020	1.5	**39**
B08-3-N	8/7/2020	1.5	**42**(e)
B08-3-S	8/7/2020	1.5	**48**
Borehole KA-10 Step-Outs(g)			
KA-10-N	6/29/2020	1.5	**16**
KA-10-N	6/29/2020	3.0	**8.0**

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND(a)
(Page 5 of 7)

Location ID	Sample Date	Sample Depth (feet bgs)(b)	Arsenic mg/kg 17.53
KA-10-S	6/29/2020	1.5	**110**
KA-10-S	6/29/2020	3	**6.2**
KA-10-S	6/29/2020	3	**5.5(c)**
KA-10-W	6/29/2020	1.5	**35**
KA-10-W	6/29/2020	3.0	**3.9**
KA-10-SS	7/20/2020	1.5	**38**
KA-10-SW	7/20/2020	1.5	**21**
KA-10-WW	7/20/2020	1.5	**14**
KA-10-WW	7/20/2020	1.5	**11(e)**
KA-10-3-S	8/7/2020	1.5	**16**
Borehole KA-17 Step-Outs (g)			
KA-17-E	6/30/2020	1.5	**17**
KA-17-E	6/30/2020	3.0	**3.6**
KA-17-N	6/30/2020	1.5	**78**
KA-17-N	6/30/2020	3.0	**3.6**
KA-17-W	6/30/2020	1.5	**150**
KA-17-W	6/30/2020	3.0	**4.1**
KA-17-NN	7/20/2020	1.5	**59**
KA-17-NW	7/20/2020	1.5	**37**
KA-17-WW	7/20/2020	1.5	**44**
KA-17-3-N	8/7/2020	1.5	**3.4**
KA-17-3-NE	8/7/2020	1.5	**140**
KA-17-3-NW	8/7/2020	1.5	**3.9**
KA-17-3-W	8/7/2020	1.5	**60**
KA-17-4-NE	8/28/2020	1.5	**14**
Borehole KA-44 Step-Outs (g)			
KA-44-E	6/30/2020	1.5	**6.3**
KA-44-E	6/30/2020	3.0	**8.5**
KA-44-N	6/30/2020	1.5	**5.0**
KA-44-N	6/30/2020	3.0	**8.8**
KA-44-S	6/30/2020	1.5	**14**
KA-44-S	6/30/2020	3.0	**6.6**
KA-44-W	6/30/2020	1.5	**4.4**
KA-44-W	6/30/2020	1.5	**4.6(e)**
KA-44-W	6/30/2020	3.0	**9.5**
Warehouse Building Step-Outs (g)			
VW56	12/21/2020	1.5	**5.7**
VW57	12/21/2020	1.5	**30**
WB01	12/22/2020	1.5(h)	**19**
WB01	12/22/2020	0.5(i)	**8.2 J**
WB01	12/22/2020	0.5(i)	**12 J(e)**
WB01A	12/22/2020	1.5(i)	**8.8**
WB02	12/22/2020	1.5(h)	**4.3**

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND[a]
(Page 6 of 7)

Location ID	Sample Date	Sample Depth (feet bgs)[b]	Arsenic mg/kg 17.53
Warehouse Building Step-Outs (continued)[g]			
WB02	12/22/2020	0.5[i]	**3.7**
WB03	12/22/2020	1.5	**4.2**
WB04	12/22/2020	1.5	**3.9**
WB05	12/22/2020	1.5	**4.4**
WB05	12/22/2020	5	**4.0**
WB06	12/22/2020	1.5	**9.2**
WB06	12/22/2020	5	**70 J**
WB06	12/22/2020	5	**39 J[e]**
WB07	12/22/2020	1.5	**7.2**
WB07	12/22/2020	5	**170**
WB08	2/23/2021	1.5[h]	**6.4**
WB08	2/23/2021	1.5[i]	**12**
WB09	2/23/2021	1.5[h]	**4.2**
WB09	2/23/2021	1.5[i]	**4.4**
WB10	2/23/2021	7.5	**65**
WB10	2/23/2021	10	**55**
WB11	2/24/2021	5	**4.3**
WB11	2/24/2021	5	**4.1**
WB11	2/24/2021	7.5	**5.8**
WB11	2/24/2021	10	**3.1**
WB12	2/24/2021	5	**15**
WB12	2/24/2021	7.5	**6.7**
WB12	2/24/2021	10	**3.6**
Borehole VW15[g]			
VW15	12/15/2020	2	**7.3**
Borehole VW31 and Associated Step-Outs[g]			
VW31	11/23/2020	2	**26**
VW-31-S	2/23/2021	2	**150**
VW-31-S	2/23/2021	5	**6.0**
VW-31-S	2/23/2021	5	**6.0**
Borehole VW35 and Associated Step-Outs[g]			
VW35	11/23/2020	2	**46**
VW35-E	2/22/2021	2	**50**
VW35-E	2/22/2021	5	**8.1**
VW35-N	2/22/2021	2	**44**
VW35-N	2/22/2021	5	**180**
VW35-N	2/22/2021	7.5	**8.4**
VW35-NN	2/24/2021	2	**100**
VW35-NN	2/24/2021	5	**4.4**
VW35-S	2/23/2021	2	**280**
VW35-S	2/23/2021	5	**8.5**
VW35-S	2/23/2021	5	**6.6**

TABLE 2-1. ARSENIC CONCENTRATIONS IN SOIL COMPARED TO BACKGROUND(a)
(Page 7 of 7)

Location ID	Sample Date	Sample Depth (feet bgs)(b)	Arsenic mg/kg 17.53
VW35-SS	2/24/2021	2	**94**
VW35-SS	2/24/2021	5	**4.3**
VW35-SS	2/24/2021	5	**4.1**
VW35-W	2/22/2021	2	**61 J+**
VW35-W	2/22/2021	5	**4.4**
Borehole VW38 (g)			
VW38	11/24/2020	2	**17**

Notes:

Concentrations detected above the laboratory MDL shown in **bold**.

🟨 Concentration exceeds site-specific background concentration.

(a) Site-specific background concentration (AECOM, 2019).

(b) Most boreholes were located in paved areas. The pavement thickness varied from 3 to 13 inches. Sample depths for the Phase II ESA investigation are referenced to the top of pavement. Sample depths for the SCR and SCR Addendum investigations are referenced to the top of soil, and in paved areas, top of soil is at the bottom of pavement unless indicated otherwise.

(c) Phase II ESA (Kleinfelder, 2016)

(d) Laboratory duplicate analytical result

(e) Field duplicate analytical result

(f) SCR (AECOM, 2019)

(g) SCR Addendum (AECOM, 2021a)

(h) Depth from bottom of dock/top of underlying fill material

(i) Depth from top of soil referenced to the surrounding grade.

bgs = below ground surface
ESA = Environmental Site Assessment
ID = identification
J = estimated; detected analyte
J+ = estimated concentration, potential high bias
MDL = method detection limit
mg/kg = milligrams per kilogram
SCR = Site Characterization Report

TABLE 4-1. ALTERNATIVE 2 EXCAVATION VOLUME
(Page 1 of 1)

Area #	Area Description	Area (square feet)	Depth of Contamination (feet)	Volume (cubic yards)
#1	West of Hazardous Materials Building	2,204	2.5	204
#2	Salvage Building Area	27,198	3.0	3,022
#3	VW35-N within Area #2	725	6.0	161
#4	East of Tool Issue Building	4,674	2.5	433
#5	KA-17-WW South of Tool Issue Building	1,369	6.5	330
#6	KA-44 South of Garage Building	280	2.5	26
#7	South of Warehouse Building	15,264	3.0	1,696
#8	Southeast of Warehouse Building	6,979	6.0	1,551
#9	PCE Contamination North of Tool Issue Building	1,693	15	941
			Total	**8,364**

Notes:

\# = number
PCE = tetrachloroethene

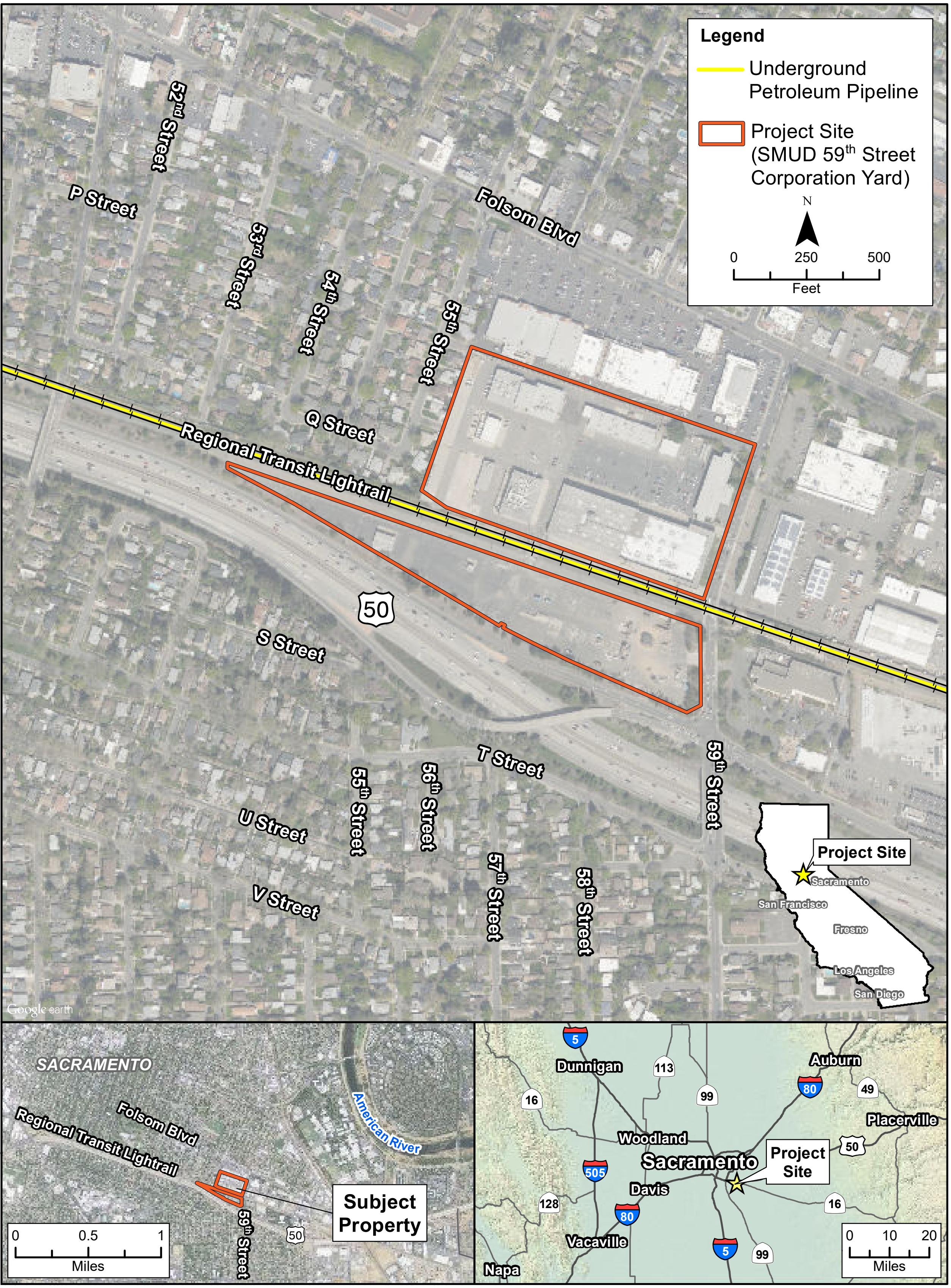
TABLE 4-2. ALTERNATIVE 3 EXCAVATION VOLUME
(Page 1 of 1)

Area #	Area Description	Area (square feet)	Depth of Contamination (feet)	Volume (cubic yards)
#1	West of Hazardous Materials Building	2,204	2.5	204
#4	East of Tool Issue Building	4,674	2.5	433
#5	KA-17-WW South of Tool Issue Building	1,369	6.5	330
#6	KA-44 South of Garage Building	280	2.5	26
#9	PCE Contamination North of Tool Issue Building	1,693	15	941
			Total	**1,934**

Notes:

# = number
PCE = tetrachloroethene

Figures



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AECOM SMUD Corporation Yard
1708 59th Street, Sacramento, California

Figure 1-1
Site Location Map

Note:
1. Only the first 10 digits of the 14-digit Assessor Parcel numbers are shown. The last four digits of each parcel are "-0000".

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1708 59th Street Sacramento, California

Figure 1-2
Site Features Map

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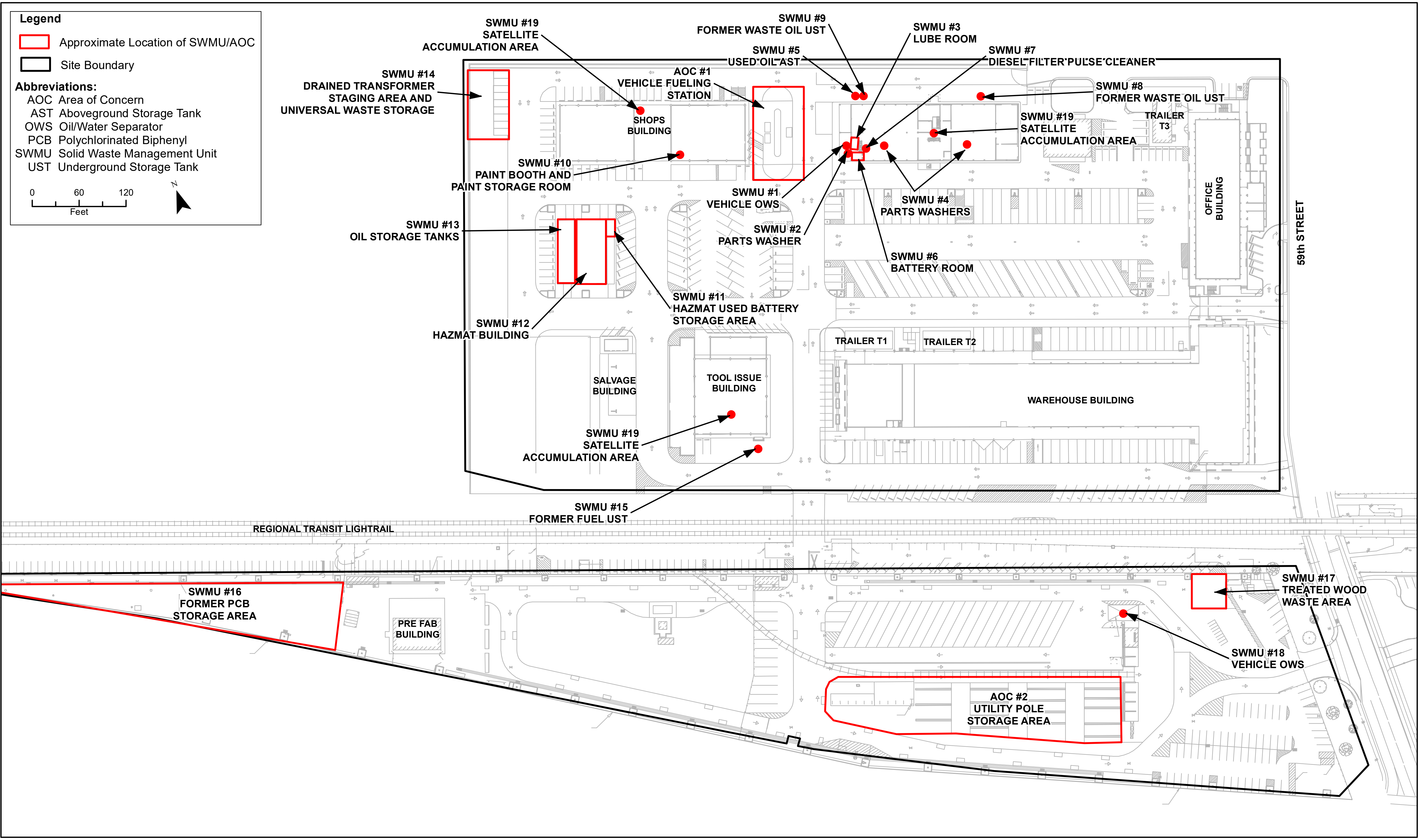

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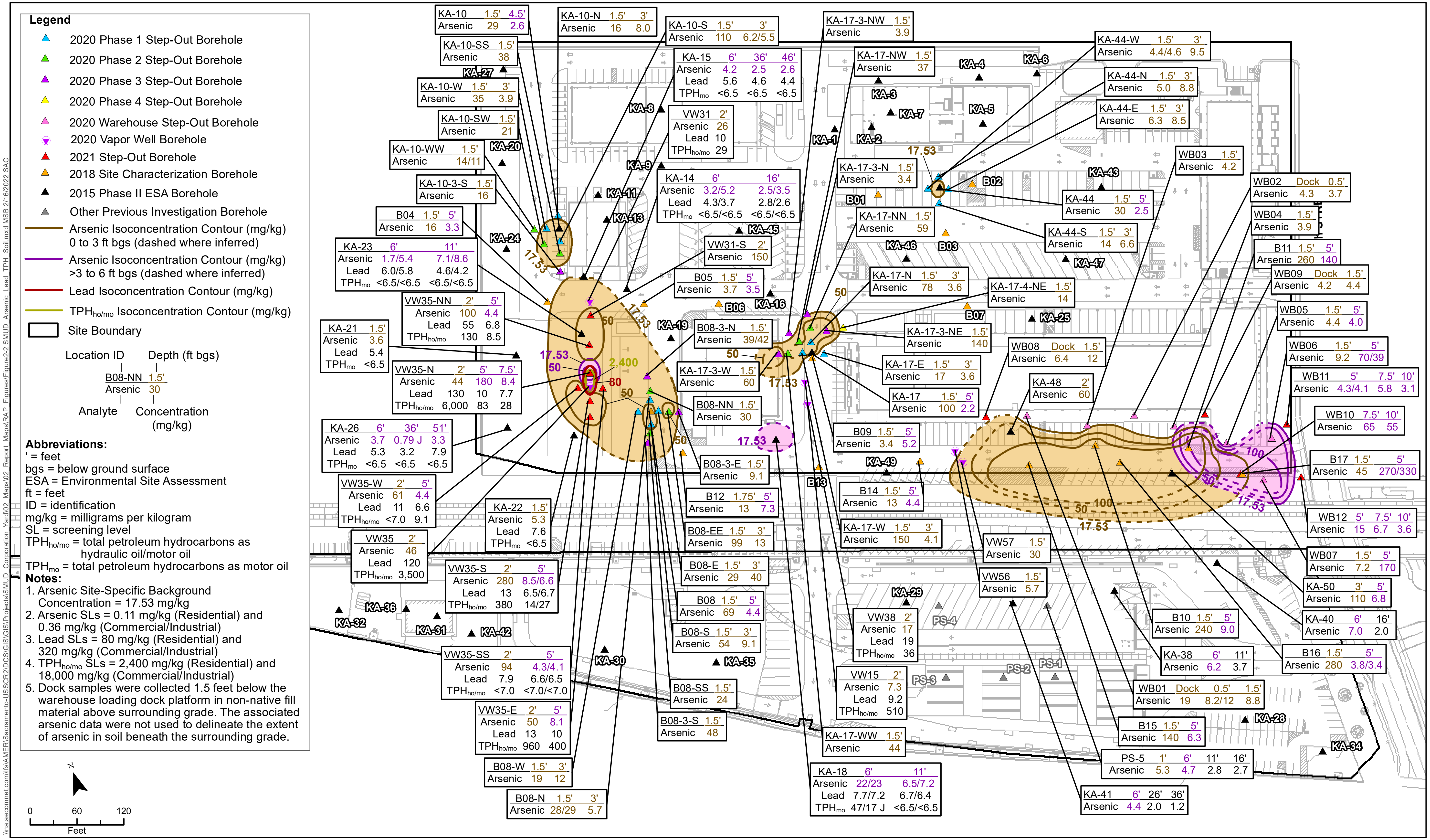
Figure 2-1
Solid Waste Management Unit
and Area of Concern Locations



Legend

- ▲ 2020 Phase 1 Step-Out Borehole
- ▲ 2020 Phase 2 Step-Out Borehole
- ▲ 2020 Phase 3 Step-Out Borehole
- ▲ 2020 Phase 4 Step-Out Borehole
- ▲ 2020 Warehouse Step-Out Borehole
- ▼ 2020 Vapor Well Borehole
- ▲ 2021 Step-Out Borehole
- ▲ 2018 Site Characterization Borehole
- ▲ 2015 Phase II ESA Borehole
- ▲ Other Previous Investigation Borehole
- — Arsenic Isoconcentration Contour (mg/kg) 0 to 3 ft bgs (dashed where inferred)
- — Arsenic Isoconcentration Contour (mg/kg) >3 to 6 ft bgs (dashed where inferred)
- — Lead Isoconcentration Contour (mg/kg)
- — $TPH_{ho/mo}$ Isoconcentration Contour (mg/kg)
- ☐ Site Boundary

Location ID Depth (ft bgs)
B08-NN 1.5'
Arsenic 30
Analyte Concentration (mg/kg)

Abbreviations:
' = feet
bgs = below ground surface
ESA = Environmental Site Assessment
ft = feet
ID = identification
mg/kg = milligrams per kilogram
SL = screening level
$TPH_{ho/mo}$ = total petroleum hydrocarbons as hydraulic oil/motor oil
TPH_{mo} = total petroleum hydrocarbons as motor oil

Notes:
1. Arsenic Site-Specific Background Concentration = 17.53 mg/kg
2. Arsenic SLs = 0.11 mg/kg (Residential) and 0.36 mg/kg (Commercial/Industrial)
3. Lead SLs = 80 mg/kg (Residential) and 320 mg/kg (Commercial/Industrial)
4. $TPH_{ho/mo}$ SLs = 2,400 mg/kg (Residential) and 18,000 mg/kg (Commercial/Industrial)
5. Dock samples were collected 1.5 feet below the warehouse loading dock platform in non-native fill material above surrounding grade. The associated arsenic data were not used to delineate the extent of arsenic in soil beneath the surrounding grade.

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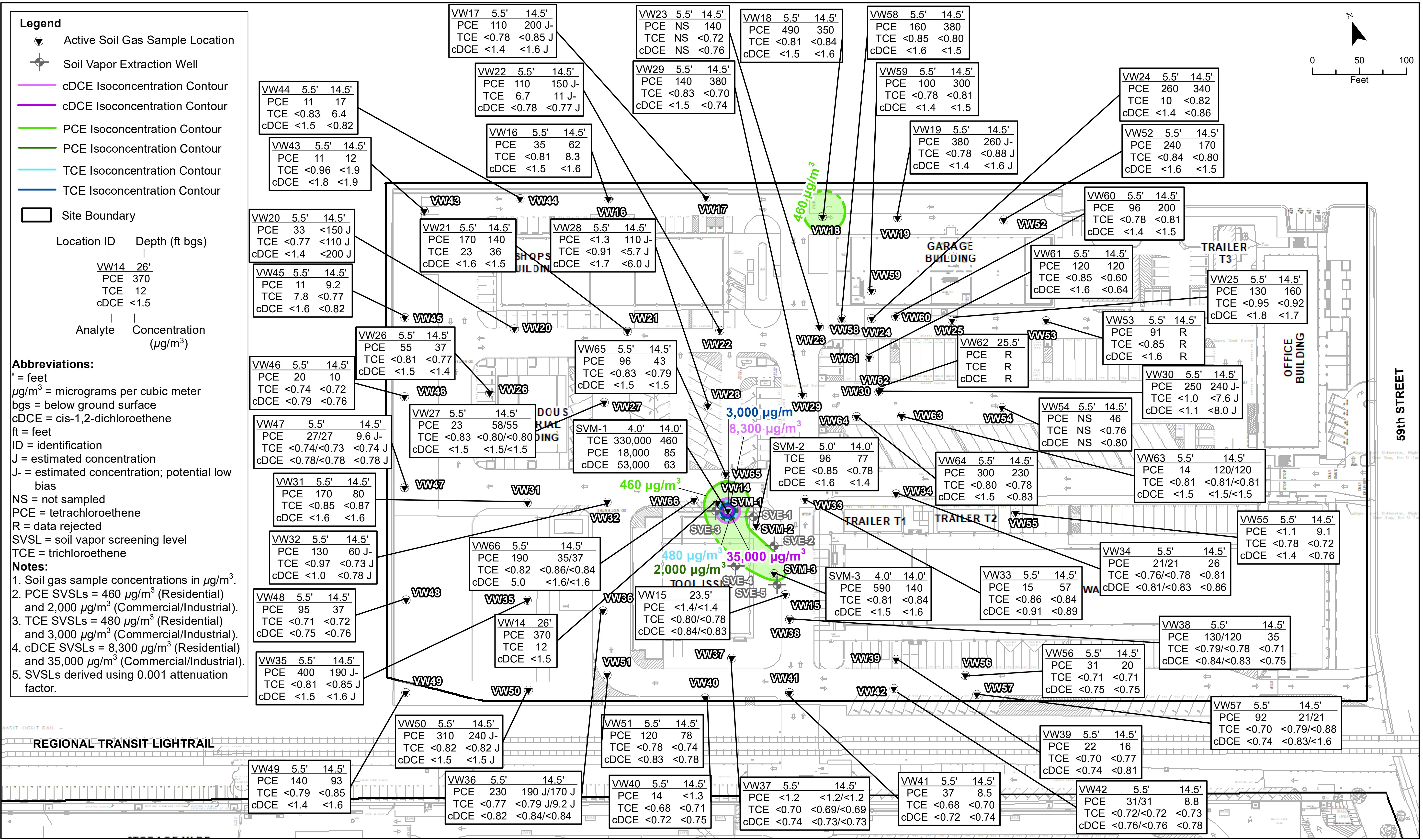
Figure 2-2
Arsenic, Lead, and TPH Concentrations in Soil



Abbreviations:
' = feet
µg/m³ = micrograms per cubic meter
bgs = below ground surface
cDCE = cis-1,2-dichloroethene
ft = feet
ID = identification
J = estimated concentration
J- = estimated concentration; potential low bias
NS = not sampled
PCE = tetrachloroethene
R = data rejected
SVSL = soil vapor screening level
TCE = trichloroethene

Notes:

1. Soil gas sample concentrations in µg/m³.
2. PCE SVSLs = 460 µg/m³ (Residential) and 2,000 µg/m³ (Commercial/Industrial).
3. TCE SVSLs = 480 µg/m³ (Residential) and 3,000 µg/m³ (Commercial/Industrial).
4. cDCE SVSLs = 8,300 µg/m³ (Residential) and 35,000 µg/m³ (Commercial/Industrial).
5. SVSLs derived using 0.001 attenuation factor.

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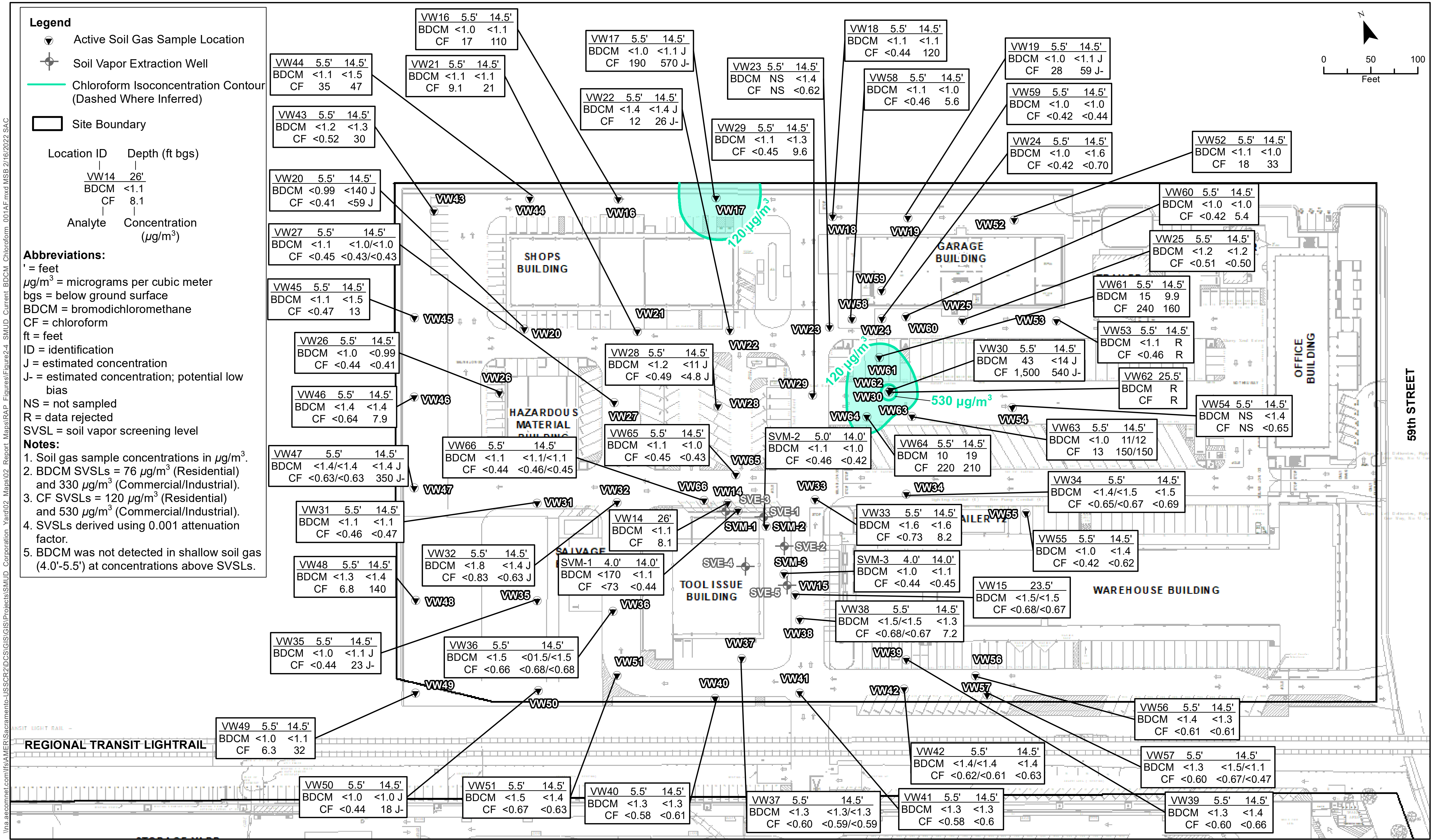
Figure 2-3
Summer 2021 PCE, TCE, and cDCE
Concentrations in Shallow Soil Gas (0.001 Attenuation Factor)



Legend

- ▼ Active Soil Gas Sample Location
- ⌖ Soil Vapor Extraction Well
- Chloroform Isoconcentration Contour (Dashed Where Inferred)
- ▭ Site Boundary

Location ID — Depth (ft bgs)
VW14 26'
BDCM <1.1
CF 8.1
Analyte — Concentration ($\mu g/m^3$)

Abbreviations:

' = feet
$\mu g/m^3$ = micrograms per cubic meter
bgs = below ground surface
BDCM = bromodichloromethane
CF = chloroform
ft = feet
ID = identification
J = estimated concentration
J- = estimated concentration; potential low bias
NS = not sampled
R = data rejected
SVSL = soil vapor screening level

Notes:

1. Soil gas sample concentrations in $\mu g/m^3$.
2. BDCM SVSLs = 76 $\mu g/m^3$ (Residential) and 330 $\mu g/m^3$ (Commercial/Industrial).
3. CF SVSLs = 120 $\mu g/m^3$ (Residential) and 530 $\mu g/m^3$ (Commercial/Industrial).
4. SVSLs derived using 0.001 attenuation factor.
5. BDCM was not detected in shallow soil gas (4.0'-5.5') at concentrations above SVSLs.

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SMUD Corporation Yard
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Figure 2-4
Summer 2021 BDCM and Chloroform Concentrations
In Shallow Soil Gas (0.001 Attenuation Factor)

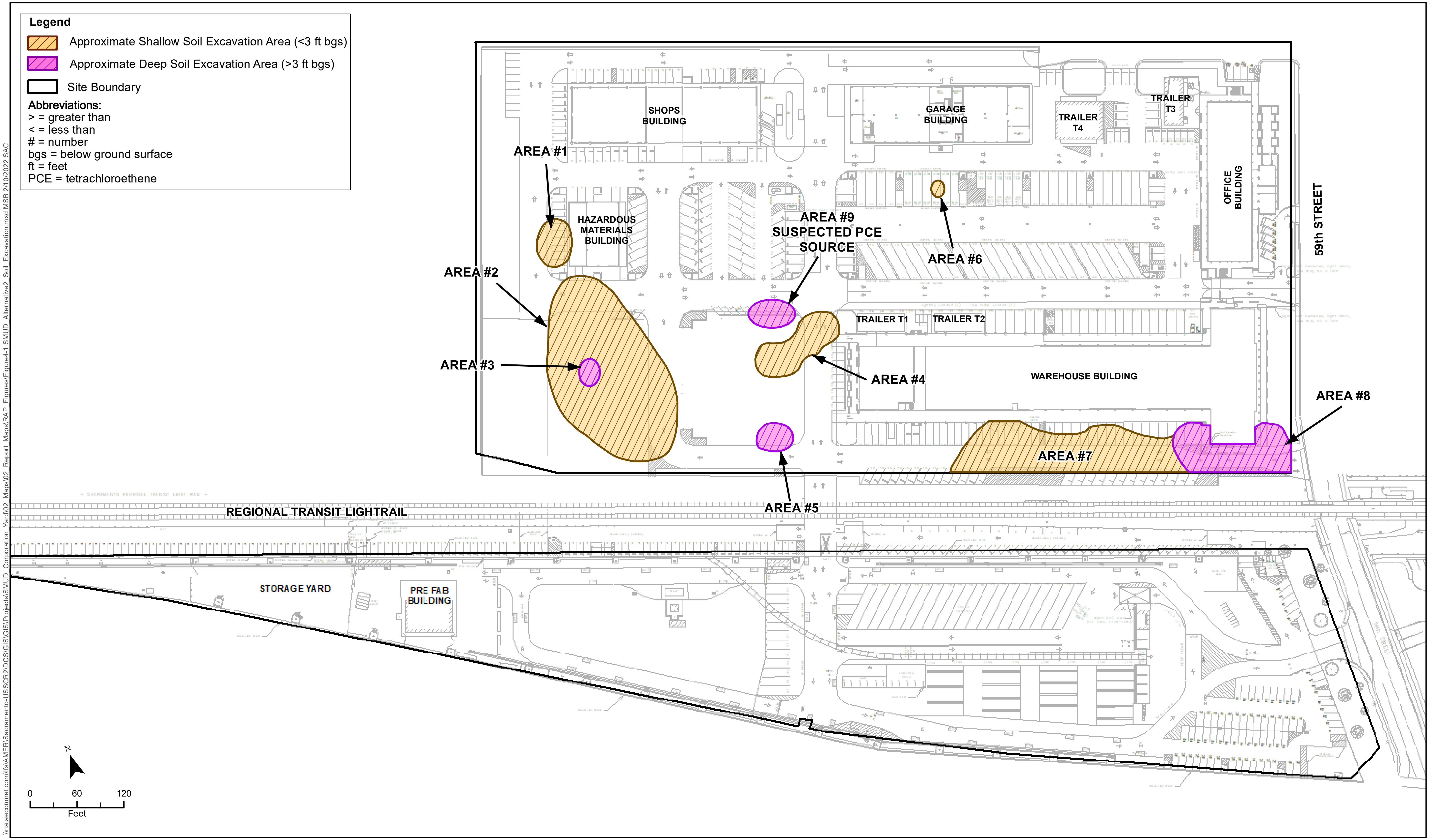

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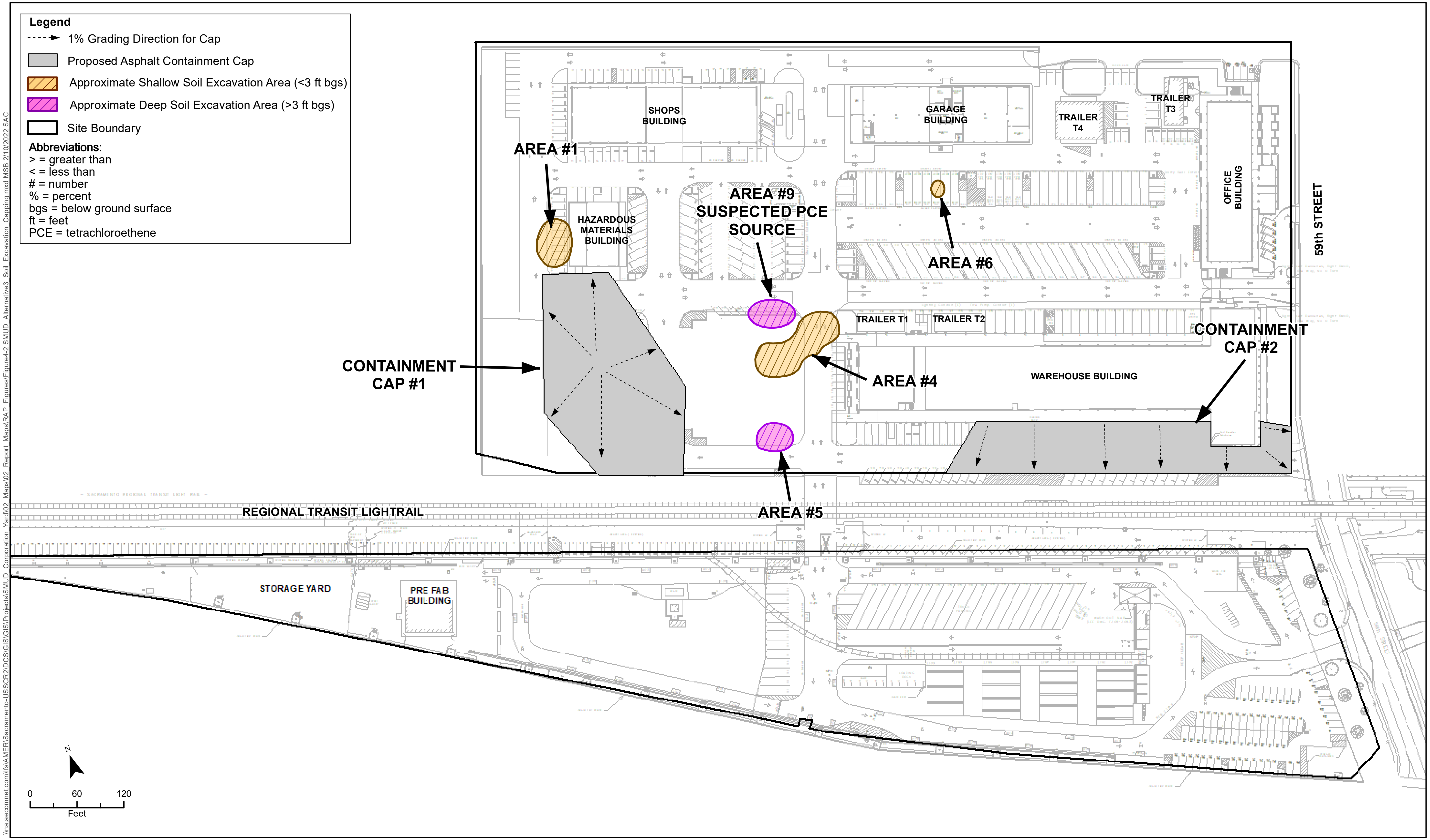
Figure 4-1
Alternative 2 - Soil Excavation/Off-Site Disposal



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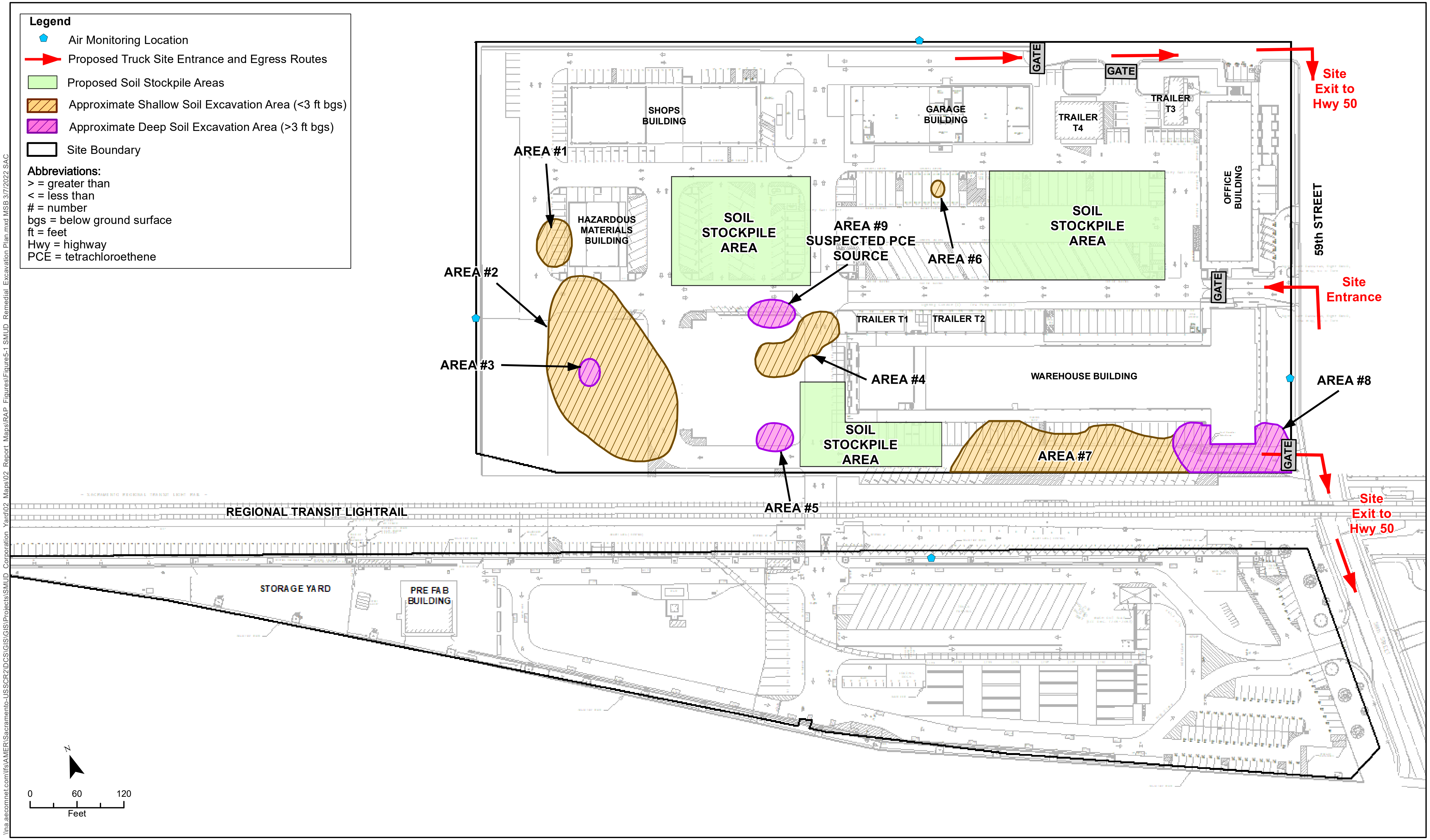
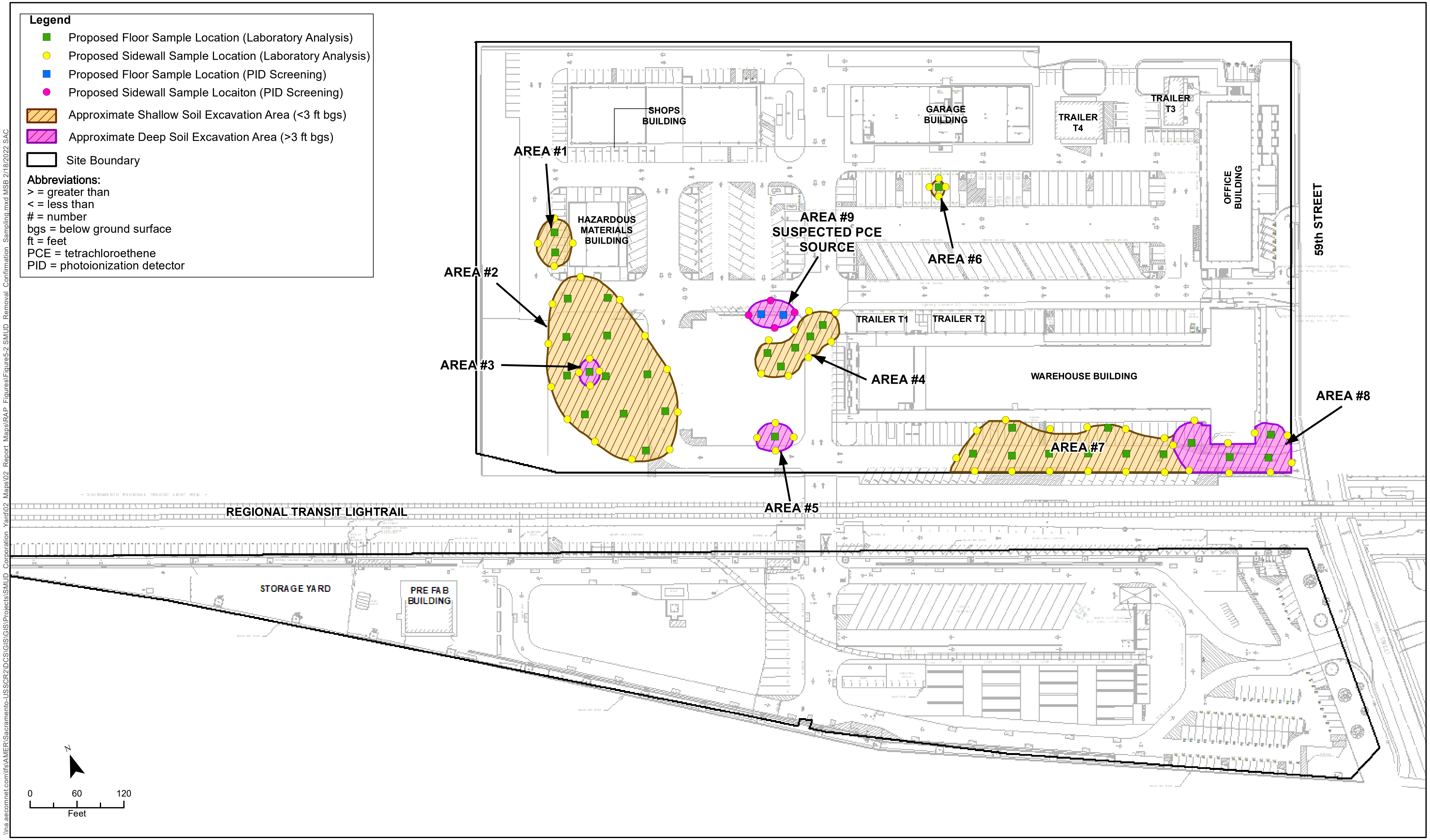
AECOM
SMUD Corporation Yard
1708 59th Street, Sacramento, California

Figure 4-2
Alternative 3 – Limited Soil Excavation/Off-Site Disposal,
Soil Containment/Capping-in-Place, and Land Use Controls



AECOM SMUD Corporation Yard
1708 59th Street, Sacramento, California

Figure 5-1
Remedial Excavation Plan



\\na.aecomnet.com\lfs\AMER\Sacramento-USSCR2\DCS\GIS\Projects\SMUD_Corporation_Yard\02_Maps\02_Report_Maps\RAP_Figures\Figure5-2_SMUD_Removal_Confirmation_Sampling.mxd MSB 2/18/2022 SAC

SMUD Corporation Yard
1708 59th Street, Sacramento, California

Figure 5-2
Removal Action Confirmation Sampling Plan

Appendix A

Applicable or Relevant and Appropriate Requirements

Table A1-1. Potential Federal Chemical-Specific[a] ARARs

Requirement	Prerequisite	Citation[b]	ARAR Determination	Comments
Resource Conservation and Recovery Act (42 U.S.C., ch. 82, §§ 6901–6991[i])[c]				
Defines RCRA hazardous waste. A solid waste is characterized as toxic, based on the TCLP, if the waste exceeds the TCLP maximum concentrations.	Waste.	Cal. Code Regs. tit. 22, §66261.21, 66261.22(a)(1), 66261.23, 66261.24(a)(1), and 66261.100	Applicable	Potentially applicable for determining whether waste is hazardous.
Groundwater protection standards: Owners/operators of RCRA treatment, storage, or disposal facilities must comply with conditions in this section that are designed to ensure that hazardous constituents entering the groundwater from a regulated unit do not exceed the concentration limits for contaminants of concern set forth under Cal. Code Regs. tit. 22, § 66264.94 in the uppermost aquifer underlying the waste management area of concern.	A regulated unit that receives or has received hazardous waste before 26 July 1982 or regulated units that ceased receiving hazardous waste prior to 26 July 1982 where constituents in or derived from the waste may pose a threat to human health or the environment.	Cal. Code Regs. tit. 22, §66264.94, except 66264.94(a)(2) and 66264.94(b)	Relevant and appropriate	Potentially relevant and appropriate for soil contamination in the vadose zone. The lowest achievable levels that are technologically and economically feasible are risk-based levels that assure protection of human health and the environment including the threat to groundwater. However, the selected remedy could result in levels lower than risk-based levels and meeting background over time. However, additional work to meet levels lower than risk-based levels is not economically feasible since risk levels will already be acceptable.
LDRs prohibit disposal of hazardous waste unless treatment standards are met.	Hazardous waste land disposal.	Cal. Code Regs. tit. 22, §66268.1(f)	Applicable	Applicable for hazardous waste.
Treatment standards including technology requirements before hazardous waste can be disposed to land.	Hazardous waste land disposal.	Cal. Code Regs. tit. 22, §66268.40	Applicable	Applicable for hazardous waste.
Universal Treatment Standards used to comply with treatment standards.	Hazardous waste land disposal.	Cal. Code Regs. tit. 22, §66268.48	Applicable	Applicable for hazardous waste.

Table A1-1. Potential Federal Chemical-Specific[a] ARARs

Notes:

[a] Many potential action-specific ARARs contain chemical-specific limitations and are addressed in the action-specific ARAR tables.

[b] Only the substantive provisions of the requirements cited in this table are potential ARARs.

[c] Statutes and policies, and their citations, are provided as headings to identify general categories of potential ARARs for the convenience of the reader; listing the statutes and policies does not indicate that SMUD accepts the entire statutes or policies as potential ARARs; specific potential ARARs are addressed in the table below each general heading; only pertinent substantive requirements of the specific citations are considered potential ARARs.

Acronyms/Abbreviations:

ARAR – applicable or relevant and appropriate requirement
Cal. Code Regs. – *California Code of Regulations*
LDR – land disposal restriction
RCRA – Resource Conservation and Recovery Act
§ – section
SMUD – Sacramento Municipal Utility District
TCLP – toxicity characteristic leaching procedure
tit. – title
U.S.C. – *United States Code*

Table A1-2. Potential State Chemical-Specific[a] ARARs

Requirement	Prerequisite	Citation[b]	ARAR Determination	Comments
Cal/EPA Department of Toxic Substances Control[c]				
Definition of “non-RCRA hazardous waste”	Waste.	Cal. Code Regs. tit. 22, §§ 66261.3(a)(2)(C) or 66261.3(a)(2)(F), 66261.22(a)(3) and (4), 66261.24(a)(2)–(a)(8), 66261.101(a)(1) and (a)(2)	Applicable	Applicable for determining whether a waste is a non-RCRA hazardous waste.
All human health risk assessments, human health risk-based screening levels, and human health risk-based remediation goals shall protect human health by using the toxicity criteria specified in Cal. Code Regs. tit. 22 § 69021. When based on human health risk or non-cancer hazard, to protect human health, screening levels for individual chemicals of potential concern shall be set to an incremental excess lifetime cancer risk of 1 x 10^{-6} and a hazard quotient of 1.	Cleanup of sites described under Cal. Code Regs. tit. 22, §69020.	Cal. Code Regs. tit. 22, §§ 69021 and 69022	Applicable	Applicable for developing human health risk-based remediation goals.
State and Regional Water Quality Control Boards[c]				
Requirement	**Prerequisite**	**Citation[b]**	**ARAR Determination**	**Comments**
Definitions of designated waste, nonhazardous waste, and inert waste.		Cal. Code Regs. tit. 27, §§ 20210, 20220, and 20230	Applicable	Potential ARARs for classifying waste and determining ARAR status of other requirements.

Table A1-2. Potential State Chemical-Specific[a] ARARs

Notes:

[a] Many potential action-specific ARARs contain chemical-specific limitations and are addressed in the action-specific ARAR tables.

[b] Only the substantive provisions of the requirements cited in this table are potential ARARs.

[c] Statutes and policies, and their citations, are provided as headings to identify general categories of potential ARARs for the convenience of the reader; listing the statutes and policies does not indicate that SMUD accepts the entire statutes or policies as potential ARARs; specific potential ARARs are addressed in the table below each general heading; only pertinent substantive requirements of specific citations are considered potential ARARs.

Acronyms/Abbreviations:

ARAR – applicable or relevant and appropriate requirement
Cal. Code Regs. – *California Code of Regulations*
Cal/EPA – California Environmental Protection Agency
RCRA – Resource Conservation and Recovery Act
§ – section
SMUD – Sacramento Municipal Utility District
tit – title

Table A2-1. Potential Federal Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
National Historic Preservation Act of 1966, as Amended (16 U.S.C. §470–470x-6)[b]					
Historic project owned or controlled by federal agency	Action to preserve historic properties; planning of action to minimize harm to properties listed on or eligible for listing on the National Register of Historic Places.	Property included in or eligible for the National Register of Historic Places.	16 U.S.C. §470–470x-6 36 C.F.R. pt. 800 40 C.F.R. §6.301(b)	Applicable	Historic period archaeological site P-34-000455 is the original Sacramento Valley Railroad alignment (current Sacramento Rapid Transit line that bisects the SMUD Corporation Yard). This archaeological site is being considered for inclusion on the National Register of Historic Places. Remedial action activities will be conducted in a manner to prevent adverse impacts to adjacent properties.
Archaeological and Historic Preservation Act (16 U.S.C. §469–469c-1)[b]					
Within area where action may cause irreparable harm, loss, or destruction of significant artifacts	Construction on previously undisturbed land would require an archaeological survey of the area. Data recovery and preservation would be required if significant archaeological or historical data were found on-site. The responsible official or Secretary of the Interior is authorized to undertake data recovery and preservation.	Regulated alteration of terrain caused as a result of a federal construction project or federally licensed activity or program where action may cause irreparable harm, loss, or destruction of significant artifacts.	16 U.S.C. §469–469c-1 40 C.F.R. §6.301(c)	Not an ARAR	Archaeological or historical resources are not known to exist on the Site. Remedial action construction activities would take place on previously disturbed land. The planned remedial action is not a federal construction project or federally-licensed activity or program.

Table A2-1. Potential Federal Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Historic Sites, Buildings, Objects, and Antiquities Act of 1935 (16 U.S.C. §§461–467)[b]					
Historic sites	Avoid undesirable impacts on landmarks.	Areas designated as historic sites.	16 U.S.C. §§461–467	Not an ARAR	The Site is not designated as an historic site.
Archaeological Resources Protection Act of 1979, as Amended (16 U.S.C. §470aa–470mm)[b]					
Archaeological resources on federal land	Prohibits unauthorized excavation, removal, damage, alteration, or defacement of archaeological resources located on public lands unless such action is conducted pursuant to a permit.	Archaeological resources on federal land.	Pub. L. No. 95-96 16 U.S.C. §470aa–470mm	Not an ARAR	There are no known or suspected archaeological resources. The planned remedial action will not take place on federal land.
Exec. Order No. 11990, Protection of Wetlands[b]					
Within wetlands	Avoid, to the extent possible, the adverse impacts associated with the destruction or loss of wetlands and avoid support of new construction in wetlands if practicable alternatives exist.	Wetlands meeting definition of Section 7(c) of the Exec. Order No. 11990.	Exec. Order No. 11990	Not an ARAR	While executive orders themselves are not ARARs, they constitute TBC guidance that should be followed in any response action. No wetlands are located at the site.
Exec. Order No. 11988, Floodplain Management[b]					
Within floodplain	Evaluate potential effects of actions in a floodplain to avoid, to the extent possible, adverse effects associated with direct and indirect development of a floodplain.	Action that will occur in a floodplain (i.e., lowlands) and relatively flat areas adjoining inland and coastal waters and other flood-prone areas.	Exec. Order No. 11988	Not an ARAR	The Site does lie within a 100- or 500-year floodplain and does not depend on a levee for flood protection.

Table A2-1. Potential Federal Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Clean Water Act of 1977, as Amended, Section 404 (33 U.S.C. §1344)[b]					
Within wetlands	Action to prohibit discharge of dredged or fill material into wetlands, or navigable waters without a permit.	Wetlands as defined by Exec. Order No. 11990 Section 7.	33 U.S.C. §1344	Not an ARAR	No discharge of dredged or fill material to a wetland is planned as part of the remedial action.
Resource Conservation and Recovery Act (42 U.S.C. §§6901–6991[i])[b]					
Within 100-year floodplain or maximum hightide	Facility must be designed, constructed, operated, and maintained to avoid washout.	RCRA hazardous waste; treatment, storage, or disposal of hazardous waste.	Cal. Code Regs. tit. 22, §66264.18(b)	Not an ARAR	The Site does not lie within a 100-year floodplain.
Wild and Scenic Rivers Act (16 U.S.C. §§1271–1287)[b]					
Within area affecting national wild, scenic, or recreational rivers	Avoid taking or assisting in action that will have direct adverse effect on scenic rivers.	Activities that affect or may affect any of the rivers specified in 16 U.S.C. §1274-1276.	16 U.S.C. §§1271–1287	Not an ARAR	Activities at the Site will not affect any national wild, scenic, or recreational rivers.
Fish and Wildlife Coordination Act (16 U.S.C. §§661–666c)[b]					
Area affecting stream or other water body	Action taken should protect fish or wildlife.	Diversion, channeling, or other activity that modifies a stream or other water body and affects fish or wildlife.	16 U.S.C. §662	Not an ARAR	No diversion, channeling or other activity that modifies a stream or other water body is proposed for the Site.
Rivers and Harbors Appropriation Act of 1899 (33 U.S.C. §§401–413)[b]					
Within navigable waters	Permits required for structures or work in or affecting navigable waters.	Activities affecting navigable waters.	33 U.S.C. §403 33 C.F.R. §322	Not an ARAR	There are no navigable waters at the Site.

Table A2-1. Potential Federal Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Endangered Species Act of 1973 (16 U.S.C. §§1531–1544)[b]					
Within endangered or threatened species area or designated critical habitat area	Federal agencies may not jeopardize the continued existence of any listed species or cause the destruction or adverse modification of critical habitat.	Presence of endangered species, listed species, or critical habitat.	16 U.S.C. §§1531–1544	Not an ARAR	No endangered species, threatened species, or critical habitats are known to be present at the Site.
Migratory Bird Treaty Act of 1972 (16 U.S.C. §§703–712)[b]					
Within migratory bird area	Protects almost all species of native migratory birds in the U.S. from unregulated “take,” which can include poisoning at hazardous waste sites.	Presence of migratory birds.	16 U.S.C. §703	Relevant and Appropriate	The Site lies beneath the Pacific Flyway for migratory birds; therefore, substantive provisions are potentially relevant and appropriate. However, the Site has little vegetation and no surface water and therefore is an unlikely location for migratory birds to stop at.
Marine Mammal Protection Act (16 U.S.C. §§1361–1421h)[b]					
Within marine mammal area	Protects any marine mammal in the U.S. except as provided by international treaties from unregulated “take.”	Presence of marine mammals.	16 U.S.C. § 372(a)(2)	Not an ARAR	There are no marine waters at the Site.
Magnuson-Stevens Fishery Conservation and Management Act of 1976, as Amended (16 U.S.C. §§1801–1882)[b]					
Within fishery under management	Provides for conservation and management of fishery resources within specified fishery conservation zones.	Presence of managed fisheries.	16 U.S.C. §§1801–1882	Not an ARAR	There are no fisheries at the Site.

Table A2-1. Potential Federal Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
National Wildlife Refuge System Administration Act of 1996, as Amended (16 U.S.C. §668dd–668ee)[b]					
Within wildlife refuge	No person shall "take" any animal or plant on any national wildlife refuge, except as authorized under 50 C.F.R. § 27.51. The disposing or dumping of wastes is prohibited.	Area designated as part of National Wildlife Refuge System.	16 U.S.C §668dd–668ee Substantive provisions of 50 C.F.R. §27.11–27.97	Not an ARAR	There are no wildlife refuges at the Site.
Wilderness Act of 1964 (16 U.S.C. §§1131–1136)[b]					
Within wilderness area	Area must be administered in such a manner as will leave it unimpaired as wilderness and preserve its wilderness character.	Federally owned area designated as wilderness area.	16 U.S.C. §§1131–1136 50 C.F.R. §35.1–35.14	Not an ARAR	There are no wilderness areas at the Site.
Coastal Zone Management Act of 1972 (16 U.S.C. §§1451–1464)[b]					
Within coastal zone	Conduct activities in a manner consistent with approved state management programs.	Activities affecting the coastal zone including lands thereunder and adjacent shore land.	16 U.S.C. §1456(c) 15 C.F.R. §930	Not an ARAR	The Site is not located within a coastal zone.
Resource Conservation and Recovery Act (42 U.S.C. §§6901–6991[i])[b]					
Within 61 meters (200 feet) of a fault displaced in Holocene time	New treatment, storage, or disposal of hazardous waste prohibited.	RCRA hazardous waste; treatment, storage, or disposal of hazardous waste.	Cal. Code Regs. tit. 22, §66264.18(a)	Not an ARAR	The Site is not within 200 feet of a known fault that was displaced in Holocene time.
Within salt dome formation, underground mine, or cave	Placement of noncontainerized or bulk liquid hazardous waste prohibited.	RCRA hazardous waste; placement.	Cal. Code Regs. tit. 22, §66264.18(c)	Not an ARAR	There are no known salt dome formations, underground mines, or caves at the Site.

Notes:

[a] Only the substantive provisions of the requirements cited in this table are potential ARARs.

[b] Statutes and policies, and their citations, are provided as headings to identify general categories of potential ARARs for the convenience of the reader; listing the statutes and policies does not indicate that SMUD accepts the entire statutes or policies as potential ARARs; specific potential ARARs are addressed in the table below each general heading; only substantive requirements of the specific citations are considered potential ARARs.

Acronyms/Abbreviations:

ARAR – applicable or relevant and appropriate requirement
Cal. Code Regs. – *California Code of Regulations*
C.F.R. – *Code of Federal Regulations*
Exec. Order No. – executive order number
No. – number
pt. – part
Pub. L. No. – public law number
RCRA – Resource Conservation and Recovery Act
§ – section
SMUD – Sacramento Municipal Utility District
TBC – to be considered
U.S. – United States
U.S.C. – *United States Code*

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
California Fish and Game Code[b]					
Area used by endangered or threatened species	No person shall "take" any endangered or threatened species.	Threatened or endangered species are present.	Cal. Fish & Game Code §2080	Not an ARAR	No threatened or endangered species are known to be present at the Site.
Area used by endangered, threatened species	The department may authorize, by permit, the 'take' of endangered species, threatened species, and candidate species if the 'take' is incidental to an otherwise lawful activity and the impacts are minimized and fully mitigated.	Potential for incidental 'take' of endangered, threatened, or candidate species.	Cal. Fish & Game Code §2081(b)	Not an ARAR	No threatened or endangered species are known to be present at the Site.
Area with rare or endangered native plants	No person shall 'take', possess, or sell within this state, except as incident to the possession or sale of the real property on which the plant is growing, any native plant, or any part or product thereof, which the commission determines to be an endangered native plant or rare native plant.	Endangered or rare native plant species must be present at site.	Cal. Fish & Game Code §1908	Not an ARAR	No endangered or rare native plant species are known to be present at the Site.
Area used by fully protected reptiles and amphibians	Fully protected reptiles and amphibians may not be 'taken' at any time.	A fully protected species must be potentially affected.	Cal. Fish & Game Code §5050	Not an ARAR	No fully protected reptiles or amphibians are known to be present at the Site.

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Area used by fully protected mammals	Fully protected mammals may not be ‘taken’ at any time.	A fully protected species must be potentially affected.	Cal. Fish & Game Code §4700	Not an ARAR	No fully protected mammals are known to be present at the Site.
Area used by fully protected birds	Fully protected birds may not be ‘taken’ at any time.	A fully protected species must be potentially affected.	Cal. Fish & Game Code §3511	Relevant and Appropriate	The Site lies beneath the Pacific Flyway for migratory birds; therefore, substantive provisions are potentially relevant and appropriate. However, the Site has little vegetation and no surface water and therefore is an unlikely location for migratory birds to stop at.
Area used by fully protected fish	Fully protected fish may not be ‘taken’ at any time.	A fully protected species must be potentially affected.	Cal. Fish & Game Code §5500-9101	Not an ARAR	No fully protected fish occur at the Site.
Area with native reptiles and amphibians	It is unlawful to capture, collect, intentionally kill or injure, possess, purchase, propagate, sell, transport, import, or export any native reptile or amphibian, or part thereof.	Potentially affect native reptiles or amphibians.	Cal. Code Regs. tit. 14, §40	Not an ARAR	The remedial action does not involve the capture, collection, intentional killing or injuring, possession, purchase, propagation, sale, transport, import, or export of any native reptile or amphibian or any part thereof.
Area with fisher, marten, river otter, desert kit fox, and red fox	Fisher, marten, river otter, desert kit fox, and red fox may not be “taken” at any time.	A fisher, marten, river otter, desert kit fox, or red fox must be potentially harmed.	Cal. Code Regs. tit. 14, §460	Not an ARAR	The listed species do not occur at the Site.

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Area with fur-bearing mammals	A fur-bearing mammal may be “taken” only with a trap, a firearm, bow and arrow, poison under a proper permit, or with the use of dogs.	Response action could potentially “take” a fur-bearing animal — pine marten, fisher, mink, river otter, gray fox, red fox, kit fox, raccoon, beaver, badger, or muskrat.	Cal. Fish & Game Code §4002	Not an ARAR	The listed species do not occur at the Site.
Area with fur bearing mammals or nongame mammals	It is unlawful for any person to trap for the purposes of recreation or commerce any fur-bearing mammal or nongame mammal with a body-gripping trap. It is unlawful for any person to buy, sell, barter, or otherwise exchange for profit, the raw fur, of any fur-bearing mammal or nongame mammal.	Trapping for recreation or commerce.	Cal. Fish & Game Code §3003.1	Not an ARAR	The Site is not used for recreation or commerce pertaining to trapping of any fur-bearing mammal or non-game mammal.
Area with nongame mammals	Nongame mammals or parts thereof may not be ‘taken’ or possessed. By definition, all mammals occurring naturally in California that are not game mammals, fully protected mammals, or fur-bearing mammals, are nongame mammals.	Response action may potentially ‘take’ a nongame mammal.	Cal. Fish & Game Code §4150	Not an ARAR	The remedial action is being taken to protect human health and the environment.

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Area with nongame birds and mammals	Nongame birds and mammals may not be "taken" except as provided.	"Taking" of nongame birds and mammals.	Cal. Code Regs. tit. 14, §472	Not an ARAR	None of the proposed remedial actions include provisions to hunt or otherwise 'take' nongame birds and mammals.
Area with birds or mammals	It is unlawful to "take" birds or mammals with any net, pound, cage, trap, set line or wire, or poisonous substance, or to possess birds or mammals so "taken", whether 'taken' within or without this state.		Cal. Fish & Game Code §3005	Not an ARAR	Cal. Fish & Game Code §3005(a) is not a state ARAR because it is not applicable or relevant and appropriate.
Area with bird nest or eggs	It is unlawful to "take", possess, or needlessly destroy the nest or eggs of any bird, except as otherwise provided by this code or any regulation made pursuant thereto.	Bird nests or eggs on-site.	Cal. Fish & Game Code §3503	Not an ARAR	Cal. Fish & Game Code §3503 is not a state ARAR because it is not applicable or relevant and appropriate. However, SMUD agrees that it will undertake appropriate measures in order to generally avoid harm to nests and eggs when there is potential that they may be impacted by remedial action construction.
Area with Falconiformes or Strigiformes	It is unlawful to 'take', possess, or destroy any birds in the orders Falconiformes or Strigiformes (birds-of-prey) or to 'take', possess, or destroy the nest or eggs of any such bird.	Falconiformes or Strigiformes birds on-site.	Cal. Fish & Game Code §3503.5	Not an ARAR	SMUD has identified substantive provisions of the MBTA as a 'relevant and appropriate' federal ARAR for this action. Therefore, inclusion of Cal. Fish & Game Code §3503.5 as an ARAR is not necessary.
Area with migratory nongame birds	Action must be taken to prevent "take" of migratory nongame birds (as designated in the MBTA).	Migratory nongame birds.	Cal. Fish & Game Code §3513	Not an ARAR	SMUD has identified substantive provisions of the MBTA as a 'relevant and appropriate' federal ARAR for this action. Cal. Fish & Game Code §3513 is not more stringent than the Federal ARAR.

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Area with nongame birds	It is unlawful to “take” any nongame bird.	All birds occurring naturally in Cal. that are not resident game birds, migratory game birds, or fully protected birds are nongame birds.	Cal. Fish & Game Code §3800(a)	Not an ARAR	None of the proposed remedial actions include provisions to ‘take’ any nongame birds.
Area with bear	It is unlawful to ‘take’ any bear with firearm, trap, or bow and arrow without first procuring a tag authorizing the taking of that bear in accordance with this chapter, but no iron or steel-jawed or any type of metal-jawed trap shall be used to ‘take’ any bear.	The response action could potentially take a bear.	Cal. Fish & Game Code §4750	Not an ARAR	Bears are not known to occur at the Site.
Area with mountain lion	It is unlawful to ‘take’, injure, possess, transport, import, or sell any mountain lion or any part or product thereof.	A mountain lion must be potentially affected by the response action.	Cal. Fish & Game Code §4800	Not an ARAR	Mountain lions are not known to occur at the Site.
Area with desert tortoise	It is unlawful to sell, purchase, harm, “take”, possess, transport, or shoot a projectile at, a tortoise (*Gopherus*).	A desert tortoise must be potentially affected by the response action.	Cal. Fish & Game Code §5000	Not an ARAR	Desert tortoise are not known to occur at the Site.

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
Waters of the state	Prohibits the passage of enumerated substances or materials into waters of the state deleterious to fish, plant life, or birds.	Discharge not authorized under Cal. Water Code §13263 or a waiver issued pursuant to subdivision (a) of §13269 of the Cal. Water Code.	Cal. Fish & Game Code §5650(a), (b), and (c)	Relevant and Appropriate	While no direct deposition of material is expected to enter into or impact waters of the state, the substantive portions of this standard will be complied with as an ARAR.
Area with mollusks, crustaceans, or invertebrates	No mollusks, crustaceans, or other invertebrates may be 'taken', possessed aboard a boat, or landed for commercial purposes by any person in any tide pool or tidal area, including tide flats or other areas between the high tidemark and 1,000 feet beyond the low tidemark.	The taking and possession of mollusks, crustaceans, or other invertebrates for any commercial purpose.	Cal. Fish & Game Code §8500	Not an ARAR	The remedial action will not take place in a tide pool or tidal area.
Within Wetlands	Cal. Fish and Game Commission Wetland Policy (adopted 1987) included in Fish and Game Code Addenda.			Not an ARAR	This is not a promulgated requirement. The Site does not contain wetlands.

Table A2-2. Potential State Location-Specific ARARs

Location	Requirement	Prerequisite	Citation[a]	ARAR Determination	Comments
State Water Resources Control Board[b]					
Waters of the State	Permit requirements for discharges of dredged or fill material outside the Federal jurisdiction	Not more than two-tenths (0.2) of an acre and 400 linear feet for fill and excavation discharges, and of not more than 50 cubic yards for dredging discharges	SWRCB Order No. 2004-0004-DWQ Statewide General Waste Discharge Requirements for Dredged or Fill Discharges to Waters Deemed by the U.S. Army Corps of Engineers to Be Outside of Federal Jurisdiction	Not an ARAR	The remedial activities do not involve discharges of dredged or fill material to waters of the State.
California Coastal Act of 1976[b]					
Coastal zone	Regulates activities associated with development to control direct significant impacts on coastal waters and to protect state and national interests in California coastal resources.	Any activity that could impact coastal waters and resources.	Cal. Pub. Res. Code §§30000–30900; Cal. Code Regs. tit. 14, §§13001–13666.4	Not an ARAR	Remedial activities will not take place within a coastal zone.

Table A2-2. Potential State Location-Specific ARARs

Notes:

[a] Only the substantive provisions of the requirements cited in this table are potential ARARs.

[b] Statutes and policies, and their citations, are provided as headings to identify general categories of potential ARARs for the convenience of the reader; listing the statutes and policies does not indicate that SMUD accepts the entire statutes or policies as potential ARARs; specific potential ARARs follow each general heading; only substantive requirements of the specific citations are considered potential ARARs.

Acronyms/Abbreviations:

ARAR – applicable or relevant and appropriate requirement
Cal. Code Regs. – *California Code of Regulations*
Cal. Fish & Game Code – *California Fish and Game Code*
Cal. Pub. Res. Code – *California Public Resources Code*
Cal. Water Code – *California Water Code*
CERCLA – Comprehensive Environmental Response, Compensation, and Liability Act
MBTA – Migratory Bird Treaty Act
§ – section
SMUD – Sacramento Municipal Utility District
SWRCB – (California) State Water Resources Control Board
tit. – title
U.S. – United States
U.S.C. – *United States Code*

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Resource Conservation and Recovery Act (42 U.S.C. §§6901–6991[i])*							
On-site waste generation	Person who generates waste shall determine if that waste is a hazardous waste.	Generator of waste.	Cal. Code Regs. tit. 22, §66262.10(a), 66262.11	2, 3			Applicable for any operation where hazardous waste is generated. The determination of whether soil excavated during remedial activities are hazardous will be made at the time the wastes are generated.
	Requirements for analyzing waste for determining whether waste is hazardous.	Generator of waste.	Cal. Code Regs. tit. 22, §66264.13(a) and (b)	2, 3			Applicable when analyzing soil excavated during the remedial action at the Site.
Hazardous waste accumulation	On-site hazardous waste accumulation is allowed for up to 90 days as long as the waste is stored in containers in accordance with §66265.171-178 or in tanks, on drip pads, inside buildings, is labeled and dated, etc.	Accumulate hazardous waste.	Cal. Code Regs. tit. 22, §66264.34	2, 3			Applicable when accumulating hazardous waste at the Site.

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Site closure	Minimize the need for further maintenance controls and minimize or eliminate, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous constituents, leachate, contaminated rainfall or runoff, or waste decomposition products to groundwater or surface water or to the atmosphere.	Hazardous waste management facility.	Cal. Code Regs. tit. 22, § 66264.111(a) and (b)				Not an ARAR. No land-based disposal units are planned for waste management.
Clean closure	During the partial and final closure periods, all contaminated equipment, structures, and soils shall be properly disposed or decontaminated by removing all hazardous waste and residues.	Hazardous waste management facility.	Cal. Code Regs. tit. 22, § 66264.114		2, 3		Relevant and appropriate for closure of staging piles.

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Container storage Container storage (continued)	Containers of RCRA hazardous waste must be: • maintained in good condition, • compatible with hazardous waste to be stored, and closed during storage except to add or remove waste.	Storage of RCRA hazardous waste not meeting small-quantity generator criteria before treatment, disposal, or storage elsewhere, in a container.	Cal. Code Regs. tit. 22, § 66264.171, 66264.172, and 66264.173	2, 3			Applicable if hazardous waste will be stored into containers.
	Inspect container storage areas weekly for deterioration.		Cal. Code Regs. tit. 22, § 66264.174	2, 3			Applicable if hazardous waste containers are stored at the Site.
	Place containers on a sloped, crack-free base, and protect from contact with accumulated liquid. Provide containment system with a capacity of 10 percent of the volume of containers of free liquids. Remove spilled or leaked waste in a timely manner to prevent overflow of the containment system.	Storage in a container of RCRA hazardous waste not meeting small-quantity generator criteria before treatment, disposal, or storage elsewhere.	Cal. Code Regs. tit. 22, § 66264.175(a) and (b)	2, 3			Applicable if hazardous waste containers are stored at the Site.
	At closure, remove all hazardous waste and residues from the containment system, and decontaminate or remove all containers and liners.		Cal. Code Regs. tit. 22, § 66264.178	2, 3			Applicable if hazardous waste containers are stored at the Site.

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Staging Piles	Regulations allow relief from LDRs for temporary storage (less than 2 years) of remediation waste on contiguous property. Placing hazardous remediation wastes in a staging pile does not trigger LDRs or MTRs. In addition, physical operations such as mixing, sizing, blending, etc., which are intended to prepare wastes for subsequent management or treatment, are allowed to occur in staging piles regardless of whether they technically meet the RCRA definition of “treatment.”	Non-RCRA hazardous waste intended for on-site treatment and disposal.	40 C.F.R. §264.554		2, 3		The substantive provisions are potential relevant and appropriate for design, operating, and closure criteria for the staging pile.
	Staging piles need to follow the federal requirements at 40 C.F.R. § 264.554.	RCRA or non-RCRA hazardous waste stored temporarily.	Cal. Code Regs. tit. 22, § 66264.552(f)				Not an ARAR. Not more stringent than federal ARARs at 40 C.F.R. §264.554.
Closure of staging pile	At closure, owner shall remove or decontaminate all waste residues, contaminated containment system components, contaminated subsoils, and structures and equipment contaminated with waste and leachate, and manage them as hazardous waste.	Staging pile used to temporarily store or treat waste.	Cal. Code Regs. tit. 22, §66264.258(a)		2, 3		Potential relevant and appropriate for design, operating, and closure criteria for the staging pile.

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Cover	At final closure of the landfill or upon closure of any cell, the owner or operator shall cover the landfill or cell with a final cover designed and constructed to conform to the provisions of subsections (e) through (r) of § 66264.228, except that a variance shall be granted from any requirement of subsections (e) through (r) that the owner or operator demonstrates is not necessary to protect public health, water quality, or other environmental quality.	RCRA Hazardous waste disposal needing cover.	§66264.310(a)(7)		3		Potentially relevant and appropriate for cap to prevent water from leaching pollutants to groundwater.
Clean Air Act (42 U.S.C. §§7401–7671)*							
Discharge to air	Provisions of SIP approved by USEPA under Section 110 of CAA.	Major sources of air pollutants.	40 U.S.C. §7410; portions of 40 C.F.R. §52.220		2, 3		Applicable to emissions from soil disturbance. Specific pertinent rules are listed below.
	A person shall not discharge from any source for a period or aggregate periods of more than three minutes in any hour, a visible emission that is as dark or darker than No. 1 on the Ringelmann Chart, or of such opacity as to obscure an observer's view to an equivalent or greater degree.		SMAQMD Rule 401, Section 301	2, 3			Applicable to controlling emissions during soil disturbing activities. Dust controls will be implemented to control dust during the remedial action.

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Discharge to air (continued)	Except as otherwise specified in SMAQMD Rule 406, a person shall not discharge into the atmosphere from any source particulate matter in excess of 0.23 gram per dry standard cubic meter.		SMAQMD Rule 404, Section 301	2, 3			Applicable to controlling emissions during soil disturbing activities. Dust controls will be implemented to control dust during the remedial action.
	A person shall not discharge into the atmosphere in any 1 hour from any source whatsoever dust or condensed fumes in total quantities in excess of the amount shown the Table for Process Weight and Allowable Discharge included in SMAQMD Rule 405.		SMAQMD Rule 405, Section 301	2, 3			Applicable to controlling emissions during soil disturbing activities. Dust controls will be implemented to control dust during the remedial action.
	A person shall not manufacture for paving, road construction, or road maintenance any rapid or medium cure cutback asphalt, or slow cure cutback asphalt or emulsified asphalt containing organic compounds that evaporate at 260 degrees Celsius (500 degrees Fahrenheit) or lower as determined by ASTM Method D244 in excess of the limits specified in SMAQMD Rule 453.		SMAQMD Rule 453, Section 301 and 302	2, 3			Applicable to paving associated with site restoration and/or capping.

Table A3-1. Potential Federal Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Note:

*Statutes and policies, and their citations, are provided as headings to identify general categories of potential ARARs for the convenience of the reader. Listing the statutes and policies does not indicate that SMUD accepts the entire statutes or policies as potential ARARs; specific potential ARARs are addressed in the table below each general heading; only substantive requirements of specific citations are considered potential ARARs.

Acronyms/Abbreviations:

A – applicable
ARAR – applicable or relevant and appropriate requirement
CAA – Clean Air Act
Cal. Code Regs. – *California Code of Regulations*
C.F.R. – *Code of Federal Regulations*
LDR – land disposal restriction
LUC – land use control
MTR – minimum technology requirement
RA – relevant and appropriate
RCRA – Resource Conservation and Recovery Act
§ – section
SIP – State Implementation Plan
SMAQMD – Sacramento Metropolitan Air Quality Management District
SMUD – Sacramento Municipal Utility District
TBC – to be considered
tit. - title
U.S.C. – *United States Code*
USEPA – United States Environmental Protection Agency

Table A3-2. Potential State Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
State Water Resources Control Board and Regional Water Quality Control Board*							
Construction and land disturbance	Requires BMPs, developing and implementing a stormwater pollution prevention plan, and monitoring of stormwater discharges. Contains numeric effluent limits and action levels.	Construction site that disturbs one or more acres of soil.	SWRCB Order No. 2009-0009-DWQ, as amended by 2010-0014-DWQ (General Construction Activity Storm Water Permit)		2, 3		SMUD will implement the substantive provisions of the State of California's General Construction Storm Water Permit (SWRCB Order No. 2009-0009-DWQ) to comply with federal CWA ARARs and State water quality ARARs for discharge to surface water. The federal and State ARARs require BMPs and a SWPPP.
State Water Resources Control Board*							
Disposal of waste	Requires that nonhazardous solid waste as defined at § 20220(a) be discharged to a classified waste management unit.	Discharge of nonhazardous solid waste after 18 July 1997 to land for treatment, storage, or disposal.	Cal. Code Regs. tit. 27, § 20220(b), (c), and (d)	2, 3			Applicable to nonhazardous solid waste disposed off-Site.
Cal/EPA Department of Toxic Substances Control*							
Disposal of non-RCRA waste	Land disposal restrictions for non-RCRA, California-regulated hazardous waste.	Non-RCRA, California-regulated hazardous waste disposal.	Cal. Code Regs. tit. 22, § 66268.105	2, 3			Applicable to disposal of non-RCRA hazardous waste.

Table A3-2. Potential State Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
Land-use covenants	A land-use covenant imposing appropriate limitations on land use shall be executed and recorded when facility closure, corrective action, remedial or removal action, or other response actions are undertaken, and hazardous materials, hazardous wastes or constituents, or hazardous substances will remain at the property at levels that are not suitable for unrestricted use of the land.		Cal. Code Regs. tit. 22, §67391.1		3		Cal. Code Regs. tit. 22, §67391.1 provides for a land-use covenant to be executed and recorded when remedial actions are taken and hazardous substances will remain at the property at concentrations that are unsuitable for unrestricted use of the land. SMUD has determined the substantive provisions of this regulation to be "relevant and appropriate".
California Civil Code*							
LUCs	Provides conditions under which land-use restrictions will apply to successive owners of land.		Cal. Civ. Code §1471		3		Generally, Cal. Civ. Code §1471 allows a landowner to make a covenant to restrict the use of land for the benefit of a covenantee. The covenant runs with the land to bind successive owners, and the restrictions must be reasonably necessary to protect present or future human health or safety or the environment as a result of the presence on the land of hazardous materials, as defined in Cal. Health & Safety Code§ 25260. Substantive provisions are the following

Table A3-2. Potential State Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
LUCs (continued)			Cal. Civ. Code §1471 (continued)				general narrative standard: "to do or refrain from doing some act on his or her own land … where (c) Each such act relates to the use of land and each such act is reasonably necessary to protect present or future human health or safety or the environment as a result of the presence of hazardous materials, as defined in Section 25260 of the California Health and Safety Code." This narrative standard would be implemented through incorporation of restrictive covenants in the deed and Environmental Restriction and Covenant Agreement.
California Health and Safety Code*							
LUCs	Allows DTSC to enter into an agreement with the owner of a hazardous waste facility to restrict present and future land uses.		Cal. Health & Safety Code § 25202.5		3		The substantive provisions of Cal. Health & Safety Code § 25202.5 are the general narrative standards to restrict "present and future uses of all or part of the land on which the … facility … is located …"

Table A3-2. Potential State Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
LUCs	Provides a streamlined process to be used to enter into an agreement to restrict specific use of property in order to implement the substantive use restrictions of Cal. Health & Safety Code §25232(b)(1)(A)–(E).		Cal. Health & Safety Code §§25222.1 and 25355.5(a)(1)(C)		3		Generally, Cal. Health & Safety Code §§25222.1 and 25355.5(a)(1)(C) provide the authority for the DTSC to enter into voluntary agreements with land owners to restrict the use of property. The agreements run with the land restricting present and future uses of the land. The substantive requirements of the following Cal. Health & Safety Code §25222.1 provisions are “relevant and appropriate”: (1) the general narrative standard: “restricting specified uses of the property…” and (2) “…the agreement is irrevocable, and shall be recorded by the owner, …as a hazardous waste easement, covenant, restriction or servitude, or any combination thereof, as appropriate, upon the present and future uses of the land.” The substantive requirements of the following Cal. Health & Safety Code §25355.5(a)(1)(C) provisions are “relevant and appropriate”: “…execution and recording of a written instrument that imposes an easement, covenant, restriction, or servitude, or combination thereof, as

Table A3-2. Potential State Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
							appropriate, upon the present and future uses of the land.”
Stockpiling	Stockpiled at the site for up to 90 days without satisfying all substantive requirements of a hazardous waste facility storage permit provided certain conditions are met with regard to storage, inspections, and management. These conditions include: the waste is non-RCRA contaminated soil; the hazardous waste being accumulated does not contain free liquids; the hazardous waste is accumulated on an impermeable surface, such as high-density polyethylene, of at least 20 mils that is supported by a foundation, or high-density polyethylene of at least 60 mils that is not supported by a foundation; the generator provides controls for windblown dispersion and precipitation runoff and run-on, and complies with any stormwater permit requirements issued by an RWQCB; the generator has the accumulation site inspected weekly and after storms to assure that the controls for	Non-RCRA hazardous waste intended for on-site treatment and disposal.	Cal. Health & Safety Code § 25123.3	2, 3			Only substantive provisions more stringent than 40 C.F.R. §264.554 relating to non-RCRA hazardous waste are applicable.

Table A3-2. Potential State Action-Specific ARARs

Remedial Action Alternatives for the SMUD 59th Street Corporation Yard Site: Alternative 1 – No Action; Alternative 2 –Soil Excavation/Off-Site Disposal; Alternative 3 – Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and LUCs

Action	Requirement	Prerequisite	Citation	A	RA	TBC	Comments
	windblown dispersion and precipitation runoff and run-on are functioning properly; the generator, after final off-site transportation, inspects the accumulation site for contamination and remediates as necessary; the site is certified by a registered engineer for compliance with the standards specified herein.						

Note:

* Statutes and policies, and their citations, are provided as headings to identify general categories of potential ARARs for the convenience of the reader; listing the statutes and policies does not indicate that SMUD accepts the entire statutes or policies as potential ARARs; specific potential ARARs are addressed in the table below each general heading; only substantive requirements of the specific actions are considered potential ARARs.

Acronyms/Abbreviations:

A – applicable
ARAR – applicable or relevant and appropriate requirement
Cal. Civil Code – *California Civil Code*
Cal. Code Regs. – *California Code of Regulations*
Cal. Health & Safety Code – *California Health and Safety Code*
C.F.R. – Code of Federal Regulations
DTSC – (Cal/EPA) Department of Toxic Substances Control
LUC – land use control
RA – relevant and appropriate
RCRA – Resource Conservation and Recovery Act
RWQCB – Regional Water Quality Control Board
§ – section
SMUD – Sacramento Municipal Utility District
TBC – to be considered
tit. – title

Appendix B

Removal Action Alternative Cost Estimates

Construction Cost Estimate

Alternate 2
Soil Excavation/Off-Site Disposal
59th Street
Sacramento, California

SMUD Corporation Yard

Table Of Contents

1.) Basis of Estimate

2.) CSI Summary

3.) Estimate Detail

A.) Temporaries
B.) Earthwork

Basis of Estimate

This estimate is based on the following assumptions and clarifications:

Qualifications

1 This estimate includes new work that interconnects with an existing structure and associated infrastructure. Pricing assumes that existing conditions will allow for required modifications to accept new work. No costs are included for code required and /or cosmetic upgrades.

2 The estimate includes pricing developed upon local Prevailing Labor Rates with extensions as applicable to the performance duration, productivity factors, material / equipment, and similar costs for projects of this type.

3 The estimate assumes that a minimum of three bids will be received in each trade.

4 This estimate assumes that soil export is allowed to be deposited at the local landfill as hard to handle.

5 The estimate assumes fill material requirements can be met locally with local transport.

6 This estimate assumes approximately 2 months of total duration including coordination, mobilization, performance of work, de-mobilization, clean up, and closeout procedures. Schedule NTP is assumed to start September 1, 2022.

7 Soil is assumed to be excavated, pushed to a pile, sampled, then offhauled when testing shows suitable for offhaul.

8 Removal Action Completion Report to be prepared following removal action completion. Cost for the report is included under design contingency.

Exclusions

1 Non-standard material sizes
2 Effects of working conditions / efficiency
3 Escalation
4 Architectural, design and construction management fees
5 Assessments, taxes, finance, legal charges
6 Environmental impact mitigation
7 Land and easement acquisition
8 Off Site Utility Upgrades and / or Off Site Infrastructure improvements
9 Utility and Service Tunnels
10 LEED Certification
11 Mock-ups
12 Off-site utility upgrades
13 Builder's risk, project wrap-up and other owner provided insurance program
14 Disconnections and diversions of existing services
15 Developers risk allowance / overall project contingency
16 Finance charges, developers costs and profit
17 Phasing requirements
18 No improvement to existing infrastructure
19 Owner furnished materials

CSI Summary by Facility

Project: **SMUD Corporation Yard**

Design Team Logo

Title: **Alternate 2 Soil Excavation/Off-Site Disposal 59th StreetSacramento, California**

Design Level:
Conceptual

Location: **Sacramento, California**
Designed by: **AECOM**
CSI Summary
Date: **February 14, 2022**

CSI	Description		Temporaries	NonHaz	HazRCRA	Total
2	Temporaries		$115,277	$0	$0	$115,277
31	Earthwork		$33,351	$1,315,346	$133,025	$1,481,722
	Subtotal		**$148,628**	**$1,315,346**	**$133,025**	**$1,596,999**
	General Conditions	4.00%	$5,945	$52,614	$5,321	$63,880
	General Requirements	2.00%	$2,973	$26,307	$2,661	$31,940
	General Contractor Markup	5.00%	$7,877	$69,713	$7,050	$84,641
	General Contractor Bond & Insurance	2.00%	$3,308	$29,280	$2,961	$35,549
	Construction Cost of Work		**$168,731**	**$1,493,259**	**$151,018**	**$1,813,009**
	Design Contingency		$0.00	$0.00	$0.00	$0
	Construction Cost and Contingency'		**$168,731**	**$1,493,259**	**$151,018**	**$1,813,009**
	Escalation		$0.00	$0.00	$0.00	$0
	Total Construction Cost		**$168,731**	**$1,493,259**	**$151,018**	**$1,813,009**

Detailed Facility Estimate

Tab Name: Temporaries
Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	UNIT COST	TOTAL COST - SUB
	02 41 00	**PROTECTION**				
	02 41 00	Temporary Fencing (not included)	0	LF	$0.00	$0
	02 41 00	Fence Maintenance	0	mo	$0.00	$0
	02 41 00				$0.00	$0
	02 41 00	Soil Sampling (per 1,000 CY)	9	EA	$352.40	$3,172
	02 41 00	Stockpile	2	EA	$352.40	$705
	02 41 00	Soil Sampling	5	EA	$338.79	$1,694
	02 41 00	Import	5	EA	$2,787.58	$13,938
	02 41 00	Laboratory	12	EA	$363.55	$4,363
	02 41 00	**PROTECTION**			**$0.00**	**$23,871**
	02 70 00	**STORM WATER PREVENTION PLAN AND IMPLEMENTATION**				
	02 70 00	Review NPDES	8	HRS	$104.69	$838
	02 70 00	Develop Plan QSP/ QSD (Not Included)		WKS	$0.00	$0
	02 70 00	NOI, Plan, NOT - Procure , Submit, File	1	WKS	$5,213.81	$5,214
	02 70 00	Fees (NIC)			$0.00	$0
	02 70 00				$0.00	$0
	02 70 00	Allowance for SWPPP material and moves	1	LS	$8,950.34	$8,950
	02 70 00	Cover with fabric and sandbags - install	2,000	SF	$2.99	$5,984
	02 70 00	Cover with fabric and sandbags - remove	2,000	SF	$2.93	$5,870
	02 70 00				$0.00	$0
	02 70 00				$0.00	$0
	02 70 00	Silt Fence 10' post spacing, 48" post, 36" fabric	1,210	LF	$9.53	$11,529
	02 70 00	Fiber Rolls	815	LF	$12.46	$10,155
	02 70 00	Stabilized Entry Rock		CY	$0.00	$0
	02 70 00	Wheel cleaner, rumble strips		LS	$0.00	$0
	02 70 00	Street Cleaning and Vacuuming	2	MO	$11,074.38	$22,149
	02 70 00				$0.00	$0
	02 70 00	Storm Drain Inlet Protection	3	EA	$477.70	$1,433
	02 70 00			MO	$0.00	$0
	02 70 00	Traffic Plan	1	LS	$4,187.65	$4,188
	02 70 00	Traffic Signage / Signaling	1	MO	$15,097.04	$15,097
	02 70 00					
	02 70 00	**STORM WATER PREVENTION PLAN AND IMPLEMENTATION**			**$0.00**	**$91,406**
	31 00 00	**SHORING ALLOWANCE (AREA 4)**				

Detailed Facility Estimate

Tab Name: Temporaries

Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	UNIT COST	TOTAL COST - SUB
	31 00 00	Mobilization	1	LS	$15,750.00	$15,750
	31 00 00	Sheet Shoring - prep	80	SF	$1.10	$88
	31 00 00	Sheet Shoring - drive	80	SF	$87.74	$7,019
	31 00 00	Brace	80	SF	$6.58	$527
	31 00 00	Cut Back	80	SF	$0.68	$54
	31 00 00	Clean	80	SF	$12.35	$988
	31 00 00	Demob	1	LS	$8,925.00	$8,925
	31 00 00	**SHORING ALLOWANCE (AREA 4)**			**$0.00**	**$33,351**
	31 60 00	**SPECIAL FOUNDATIONS**			**$0.00**	**$0**
	32 12 00	**PAVING**			**$0.00**	**$0**
	32 16 00	**CONCRETE CURBS AND GUTTERS**			**$0.00**	**$0**
	32 30 00	**CONCRETE RAMPS AND RETAINING WALLS**			**$0.00**	**$0**
	32 20 00	**MISC. SITE PAVING SYSTEMS**			**$0.00**	**$0**
	32 80 00	**LANDSCAPE AND IRRIGATION**			**$0.00**	**$0**
	32 31 00	**FENCES & GATES**			**$0.00**	**$0**
	12 93 00	**SITE FURNISHINGS**			**$0.00**	**$0**
	33 10 00	**DOMESTIC & FIRE WATER**			**$0.00**	**$0**
	33 51 00	**NATURAL GAS DISTRIBUTION**			**$0.00**	**$0**
	33 30 00	**SANITARY SEWER**			**$0.00**	**$0**
	33 40 00	**STORM SEWER**			**$0.00**	**$0**
	33 60 00	**HYDRONIC AND STEAM ENERGY UTILITIES**			**$0.00**	**$0**
	26 30 00	**EMERGENCY GENERATOR**			**$0.00**	**$0**
	33 73 00	**UTILITY CO TRANSFORMERS AND CONDUCTORS**			**$0.00**	**$0**
	26 10 00	**SITE ELECTRICAL POWER AND DISTRIBUTION**			**$0.00**	**$0**
	26 56 00	**SITE LIGHTING**			**$0.00**	**$0**
	33 82 00	**LOW VOLTAGE AND SECURITY**			**$0.00**	**$0**
	33 82 00	**MISCELLANEOUS SITE IMPROVEMENTS**			**$0.00**	**$0**
	Total	**Subtotal subcontractor cost**			**$0.00**	**$148,628**

Detailed Facility Estimate

Tab Name: NonHaz

Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	MH / UNIT	CREW	Days	MH COST	UNIT MATL	Hr Rate	UNIT EQUIP	UNIT SUB	UNIT COST	TOTAL COST - SUB
	02 41 00	**DEMOLITION**									**0.00**			
	02 41 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 41 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 41 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 41 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 41 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 41 00										0.00			
	02 41 00	**DEMOLITION**									**0.00**		**$0.00**	**$0**
	02 70 00	**FACILITY REMEDIATION**									0.00			
	02 70 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 70 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 70 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 70 00							$0.00	0.00		0.00	0.00	$0.00	$0
	02 70 00										0.00			
	02 70 00	**FACILITY REMEDIATION**									**0.00**		**$0.00**	**$0**
	31 00 00	**EARTHWORK**												
	31 00 00	Excavation	7,422	CY	0.020	EQHV	18.555	$88.29	0.00	165.65	3.31	0.00	$6.33	$47,017
	31 00 00	Push	8,535	CY	0.020	EQHV	21.338	$88.29	0.00	208.68	4.17	0.00	$7.37	$62,938
	31 00 00	Load	8,535	CY	0.020	EQHV	21.338	$88.29	0.00	165.65	3.31	0.00	$6.33	$54,070
	31 00 00	Offhaul, truck and disposal	590	LOAD	1.250	TRLT	92.188	$23.51	0.00	68.50	85.63	425.00	$588.48	$347,206
	31 00 00	Purchase / transport clean backfill	514	LOAD	1.250	TRLT	80.256	$23.51	378.00	68.50	85.63	425.00	$1,044.83	$536,660
	31 00 00	Clean Backfill - handling	7,793	CY	0.020	EQHV	19.483	$88.29	0.00	165.65	3.31	0.00	$6.33	$49,368
	31 00 00	Compact with Sheepsfoot	7,793	CY	0.002	EQHV	1.9483	$88.29	0.00	165.65	0.33	0.00	$0.63	$4,937
	31 00 00	Water buffalo (trailer mount)	7,793	CY	0.255	CLAB	248.41	$66.50	0.00	16.00	4.08	0.00	$27.35	$213,149
	31 00 00							$0.00	0.00	215.00	0.00	0.00	$0.00	$0
	31 00 00										0.00			
	31 00 00	**EARTHWORK**									**0.00**		**$0.00**	**$1,315,346**
	31 60 00	**SPECIAL FOUNDATIONS**									**0.00**		**$0.00**	**$0**
	32 12 00	**SITE PREP**									**0.00**		**$0.00**	**$0**
	32 16 00	**CONCRETE CURBS AND GUTTERS**									**0.00**		**$0.00**	**$0**
	32 30 00	**CONCRETE RAMPS AND RETAINING WALLS**									**0.00**		**$0.00**	**$0**
	32 20 00	**MISC. SITE PAVING SYSTEMS**									**0.00**		**$0.00**	**$0**
	32 80 00	**LANDSCAPE AND IRRIGATION**									**0.00**		**$0.00**	**$0**
	32 31 00	**FENCES & GATES**									**0.00**		**$0.00**	**$0**
	12 93 00	**SITE FURNISHINGS**									**0.00**		**$0.00**	**$0**
	33 10 00	**DOMESTIC & FIRE WATER**									**0.00**		**$0.00**	**$0**
	33 51 00	**NATURAL GAS DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	33 30 00	**SANITARY SEWER**									**0.00**		**$0.00**	**$0**
	33 40 00	**STORM SEWER**									**0.00**		**$0.00**	**$0**
	33 60 00	**HYDRONIC AND STEAM ENERGY UTILITIES**									**0.00**		**$0.00**	**$0**
	26 30 00	**EMERGENCY GENERATOR**		**KW**							**0.00**		**$0.00**	**$0**
	33 73 00	**UTILITY CO TRANSFORMERS AND CONDUCTORS**									**0.00**		**$0.00**	**$0**
	26 10 00	**SITE ELECTRICAL POWER AND DISTRIBUTION**									**0.00**		**$0.00**	**$0**

Detailed Facility Estimate

Tab Name: NonHaz

Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	MH / UNIT	CREW	Days	MH COST	UNIT MATL	Hr Rate	UNIT EQUIP	UNIT SUB	UNIT COST	TOTAL COST - SUB
	26 56 00	**SITE LIGHTING**									**0.00**		**$0.00**	**$0**
	33 82 00	**LOW VOLTAGE AND SECURITY**									**0.00**		**$0.00**	**$0**
	33 82 00	**MISCELLANEOUS SITE IMPROVEMENTS**									**0.00**		**$0.00**	**$0**
	Total	**Subtotal subcontractor cost**									0.00		**$0.00**	**$1,315,346**

Detailed Facility Estimate

Tab Name: HazRCRA

Date: February 14, 2022

Total GSF: 941 sf

ADA I1	TRADE	SYSTEM	DESCRIPTION	QTY	UNIT	MH / UNIT	CREW		MH COST	UNIT MATL		UNIT EQUIP	UNIT SUB	UNIT COST	TOTAL COST - SUB
	02 41 00	**F30**	**DEMOLITION**									**0.00**		**$0.00**	**$0**
	02 70 00	**F20**	**FACILITY REMEDIATION**									**0.00**		**$0.00**	**$0**
	31 00 00	**G10**	**EARTHWORK**												
	31 00 00	G10	Excavation	941	CY	0.050	EQHV	5.8813	$88.29	0.00	165.65	8.28	0.00	$15.84	$14,903
	31 00 00	G10	Push	1,082	CY	0.075	EQHV	10.145	$88.29	0.00	208.68	15.65	0.00	$27.65	$29,923
	31 00 00	G10	Load	1,082	CY	0.020	EQHV	2.7054	$88.29	0.00	165.65	3.31	0.00	$6.33	$6,855
	31 00 00	G10	Offhaul, Haz RCRA to buttonwillow , truck and disposal	75	LOAD				$0.00	0.00		0.00	425.00	$446.25	$33,469
	31 00 00	G10	Purchase / transport clean backfill	65	LOAD				$0.00	336.00		0.00	425.00	$851.89	$55,476
	31 00 00	G10	Clean Backfill - handling	988	CY	0.020	EQHV	2.4701	$88.29	0.00	165.65	3.31	0.00	$6.33	$6,259
	31 00 00	G10	Compact with Sheepsfoot	988	CY	0.002	EQHV	0.247	$88.29	0.00	165.65	0.33	0.00	$0.63	$626
	31 00 00	G10	Water truck	988	CY	0.050	TRLT	6.1753	$23.51	0.00	68.12	3.41	0.00	$5.67	$5,599
	31 00 00	G10				0.000			$0.00	0.00		0.00	0.00	$0.00	$0
	31 00 00	G10							$0.00	0.00		0.00	0.00	$0.00	$0
	31 00 00	**G10**	**EARTHWORK**									**0.00**		**$1,360.59**	**$153,110**
	31 60 00	**G20**	**SPECIAL FOUNDATIONS**									**0.00**		**$0.00**	**$0**
	32 12 00	**G20**	**PAVING**									**0.00**		**$0.00**	**$0**
	32 16 00	**G20**	**CONCRETE CURBS AND GUTTERS**									**0.00**		**$0.00**	**$0**
	32 30 00	**G20**	**CONCRETE RAMPS AND RETAINING WALLS**									**0.00**		**$0.00**	**$0**
	32 20 00	**G20**	**MISC. SITE PAVING SYSTEMS**									**0.00**		**$0.00**	**$0**
	32 80 00	**G20**	**LANDSCAPE AND IRRIGATION**									**0.00**		**$0.00**	**$0**
	32 31 00	**G20**	**FENCES & GATES**									**0.00**		**$0.00**	**$0**
	12 93 00	**G20**	**SITE FURNISHINGS**									**0.00**		**$0.00**	**$0**
	33 10 00	**G30**	**DOMESTIC & FIRE WATER**									**0.00**		**$0.00**	**$0**
	33 51 00	**G30**	**NATURAL GAS DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	33 30 00	**G30**	**SANITARY SEWER**									**0.00**		**$0.00**	**$0**
	33 40 00	**G30**	**STORM SEWER**									**0.00**		**$0.00**	**$0**
	33 60 00	**G30**	**SITE SPECIFIC REQUIREMENTS**									**0.00**		**$0.00**	**$0**
	26 30 00	**G40**	**EMERGENCY GENERATOR**		**KW**							**0.00**		**$0.00**	**$0**
	33 73 00	**G40**	**UTILITY CO TRANSFORMERS AND CONDUCTORS**									**0.00**		**$0.00**	**$0**
	26 10 00	**G40**	**SITE ELECTRICAL POWER AND DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	26 56 00	**G40**	**SITE LIGHTING**									**0.00**		**$0.00**	**$0**
	33 82 00	**G50**	**LOW VOLTAGE AND SECURITY**									**0.00**		**$0.00**	**$0**
	33 82 00	**G90**	**MISCELLANEOUS SITE IMPROVEMENTS**									**0.00**		**$0.00**	**$0**
	Total		**Subtotal subcontractor cost**									0.00		**$162.71**	**$153,110**

Construction Cost Estimate

Alternate 3
Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

SMUD Corporation Yard

Table Of Contents

Basis of Estimate

This estimate is based on the following assumptions and clarifications:

Qualifications

1 This estimate includes new work that interconnects with an existing structure and associated infrastructure. Pricing assumes that existing conditions will allow for required modifications to accept new work. No costs are included for code required and /or cosmetic upgrades.
2 The estimate includes pricing developed upon local Prevailing Labor Rates with extensions as applicable to the performance duration, productivity factors, material / equipment, and similar costs for projects of this type.
3 The estimate assumes that a minimum of three bids will be received in each trade.
4 This estimate assumes that soil export is allowed to be deposited at the local landfill as hard to handle.
5 The estimate assumes fill material requirements can be met locally with local transport.
6 This estimate assumes approximately 2 months of total duration including coordination, mobilization, performance of work, de-mobilization, clean up, and closeout procedures. Schedule NTP is assumed to start September 1, 2022.
7 Soil is assumed to be excavated, pushed to a pile, sampled, then offhauled when testing shows suitable for offhaul.
8 Removal Action Completion Report to be prepared following removal action completion. Cost for the report is included under design contingency.
9 Present value calculations utilize 3.25% interest and 3.50% inflation.

Exclusions

1 Non-standard material sizes
2 Effects of working conditions / efficiency
3 Escalation
4 Architectural, design and construction management fees
5 Assessments, taxes, finance, legal charges
6 Environmental impact mitigation
7 Land and easement acquisition
8 Off Site Utility Upgrades and / or Off Site Infrastructure improvements
9 Utility and Service Tunnels
10 LEED Certification
11 Mock-ups
12 Off-site utility upgrades
13 Builder's risk, project wrap-up and other owner provided insurance program
14 Disconnections and diversions of existing services
15 Developers risk allowance / overall project contingency
16 Finance charges, developers costs and profit
17 Phasing requirements
18 No improvement to existing infrastructure
19 Owner furnished materials

CSI Summary by Facility

Project: SMUD Corporation Yard **Design Team Logo**

Title: Alternate 3Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

Location: Sacramento, California

Designed by: AECOM

CSI Summary

Date: February 14, 2022

Design Level:
Conceptual

CSI	Description		Temporaries	NonHaz	HazRCRA	Total
2	Temporaries		$115,277	$0	$0	$115,277
31	Earthwork		$33,351	$282,621	$213,502	$529,474
	Subtotal		**$148,628**	**$668,114**	**$213,502**	**$1,030,243**
	General Conditions	4.00%	$5,945	$26,725	$8,540	$41,210
	General Requirements	2.00%	$2,973	$13,362	$4,270	$20,605
	General Contractor Markup	5.00%	$7,877	$35,410	$11,316	$54,603
	General Contractor Bond & Insurance	2.00%	$3,308	$14,872	$4,753	$22,933
	Construction Cost of Work		**$168,731**	**$758,483**	**$242,380**	**$1,169,594**
	Design Contingency		$0.00	$0.00	$0.00	$0
	Construction Cost and Contingency'		**$168,731**	**$758,483**	**$242,380**	**$1,169,594**
	Escalation		$0.00	$0.00	$0.00	$0
	Total Construction Cost (Year 1)		**$168,731**	**$758,483**	**$242,380**	**$1,169,594**

Detailed Facility Estimate

Tab Name: Temporaries
Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	UNIT COST	TOTAL COST - SUB
	02 41 00	**PROTECTION**				
	02 41 00	Temporary Fencing (not included)	0	LF	$0.00	$0
	02 41 00	Fence Maintenance	0	mo	$0.00	$0
	02 41 00				$0.00	$0
	02 41 00	Soil Sampling (per 1,000 CY)	9	EA	$352.40	$3,172
	02 41 00	Stockpile	2	EA	$352.40	$705
	02 41 00	Soil Sampling	5	EA	$338.79	$1,694
	02 41 00	Import	5	EA	$2,787.58	$13,938
	02 41 00	Laboratory	12	EA	$363.55	$4,363
	02 41 00	**PROTECTION**			**$0.00**	**$23,871**
	02 70 00	**STORM WATER PREVENTION PLAN AND IMPLEMENTATION**				
	02 70 00	Review NPDES	8	HRS	$104.69	$838
	02 70 00	Develop Plan QSP/ QSD (Not Included)		WKS	$0.00	$0
	02 70 00	NOI, Plan, NOT - Procure , Submit, File	1	WKS	$5,213.81	$5,214
	02 70 00	Fees (NIC)			$0.00	$0
	02 70 00				$0.00	$0
	02 70 00	Allowance for SWPPP material and moves	1	LS	$8,950.34	$8,950
	02 70 00	Cover with fabric and sandbags - install	2,000	SF	$2.99	$5,984
	02 70 00	Cover with fabric and sandbags - remove	2,000	SF	$2.93	$5,870
	02 70 00				$0.00	$0
	02 70 00				$0.00	$0
	02 70 00	Silt Fence 10' post spacing, 48" post, 36" fabric	1,210	LF	$9.53	$11,529
	02 70 00	Fiber Rolls	815	LF	$12.46	$10,155
	02 70 00	Stabilized Entry Rock		CY	$0.00	$0
	02 70 00	Wheel cleaner, rumble strips		LS	$0.00	$0
	02 70 00	Street Cleaning and Vacuuming	2	MO	$11,074.38	$22,149
	02 70 00				$0.00	$0
	02 70 00	Storm Drain Inlet Protection	3	EA	$477.70	$1,433
	02 70 00			MO	$0.00	$0
	02 70 00	Traffic Plan	1	LS	$4,187.65	$4,188
	02 70 00	Traffic Signage / Signaling	1	MO	$15,097.04	$15,097
	02 70 00					
	02 70 00	**STORM WATER PREVENTION PLAN AND IMPLEMENTATION**			**$0.00**	**$91,406**
	31 00 00	**SHORING ALLOWANCE (AREA 4)**				

Detailed Facility Estimate

Tab Name: Temporaries
Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	UNIT COST	TOTAL COST - SUB
	31 00 00	Mobilization	1	LS	$15,750.00	$15,750
	31 00 00	Sheet Shoring - prep	80	SF	$1.10	$88
	31 00 00	Sheet Shoring - drive	80	SF	$87.74	$7,019
	31 00 00	Brace	80	SF	$6.58	$527
	31 00 00	Cut Back	80	SF	$0.68	$54
	31 00 00	Clean	80	SF	$12.35	$988
	31 00 00	Demob	1	LS	$8,925.00	$8,925
	31 00 00	**SHORING ALLOWANCE (AREA 4)**			**$0.00**	**$33,351**
	31 60 00	**SPECIAL FOUNDATIONS**			**$0.00**	**$0**
	32 12 00	**PAVING**			**$0.00**	**$0**
	32 16 00	**CONCRETE CURBS AND GUTTERS**			**$0.00**	**$0**
	32 30 00	**CONCRETE RAMPS AND RETAINING WALLS**			**$0.00**	**$0**
	32 20 00	**MISC. SITE PAVING SYSTEMS**			**$0.00**	**$0**
	32 80 00	**LANDSCAPE AND IRRIGATION**			**$0.00**	**$0**
	32 31 00	**FENCES & GATES**			**$0.00**	**$0**
	12 93 00	**SITE FURNISHINGS**			**$0.00**	**$0**
	33 10 00	**DOMESTIC & FIRE WATER**			**$0.00**	**$0**
	33 51 00	**NATURAL GAS DISTRIBUTION**			**$0.00**	**$0**
	33 30 00	**SANITARY SEWER**			**$0.00**	**$0**
	33 40 00	**STORM SEWER**			**$0.00**	**$0**
	33 60 00	**HYDRONIC AND STEAM ENERGY UTILITIES**			**$0.00**	**$0**
	26 30 00	**EMERGENCY GENERATOR**			**$0.00**	**$0**
	33 73 00	**UTILITY CO TRANSFORMERS AND CONDUCTORS**			**$0.00**	**$0**
	26 10 00	**SITE ELECTRICAL POWER AND DISTRIBUTION**			**$0.00**	**$0**
	26 56 00	**SITE LIGHTING**			**$0.00**	**$0**
	33 82 00	**LOW VOLTAGE AND SECURITY**			**$0.00**	**$0**
	33 82 00	**MISCELLANEOUS SITE IMPROVEMENTS**			**$0.00**	**$0**
	Total	**Subtotal subcontractor cost**			**$0.00**	**$148,628**

Detailed Facility Estimate

Tab Name: NonHaz

Date: February 14, 2022

Total

ADA I1	TRADE	DESCRIPTION	QTY	UNIT	MH / UNIT	CREW	Days	MH COST	UNIT MATL	Hr Rate	UNIT EQUIP	UNIT SUB	UNIT COST	TOTAL COST - SUB
	02 41 00	**DEMOLITION**									**0.00**			
	02 41 00	**DEMOLITION**									**0.00**		**$0.00**	**$0**
	02 70 00	**FACILITY REMEDIATION**									**0.00**		**$0.00**	**$0**
	31 00 00	**EARTHWORK**												
	31 00 00	Excavation	992	CY	0.050	EQHV	6.2	$88.29	0.00	165.65	8.28	0.00	$15.84	$15,710
	31 00 00	Push	1,141	CY	0.050	EQHV	7.13	$88.29	0.00	208.68	10.43	0.00	$18.43	$21,030
	31 00 00	Load	1,141	CY	0.050	EQHV	7.13	$88.29	0.00	165.65	8.28	0.00	$15.84	$18,067
	31 00 00	Offhaul, truck and disposal	79	LOAD	0.500	TRLT	4.9375	$23.51	0.00	68.50	34.25	425.00	$503.14	$39,748
	31 00 00	Purchase / transport clean backfill	138	LOAD	0.500	TRLT	8.616	$23.51	336.00	68.50	34.25	425.00	$908.78	$125,280
	31 00 00	Clean Backfill - handling (includes area under AC Cap)	2,042	CY	0.020	EQHV	5.104	$88.29	0.00	165.65	3.31	0.00	$6.33	$12,933
	31 00 00	Compact with Sheepsfoot	2,042	CY	0.050	EQHV	12.76	$88.29	0.00	165.65	8.28	0.00	$15.84	$32,333
	31 00 00	Water buffalo (trailer mount)	2,042	CY	0.080	CLAB	20.416	$66.50	0.00	16.00	1.28	0.00	$8.58	$17,518
	31 00 00							$0.00	0.00	215.00	0.00	0.00	$0.00	$0
	31 00 00										0.00			
	31 00 00	**EARTHWORK**									**0.00**		**$0.00**	**$282,621**
	31 60 00	**SPECIAL FOUNDATIONS**									**0.00**		**$0.00**	**$0**
	32 12 00	**SITE PREP**									**0.00**		**$0.00**	**$0**
	32 16 00	**CONCRETE CURBS AND GUTTERS**									**0.00**		**$0.00**	**$0**
	32 30 00	**CONCRETE RAMPS AND RETAINING WALLS**									**0.00**		**$0.00**	**$0**
	32 20 00	**MISC. SITE PAVING SYSTEMS**									0.00			
	32 20 00	AC Paving Cap	37,000	SF	0.005	EQHV	23.125	$88.29	1.85	171.67	0.86	2.25	$6.22	$230,052
	32 20 00	AC Paving Cap	25,000	SF	0.005	EQHV	15.625	$88.29	1.85	171.67	0.86	2.25	$6.22	$155,441
	32 20 00							$0.00	0.00		0.00	0.00	$0.00	$0
	32 20 00										0.00			
	32 20 00	**MISC. SITE PAVING SYSTEMS**									**0.00**		**$0.00**	**$385,493**
	32 80 00	**LANDSCAPE AND IRRIGATION**									**0.00**		**$0.00**	**$0**
	32 31 00	**FENCES & GATES**									**0.00**		**$0.00**	**$0**
	12 93 00	**SITE FURNISHINGS**									**0.00**		**$0.00**	**$0**
	33 10 00	**DOMESTIC & FIRE WATER**									**0.00**		**$0.00**	**$0**
	33 51 00	**NATURAL GAS DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	33 30 00	**SANITARY SEWER**									**0.00**		**$0.00**	**$0**
	33 40 00	**STORM SEWER**									**0.00**		**$0.00**	**$0**
	33 60 00	**HYDRONIC AND STEAM ENERGY UTILITIES**									**0.00**		**$0.00**	**$0**
	26 30 00	**EMERGENCY GENERATOR**		**KW**							**0.00**		**$0.00**	**$0**
	33 73 00	**UTILITY CO TRANSFORMERS AND CONDUCTORS**									**0.00**		**$0.00**	**$0**
	26 10 00	**SITE ELECTRICAL POWER AND DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	26 56 00	**SITE LIGHTING**									**0.00**		**$0.00**	**$0**
	33 82 00	**LOW VOLTAGE AND SECURITY**									**0.00**		**$0.00**	**$0**
	33 82 00	**MISCELLANEOUS SITE IMPROVEMENTS**									**0.00**		**$0.00**	**$0**
	Total	**Subtotal subcontractor cost**									0.00		**$0.00**	**$668,114**

Detailed Facility Estimate

Tab Name: HazRCRA
Date: February 14, 2022

Total GSF: 941 sf

ADA	TRADE	SYSTEM	DESCRIPTION	QTY	UNIT	MH / UNIT	CREW		MH COST	UNIT MATL		UNIT EQUIP	UNIT SUB	UNIT COST	TOTAL COST - SUB
	02 41 00	**F30**	**DEMOLITION**									**0.00**		**$0.00**	**$0**
	02 70 00	**F20**	**FACILITY REMEDIATION**									**0.00**		**$0.00**	**$0**
	31 00 00	**G10**	**EARTHWORK**												
	31 00 00	G10	Excavation	941	CY	0.150	EQHV	17.644	$88.29	0.00	165.65	24.85	0.00	$47.51	$44,708
	31 00 00	G10	Push	1,082	CY	0.100	EQHV	13.527	$88.29	0.00	208.68	20.87	0.00	$36.87	$39,898
	31 00 00	G10	Load	1,082	CY	0.150	EQHV	20.29	$88.29	0.00	165.65	24.85	0.00	$47.51	$51,415
	31 00 00	G10	Offhaul, Haz RCRA to buttonwillow , truck and disposal	75	LOAD	1.000	TRLT	9.375	$23.51	0.00	68.00	68.00	425.00	$559.43	$41,958
	31 00 00	G10	Purchase / transport clean backfill	65	LOAD	1.000	TRLT	8.1402	$23.51	336.00	68.00	68.00	425.00	$965.07	$62,847
	31 00 00	G10	Clean Backfill - handling	988	CY	0.020	EQHV	2.4701	$88.29	0.00	165.65	3.31	0.00	$6.33	$6,259
	31 00 00	G10	Compact with Sheepsfoot	988	CY	0.002	EQHV	0.247	$88.29	0.00	165.65	0.33	0.00	$0.63	$626
	31 00 00	G10	Water truck	988	CY	0.050	TRLT	6.1753	$23.51	0.00	68.12	3.41	0.00	$5.67	$5,599
	31 00 00	G10				0.000			$0.00	0.00		0.00	0.00	$0.00	$0
	31 00 00	G10							$0.00	0.00		0.00	0.00	$0.00	$0
	31 00 00	**G10**	**EARTHWORK**									**0.00**		**$1,669.02**	**$253,309**
	31 60 00	**G20**	**SPECIAL FOUNDATIONS**									**0.00**		**$0.00**	**$0**
	32 12 00	**G20**	**PAVING**									**0.00**		**$0.00**	**$0**
	32 16 00	**G20**	**CONCRETE CURBS AND GUTTERS**									**0.00**		**$0.00**	**$0**
	32 30 00	**G20**	**CONCRETE RAMPS AND RETAINING WALLS**									**0.00**		**$0.00**	**$0**
	32 20 00	**G20**	**MISC. SITE PAVING SYSTEMS**									**0.00**		**$0.00**	**$0**
	32 80 00	**G20**	**LANDSCAPE AND IRRIGATION**									**0.00**		**$0.00**	**$0**
	32 31 00	**G20**	**FENCES & GATES**									**0.00**		**$0.00**	**$0**
	12 93 00	**G20**	**SITE FURNISHINGS**									**0.00**		**$0.00**	**$0**
	33 10 00	**G30**	**DOMESTIC & FIRE WATER**									**0.00**		**$0.00**	**$0**
	33 51 00	**G30**	**NATURAL GAS DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	33 30 00	**G30**	**SANITARY SEWER**									**0.00**		**$0.00**	**$0**
	33 40 00	**G30**	**STORM SEWER**									**0.00**		**$0.00**	**$0**
	33 60 00	**G30**	**SITE SPECIFIC REQUIREMENTS**									**0.00**		**$0.00**	**$0**
	26 30 00	**G40**	**EMERGENCY GENERATOR**		**KW**							**0.00**		**$0.00**	**$0**
	33 73 00	**G40**	**UTILITY CO TRANSFORMERS AND CONDUCTORS**									**0.00**		**$0.00**	**$0**
	26 10 00	**G40**	**SITE ELECTRICAL POWER AND DISTRIBUTION**									**0.00**		**$0.00**	**$0**
	26 56 00	**G40**	**SITE LIGHTING**									**0.00**		**$0.00**	**$0**
	33 82 00	**G50**	**LOW VOLTAGE AND SECURITY**									**0.00**		**$0.00**	**$0**
	33 82 00	**G90**	**MISCELLANEOUS SITE IMPROVEMENTS**									**0.00**		**$0.00**	**$0**
	Total		**Subtotal subcontractor cost**									0.00		**$269.19**	**$253,309**

Post-Construction Cost Summary

Project: SMUD Corporation Yard

Title: Alternate 3
Limited Soil Excavation/Off-Site Disposal, Soil Containment/Capping-in-Place, and Land Use Controls

Location: Sacramento, California
Designed by: AECOM
CSI Summary
Date: February 14, 2022

YEAR	Future Costs			Present Value
	Annual Inspection and Reporting	Maintenance - Seal Cracks/Repairs	Sub-Total	
2	$7,781		$7,781	$7,518
3	$8,073		$8,073	$7,536
4	$8,376		$8,376	$7,554
5	$8,690		$8,690	$7,573
6	$9,016		$9,016	$7,591
7	$9,354		$9,354	$7,609
8	$9,705		$9,705	$7,628
9	$10,069		$10,069	$7,646
10	$10,446	$28,901	$39,347	$28,870
11	$10,838		$10,838	$7,683
12	$11,244		$11,244	$7,702
13	$11,666		$11,666	$7,720
14	$12,103		$12,103	$7,739
15	$12,557		$12,557	$7,758
16	$13,028		$13,028	$7,776
17	$13,517		$13,517	$7,795
18	$14,024		$14,024	$7,814
19	$14,549		$14,549	$7,833
20	$15,095	$41,763	$56,858	$29,575
21	$15,661		$15,661	$7,871
22	$16,248		$16,248	$7,890
23	$16,858		$16,858	$7,909
24	$17,490		$17,490	$7,928
25	$18,146		$18,146	$7,947
26	$18,826		$18,826	$7,966
27	$19,532		$19,532	$7,986
28	$20,265		$20,265	$8,005
29	$21,025		$21,025	$8,024
30	$21,813	$42,245	$64,058	$23,621
Total Present Value				**$284,067**

Appendix C

Transportation Plan

Prepared for:
Sacramento Municipal Utility District
Sacramento, CA

Prepared by:
AECOM
Sacramento, CA
60632793
July 2022

Appendix C Transportation Plan

SMUD 59th Street Corporation Yard

Prepared for:

Sacramento Municipal Utility District
Environmental Services
6201 S Street, Mail Stop H201
Sacramento, California 95817

Prepared by:

AECOM Technical Services, Inc.
2020 L Street, Suite 400
Sacramento, California 95811

July 2022

Table of Contents

List of Attachments

List of Acronyms and Abbreviations

$\mu g/m^3$	micrograms per cubic meter
AF	attenuation factor
CCR	California Code of Regulations
CFR	Code of Federal Regulations
COC	contaminant of concern
DCE	dichloroethane
DTSC	California Department of Toxic Substances Control
e.g.	*exempli gratia*, for example
HASP	Health and Safety Plan
ID	identification number
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
PCE	tetrachloroethene
RCRA	Resource Conservation and Recovery Act
Site	59th Street Corporation Yard
SMUD	Sacramento Municipal Utility District
STLC	Soluble Threshold Limit Concentration
TCE	trichloroethene
TCLP	Toxicity Characteristic Leaching Procedure
TPH	total petroleum hydrocarbons
TPH_g	total petroleum hydrocarbons as gasoline
$TPH_{ho/mo}$	total petroleum hydrocarbons as hydraulic oil/motor oil
TTLC	Total Threshold Limit Concentration
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound

C.0 Introduction

The purpose of the transportation plan is to minimize potential health, safety, and environmental risks resulting from the movement of material and/or equipment during site cleanup. This transportation plan describes the excavation/offsite disposal remedial action procedures for the cleanup of metal-impacted soils. The following sections discuss each component of the plan: characteristic and destination of soil to be transported (Section C.1); truck transportation (Section C.2); site traffic control (Section C.3); record keeping (Section C.4); health and safety (Section C.5); and contingency plan (Section C.6).

C.1 Characteristic and Destination of Soil to be Transported

Elevated levels of arsenic and lead, up to 330 milligrams per kilogram (mg/kg) and 130 mg/kg, respectively were detected in the SMUD 59th Street Corporation Yard (Site) soil. The Total Threshold Limit Concentration (TTLC) for hazardous waste classification is 500 mg/kg for arsenic and 1,000 mg/kg for lead. The soluble threshold limit concentration (STLC) for hazardous waste classification is 5 milligrams per liter (mg/L) for soluble arsenic and lead. The Toxicity Characteristic Leaching Procedure (TCLP) limit for classifying arsenic or lead-impacted soil as a hazardous waste under the Resource Conservation and Recovery Act (RCRA) of 1976 (and as amended) is 5 mg/L. One soil sample (VW-35-2) with a lead concentration of 120 mg/kg has been analyzed for soluble lead using the Waste Extraction Test and the TCLP with results of 7.6 mg/L and 0.052 mg/L, respectively. Therefore, based on total and soluble lead and arsenic concentrations, it is anticipated that the majority of arsenic and lead-impacted soils removed from the Site will be non-hazardous waste and 5 percent will be non-RCRA hazardous waste.

As a hazardous waste generator, the Sacramento Municipal Utility District (SMUD) has a United States Environmental Protection Agency (USEPA) Identification Number from the California Department of Toxic Substances Control (DTSC) for proper management of the hazardous waste. Compliance with the DTSC requirements of hazardous waste generation, temporary onsite storage, transportation and disposal is required. Any container used for onsite storage will be properly labeled with a hazardous waste label. Within 90 days after its generation, the hazardous waste will be transported off-site for disposal. Any shipment of hazardous wastes in California will be transported by a registered hazardous waste hauler under a uniform hazardous waste manifest. Land disposal restrictions will also be followed, as necessary. Any shipment of non-hazardous waste in California will be transported under a non-hazardous waste manifest or bill-of-lading.

Soils classified as non-hazardous will likely be transported to the following Class III facility:

Kiefer Landfill
12701 Kiefer Boulevard and Grant Line Road
Sloughhouse, California 95683
(916) 875-5555
Monday-Friday: 6:30 a.m. to 4:30 p.m.
Saturday and Sunday - 8:30 a.m. to 4:30 p.m.

Soils classified as designated waste will likely be transported to the following Class II facility:

Recology Hay Road Landfill
6426 Hay Road
Vacaville, California 95687
(707) 678-4718
8 a.m. to 4 p.m.

Soils classified as RCRA or non-RCRA hazardous waste will likely be transported to one or more licensed Class I disposal facilities located at the following addresses:

Buttonwillow Landfill Facility
2500 West Lokern Road
Buttonwillow, California 93206
(661) 762-6200
EPA Identification Number (ID) # CAD980675276

Kettleman Hills Facility
35251 Old Skyline Road
Kettleman City, California 93239
Eric Lynch
510-295-5956
elynch2@wm.com
EPA ID # CAT000646117

C.2 Truck Transportation

Approximately 8,400 bank cubic yards (or an estimated 12,600 tons) of soil will be removed from the Site. Assuming each truck carries a maximum of 23 tons, at least 548 trucks will be needed to transport the impacted soil. All permitted disposal facilities operate a certified weight station at their facility. As such, each truck will be weighed before offloading its payload. Weight tickets or bills of lading will be provided to the removal action subcontractor after all the soil has been shipped offsite. Attachments C-1 through C-4 provide the truck routes from the Site to the disposal facilities listed above.

The site manager will verify that each transporter possesses a valid certification to transport hazardous waste (if applicable) and that all vehicles used for transport are properly registered, operated, and placarded in compliance with local, state, and federal regulations. Before leaving the Site, each truck driver will be instructed to notify the site manager. Each truck driver will be provided with a Uniform Hazardous Waste Manifest, Non-Hazardous Waste Manifest, or bill-of-lading and the cellular phone number for the site manager. It will be the responsibility of the site manager to notify DTSC of any unforeseen incidences. Each truck driver will be instructed to use the freeway Call Box System (if available), a cellular telephone, and/or their radio dispatch system to call for roadside assistance and report roadside emergencies.

C.3 Site Traffic Control

During soil transport activities, trucks will enter the Site through the central gate located on 59th Street. During time of heavy traffic, a flag person will be located at the site to assist the truck drivers to safely drive onto the site. Transportation will be coordinated in such a manner that at any given time, on-site trucks will be in communication with the site trucking coordinator. In addition, all vehicles will be required to maintain slow speeds (e.g., less than 5 mph) for safety and for dust control purposes.

Prior to exiting the Site, the vehicle will be swept to remove any extra soil from areas not covered or protected. This cleanup/decontamination area will be set up as close to the loading area as possible so as to minimize spreading the impacted soil. Prior to the off-site transport, the site manager will be responsible for inspecting each truck to ensure that the payloads are adequately covered, the trucks are cleaned of excess soil and properly placarded, and that the truck's manifest has been completed and signed by SMUD (or its agent) and the transporter. As the trucks leave the site, the flag person will assist the truck drivers so that they can safely merge with traffic on 59th Street.

C.4 Record Keeping

The removal action contractor will be responsible for maintaining a field logbook, which will serve to document observations, personnel on site, equipment arrival and departure times, and other important project information. Logbook entries will be complete and accurate enough to permit reconstruction of field activities. Logbooks will be bound, with consecutively numbered pages and each page will indicate the date and time of the entry. All entries will be legible, written in black or blue ink, and signed by the author. Language will be factual and objective. If an error is made, corrections will be made by crossing a line through the error and entering the correct information. Corrections will be dated and initialed.

Because some portion of the excavated soil likely will be profiled as hazardous waste under California or USEPA regulations, the Uniform Hazardous Waste Manifest (hazardous waste manifest) form will be used to track the movement of soil from the point of generation to the point of ultimate disposition. The hazardous waste manifests will include the following information:

- Name and address of the generator, transporter, and the destination facility
- United States Department of Transportation description of the waste being transported and any associated hazards
- Waste quantity
- Name and phone number of a contact in case of an emergency
- USEPA Hazardous Waste Generator Number
- Other information required either by USEPA and/or DTSC

Any soil that is profiled as non-hazardous and sent for offsite disposal will be documented using a Non-Hazardous Waste Manifest or Bill-of-Lading form. At a minimum, this form will include the following information:

- Generator name and address
- Transportation company
- Accepting facility name and address
- Waste shipping name and description
- Quantity shipped

Prior to transporting the excavated soil off site, an authorized representative of SMUD will sign each hazardous and/or non-hazardous waste manifest. The removal action site manager will maintain one copy of all hazardous and/or non-hazardous waste manifests on site.

C.5 Health and Safety

The Contractor will implement a Site-Specific Health and Safety Plan (HASP), as applicable to transportation personnel. At a minimum, the HASP will include the following:

- All workers will be properly trained in hazardous waste operations in accordance with Code of Federal Regulations (CFR) Title 29 Part 1910.120 and California Code of Regulations (CCR) Title 8 Section 5192.
- The type of health and safety training that will be provided to site personnel and vehicle operators;
- A description of what the transportation personnel will and will not be permitted to do, based on training, during loading. For example, truck drivers will be in an enclosed truck cab equipped with air filter to minimize his exposure to airborne particles or will leave the cab after staging the truck at the loading area prior to commencing the loading. The driver will observe the loading while standing outside the exclusion zone, upstream of any prevailing wind direction. Truck drivers are permitted to cover their trucks after completion of loading prior to leaving the Site.
- A discussion of how the health and safety plan will be communicated to drivers (e.g., tailgate meetings) and how the plan will be enforced.
- A description of notification procedures and contingency plans for accidents or breakdowns in route.

Site personnel will be qualified and trained in accordance with the requirements of the contractor's site-specific HASP. All personnel will receive a site-specific orientation on the physical and chemical hazards anticipated to be present in the wastes they may be potentially exposed to or work within the course of assigned job duties.

C.6 Contingency Plan

A contingency plan for accidental offsite releases provides information to allow emergency service organizations to determine appropriate response actions and if evacuation is necessary. The transportation contractor will provide their drivers with their Spill Contingency Plan that includes notification procedures, emergency phone numbers, and spill containment and cleanup procedures. In addition, a copy of this plan will be provided to drivers carrying hazardous waste removed from the Site and be trained by the transportation contractor to implement provisions of the contingency plan for which they are equipped and capable. It is the responsibility of the transportation contractor to notify the appropriate emergency service organizations, law enforcement agencies, and transportation authorities that have jurisdiction along the proposed route prior to the transportation of hazardous wastes through their areas, as required.

C.6.1 Description of Contaminants

The contaminated soil is impacted with arsenic and lead concentrations that may exceed hazardous waste criteria. Elevated levels of arsenic (up to 330 mg/kg) and lead (up to 130 mg/kg) were detected in Site soil. Total petroleum hydrocarbons as hydraulic oil/motor oil ($TPH_{ho/mo}$) up to 6,000 mg/kg were detected in soil.

Volatile organic compounds (VOCs) were detected in Site soil gas. The following VOCs were identified as contaminants of concern (COCs) in soil gas because they were detected at concentrations exceeding human health criteria based on potential exposure via vapor intrusion into indoor air and assuming a vapor attenuation factor (AF) of 0.001 (AECOM, 2021):

- Chloroform (detected in soil gas at concentrations up to 1,500 micrograms per cubic meter [$\mu g/m^3$])
- 1,2-Dibromoethane (detected in soil gas at concentrations up to 24 $\mu g/m^3$)
- *cis*-1,2-Dichloroethene (DCE) (detected in soil gas at concentrations up to 53,000 $\mu g/m^3$)
- Tetrachloroethene (PCE) (detected in soil gas at concentrations up to 1,200,000 $\mu g/m^3$)
- Trichloroethene (TCE) (detected in soil gas at concentrations up to 18,000 $\mu g/m^3$)

When a more conservative 0.03 vapor AF was used, the following VOCs were identified as additional COCs in soil gas:

- Benzene (detected in soil gas at concentrations up to 2,500 $\mu g/m^3$)
- Bromodichloromethane (detected in soil gas at concentrations up to 60 $\mu g/m^3$)
- 1,2-Dichloropropane (detected in soil gas at concentrations up to 820 $\mu g/m^3$)
- Ethylbenzene (detected in soil gas at concentrations up to 220 $\mu g/m^3$)
- Naphthalene (detected in soil gas at concentrations up to 70 $\mu g/m^3$)
- Toluene (detected in soil gas at concentrations up to 11,000 $\mu g/m^3$)

Additionally, total petroleum hydrocarbons as gasoline (TPH_g) were detected in soil gas at concentrations up to 1,900,000 $\mu g/m^3$.

C.6.2 Hazard Analysis

The primary risk of an accidental release of contaminated soil during transportation is human exposure, which includes chemical and physical hazards. Human exposure to contaminants in soil can occur through ingestion, inhalation, or dermal contact. Therefore, preventing unauthorized personnel access to the spill area is the first and most important step. The physical hazard risk depends on the amount of the spilled soil or debris. A large spill on a public road would require lane closure and could pose a significant risk to motorists. The driver will make mandatory notifications described in their Spill Contingency Plan so that highway patrol, police, and local agency personnel can help in performing lane closure and securing the perimeter of the spilled area. In the event of a small spill, the driver will don appropriate personal protective equipment and use hand tools such as brooms, pan and shovel to return the waste to the bin or truck.

A secondary risk is impact on the environment. Such risk is considered very low, since a spill will most likely occur on a public road, where the likelihood of impacting the subsurface soil, surface water, or groundwater is minimal. The risk from airborne contaminants is greatly diminished by having the waste already moist when it is loaded and covered during transportation. Should a spill happen during transportation, potential airborne contaminants will be further minimized by controlling the spilled area.

C.6.3 Method of Containment of Accidental Release

Each driver will be trained in Emergency Response, in accordance with CFR Title 49, Part 172-704 (a),(1),(2),(3), Subpart H. Each driver will be equipped with:

- a copy of the transportation contractor’s Spill Contingency Plan, which includes a list of emergency contacts;
- a wireless communication device; and
- small cleanup accessories, traffic cones, signs, caution tape and personal protective equipment.

In case of hazardous waste release during transportation, the driver will contact the emergency contacts listed in the transportation contractor’s Spill Contingency Plan. The driver or transportation contractor will contact a hazardous emergency response company to provide cleanup services (e.g., CHEMTREC), as necessary. The driver or transportation company will also contact the site manager.

C.7 References

AECOM Technical Services, Inc. (AECOM), 2021. *Site Characterization Report Addendum No. 2, SMUD 59th Street Corporation Yard, 1708 59th Street, Sacramento, California 95819.* November.

California Code of Regulations (CCR). Title 8, Section 5192, *Hazardous Waste Operations and Emergency Response*.

Code of Federal Regulations (CFR). Title 29, Part 1910, *Occupational Safety and Health Standards*.

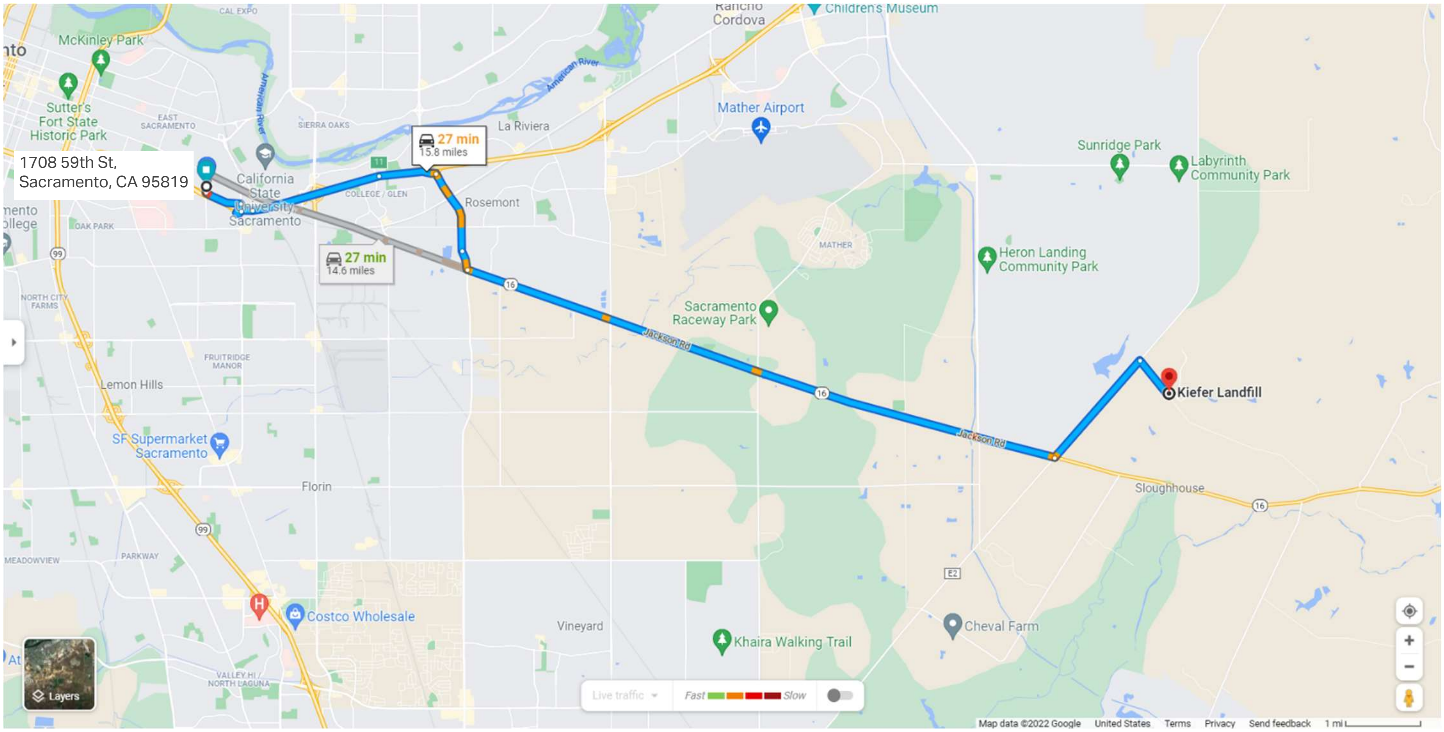
CFR. Title 49. *Transportation*.

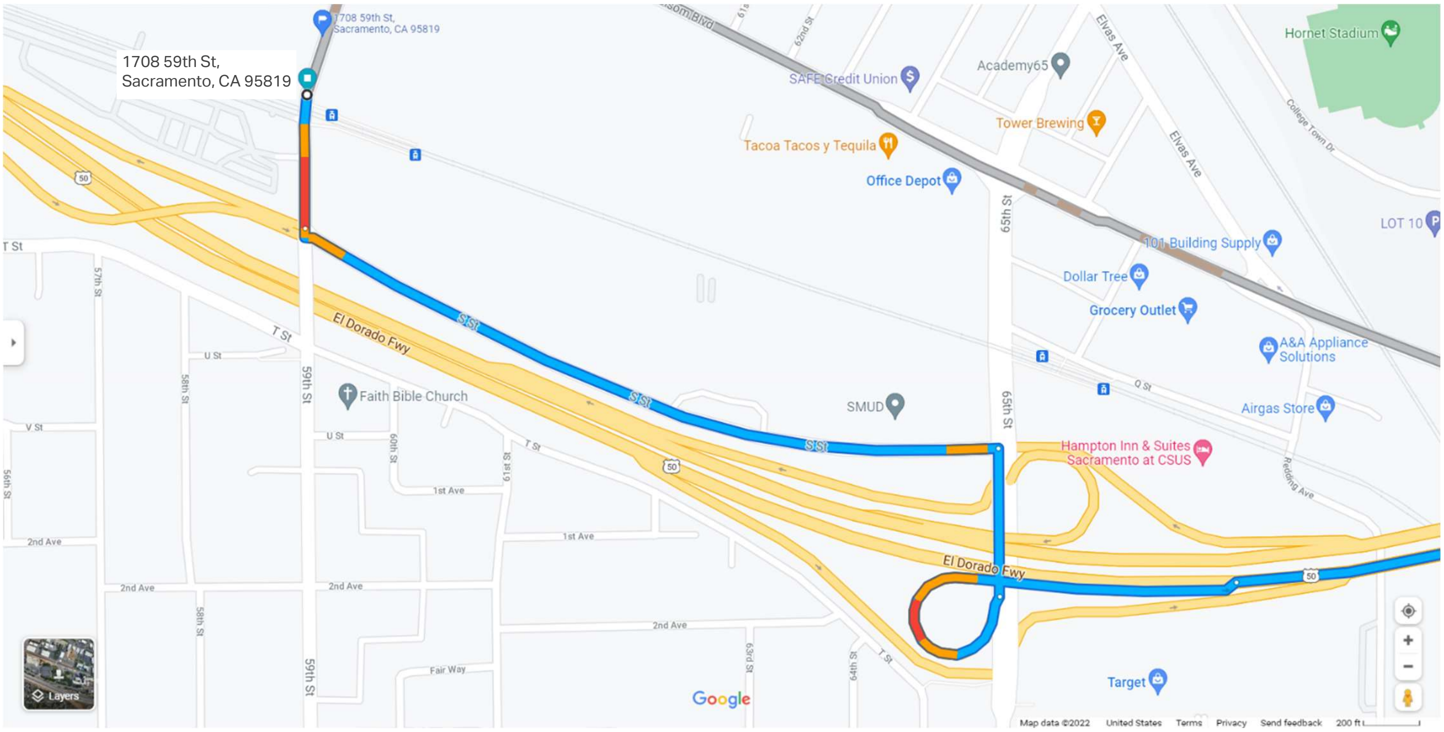
Attachments

Attachment C-1: Kiefer Landfill, Sloughhouse, California Truck Route

Kiefer Landfill

12701 Kiefer Boulevard and Grant Line Road, Sloughhouse, California 95683





Google Maps 1708 59th Street, Sacramento CA 95819 to Kiefer Landfill Drive 15.8 miles, 27 min

1708 59th St
Sacramento, CA 95819

Get on US-50 E from S St

3 min (1.0 mi)

↑ 1. Head south on 59th St

459 ft

↰ 2. Turn left onto S St

0.5 mi

↱ 3. Use the right lane to turn right onto 65th St

0.1 mi

4. Use the right lane to merge onto US-50 E via the ramp to Placerville

0.3 mi

Continue on US-50 E to Watt Ave. Take exit 11 from US-50 E

3 min (2.6 mi)

5. Merge onto US-50 E

1.8 mi

6. Take exit 11 for Watt Ave

0.8 mi

Follow Watt Ave to CA-16 E/Jackson Rd in Rosemont

3 min (1.4 mi)

↱ 7. Use the right 2 lanes to turn right onto Watt Ave

1.2 mi

↑ 8. Continue onto S Watt Ave

0.3 mi

↰ 9. Turn left onto CA-16 E/Jackson Rd

11 min (8.4 mi)

Continue on Grant Line Rd. Drive to Kiefer Blvd

4 min (2.4 mi)

↰ 10. Turn left onto Grant Line Rd

1.8 mi

↱ 11. Turn right onto Kiefer Blvd
ⓘ Destination will be on the left

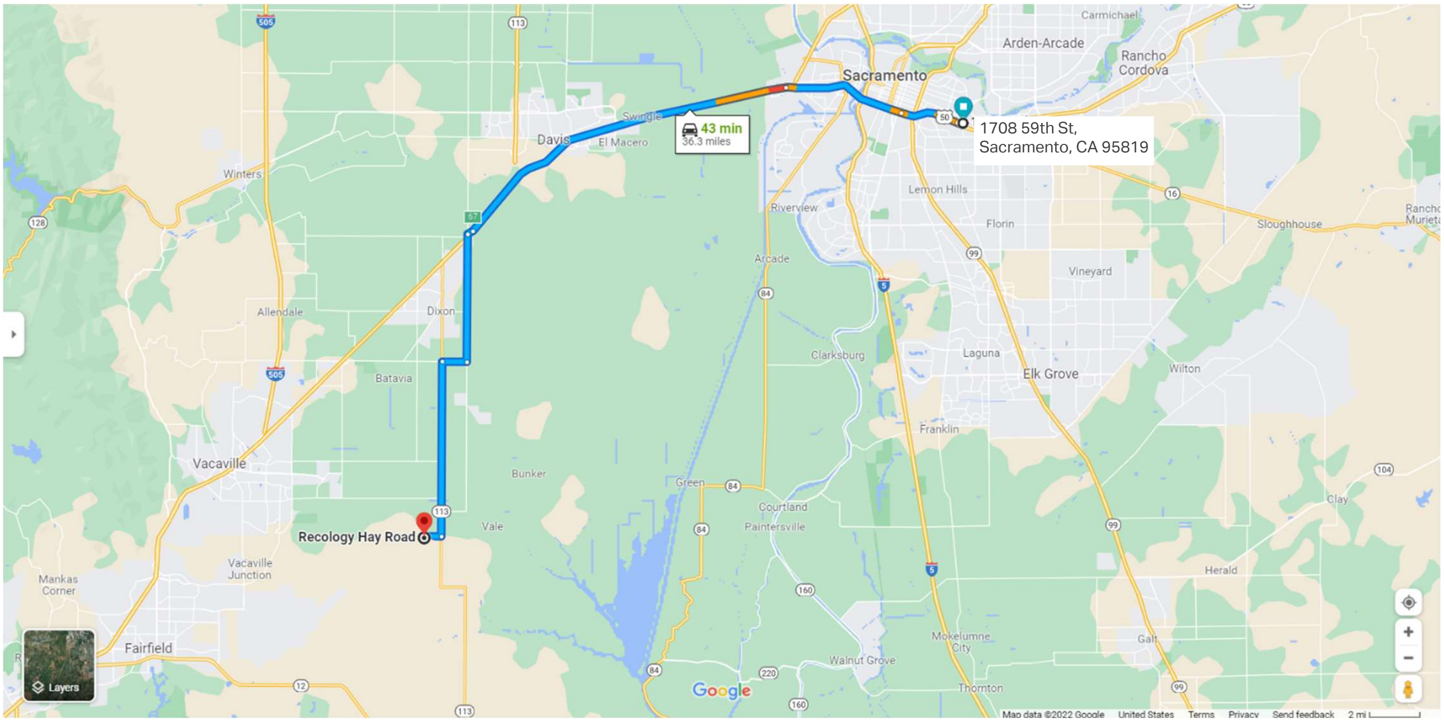
0.6 mi

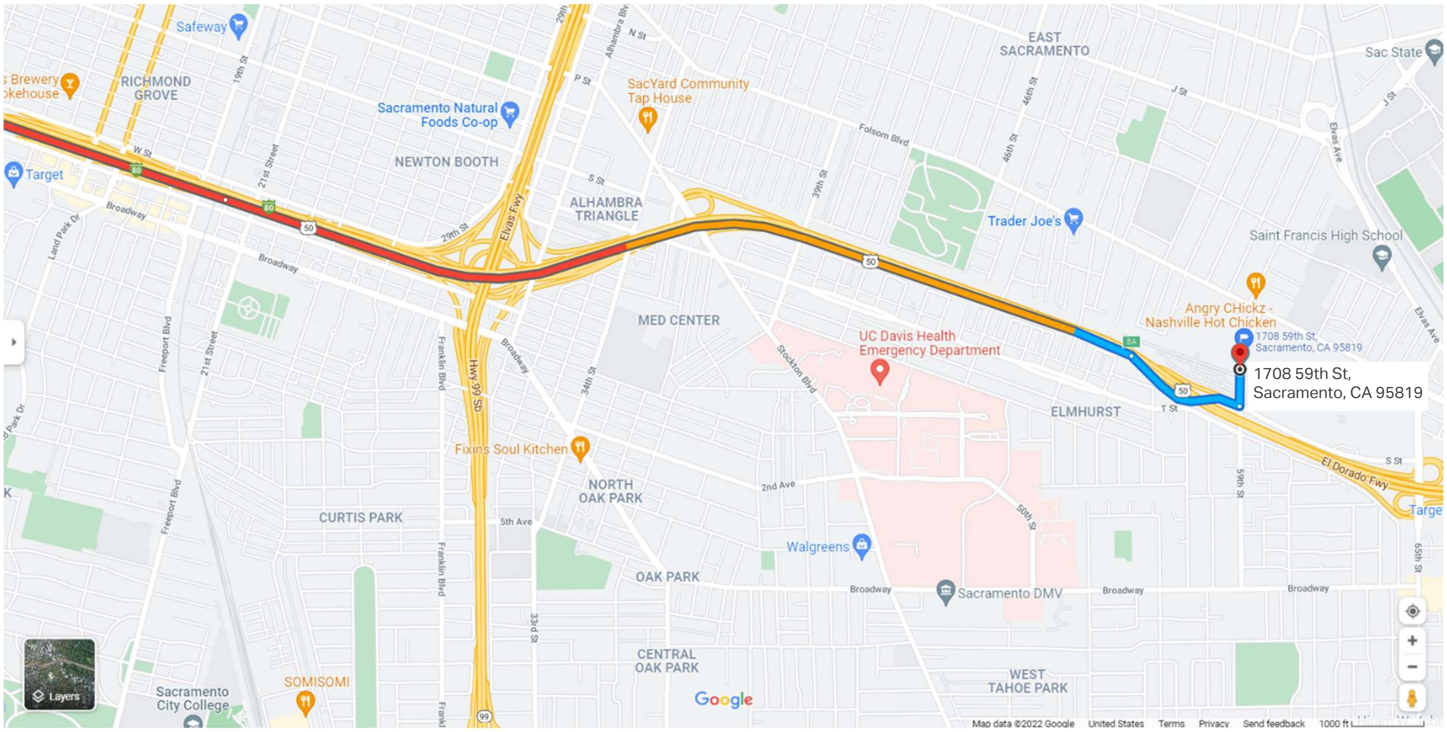
Kiefer Landfill
12701 Kiefer Blvd, Sloughhouse, CA 95683

Attachment C-2: Recology Hay Road Landfill, Vacaville, California Truck Route

Recology Hay Road Landfill

Recology Hay Road, 6426 Hay Rd, Vacaville, CA 95687





1708 59th Street, Sacramento CA 95819 to Recology Hay Road

Drive 36.3 miles, 44 min

1708 59th St
Sacramento, CA 95819

Get on US-50 W

52 s (0.3 mi)

1. Head south on 59th St

479 ft

2. Turn right to merge onto US-50 W toward I-80 BUS/CA-99

0.2 mi

Take I-80BUS W and I-80 W to Pedrick Rd in Solano County. Take exit 67 from I-80 W

22 min (21.9 mi)

3. Merge onto US-50 W

2.4 mi

4. Continue onto I-80BUS W/US-50 W

5.0 mi

5. Continue onto I-80 W

14.3 mi

6. Take exit 67 for Pedrick Road

0.3 mi

7. Keep left at the fork, follow signs for Sievers Rd/Sacramento/Pedrick Rd

66 ft

Continue on Pedrick Rd to your destination

19 min (14.0 mi)

8. Turn left onto Pedrick Rd

5.1 mi

9. Turn right onto Midway Rd

1.0 mi

10. Turn left onto CA-113 S

7.0 mi

11. Turn right onto Hay Rd

0.8 mi

12. Turn left

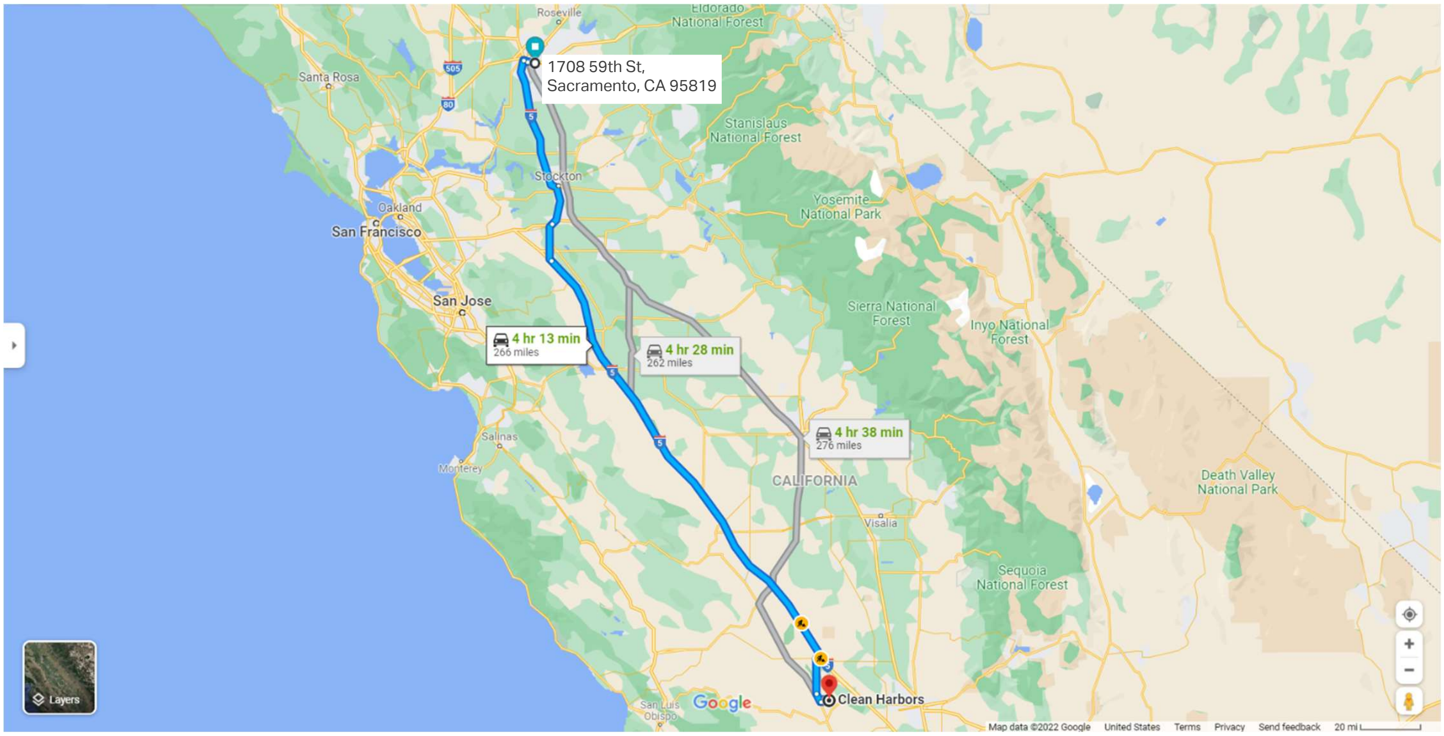
0.1 mi

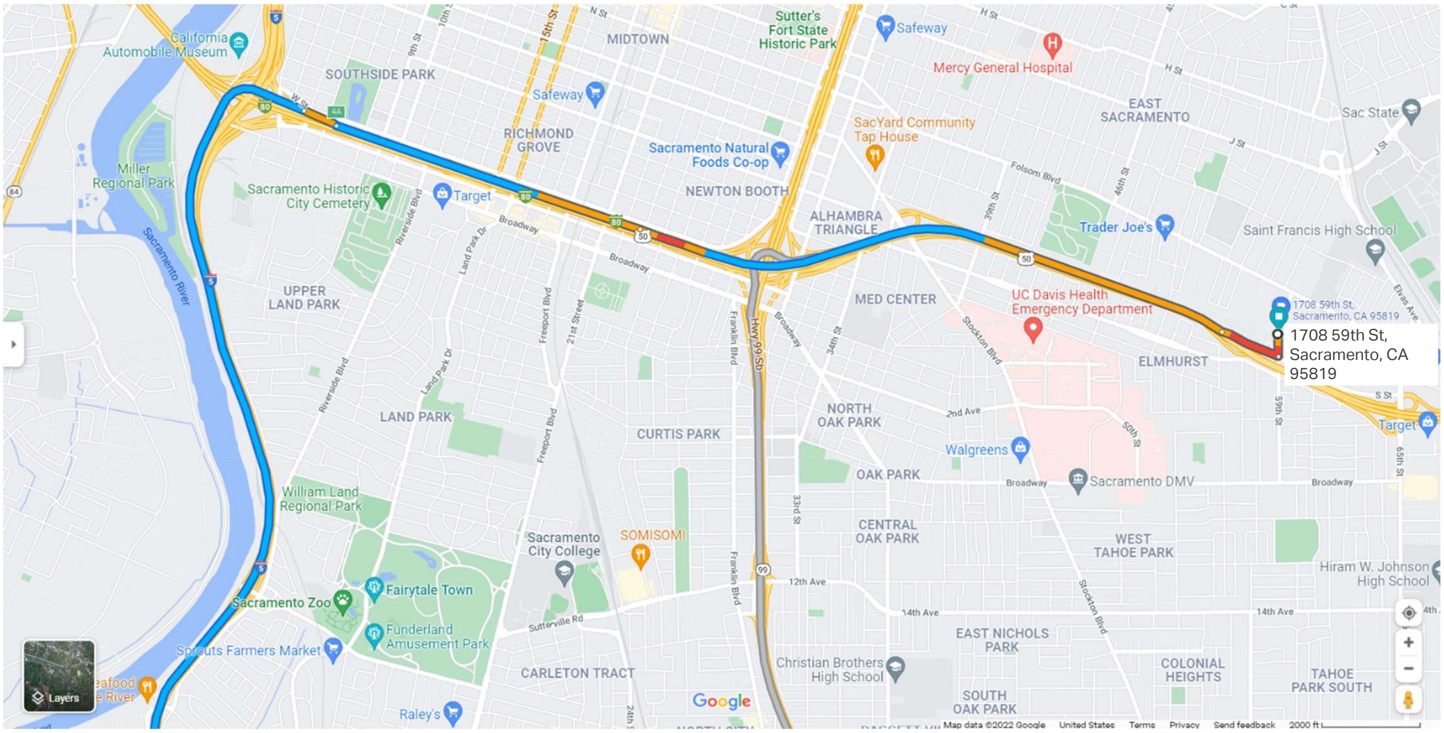
Recology Hay Road
6426 Hay Rd, Vacaville, CA 95687

Attachment C-3: Buttonwillow Landfill Facility, Buttonwillow, California Truck Route

Buttonwillow Landfill Facility

2500 West Lokern Road, Buttonwillow, California 93206





Google Maps 1708 59th Street, Sacramento CA 95819 to Clean Harbors

Drive 266 miles, 4 hr 13 min

1708 59th St
Sacramento, CA 95819

Get on US-50 W

51 s (0.3 mi)

1. Head south on 59th St

459 ft

2. Turn right to merge onto US-50 W toward I-80 BUS/CA-99

0.2 mi

Follow I-5 S to CA-46 W in Lost Hills. Take exit 278 from I-5 S

3 hr 41 min (244 mi)

3. Merge onto US-50 W

2.4 mi

4. Continue onto I-80BUS W/US-50 W

1.2 mi

5. Take exit 4A for Interstate 5 N/Interstate 5 S/State Route 99 North toward Redding/Los Angeles

0.1 mi

6. Keep left at the fork, follow signs for I-5 S/Los Angeles and merge onto I-5 S

59.8 mi

7. Continue straight to stay on I-5 S

12.9 mi

8. I-5 S turns slightly right and becomes I-5 S

167 mi

9. Take exit 278 for CA-46 toward Lost Hills/Wasco

0.3 mi

Take Lost Hills Rd and CA-33 S to Delfern Rd

31 min (21.4 mi)

10. Turn right onto CA-46 W

1.9 mi

11. Turn left onto Woodward St

0.3 mi

12. Continue onto Lost Hills Rd

12.1 mi

13. Turn left onto CA-33 S

3.1 mi

14. Turn left onto Lokern Rd

1.3 mi

15. Turn left

1.0 mi

16. Turn right onto Delfern Rd

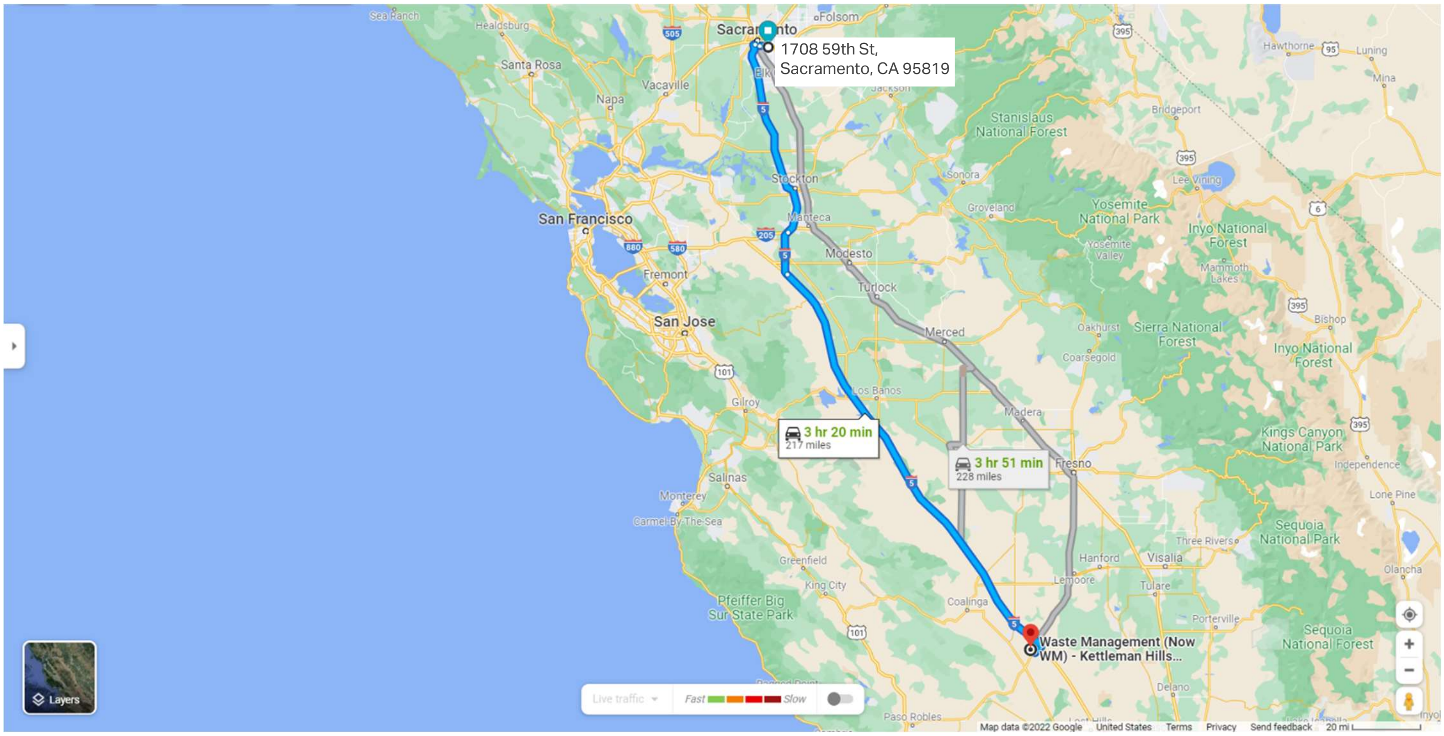
1.8 mi

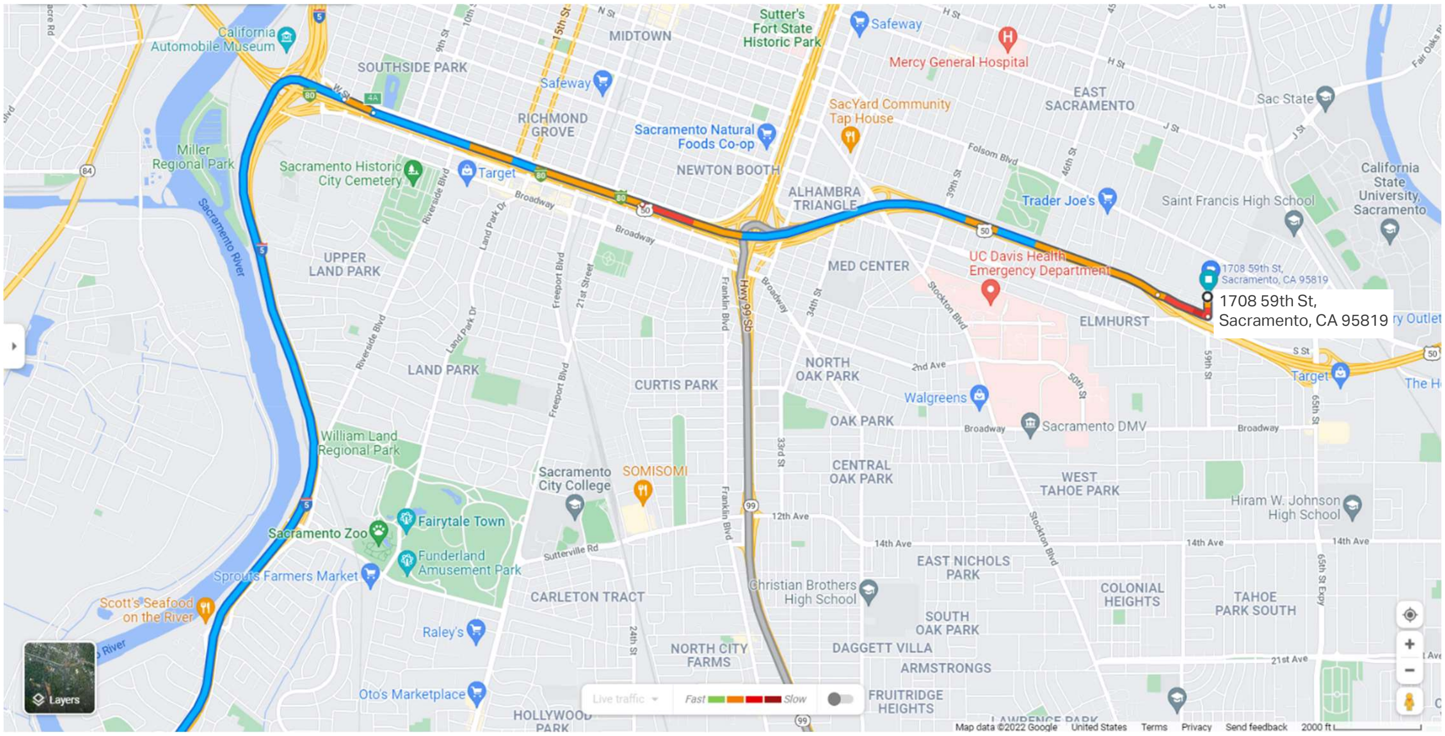
Clean Harbors
2500 Lokern Rd, Buttonwillow, CA 93206

Attachment C-4: Kettleman Hills Facility, Kettleman City, California Truck Route

Kettleman Hills Facility

35251 Old Skyline Road, Kettleman City, California 93239





Google Maps 1708 59th Street, Sacramento, CA 95819 to Waste Management (Now WM) - Kettleman Hills Hazardous Waste Facility
Drive 217 miles, 3 hr 20 min

1708 59th St
Sacramento, CA 95819

Get on US-50 W

51 s (0.3 mi)

1. Head south on 59th St

459 ft

2. Turn right to merge onto US-50 W toward I-80 BUS/CA-99

0.2 mi

Follow I-5 S to CA-41 S in Kings County. Take exit 309 from I-5 S

3 hr 14 min (213 mi)

3. Merge onto US-50 W

2.4 mi

4. Continue onto I-80BUS W/US-50 W

1.2 mi

5. Take exit 4A for Interstate 5 N/Interstate 5 S/State Route 99 North toward Redding/Los Angeles

0.1 mi

6. Keep left at the fork, follow signs for I-5 S/Los Angeles and merge onto I-5 S

59.8 mi

7. Continue straight to stay on I-5 S

12.9 mi

8. I-5 S turns slightly right and becomes I-5 S

137 mi

9. Take exit 309 for CA-41 toward Kettleman City/Paso Robles

0.3 mi

Continue on CA-41 S. Drive to Skyline Rd

5 min (3.4 mi)

10. Turn right onto CA-41 S

2.6 mi

11. Turn right onto Old State Hwy
⚠ Restricted usage road

0.7 mi

12. Continue onto Skyline Rd
⚠ Restricted usage road

0.2 mi

Waste Management (Now WM) - Kettleman Hills Hazardous Waste Facility
35251 Old, Skyline Rd, Kettleman City, CA 93239

Appendix D

Dust Control and Air Monitoring Plan

Appendix D Dust Control and Air Monitoring Plan

SMUD 59th Street Corporation Yard

Prepared for:

Sacramento Municipal Utility District
Environmental Services
6201 S Street, Mail Stop H201
Sacramento, California 95817

Prepared by:

AECOM Technical Services, Inc.
2020 L Street, Suite 300
Sacramento, California 95811

July 2022

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List of Acronyms and Abbreviations

$\mu g/m^3$	micrograms per cubic meter
AF	attenuation factor
AL_{COC}	action level for a contaminant of concern
AL_{PID}	action level for organic vapor measured by PID
BMP	best management practice
CAAQS	California Ambient Air Quality Standard
CF	conversion factor
COC	contaminant of concern
DCE	dichloroethene
e.g.	*exempli gratia*, for example
HASP	Health and Safety Plan
HEPA	high efficiency particulate air
i.e.	*id est*, that is
mg/kg	milligrams per kilogram
mg/m^3	milligrams per cubic meter
mph	miles per hour
NA	not applicable
OSHA	Occupational Safety and Health Administration
PCE	tetrachloroethene
PEL	Permissible Exposure Limit
PID	photoionization detector
$PM_{2.5}$	fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller
PM_{10}	inhalable particles, with diameters that are generally 10 micrometers and smaller
ppm	parts per million
REL	Recommended Exposure Limit
Site	59th Street Corporation Yard
SMUD	Sacramento Municipal Utility District
TCE	trichloroethene
TPH_g	total petroleum hydrocarbons as gasoline
$TPH_{ho/mo}$	total petroleum hydrocarbons as hydraulic oil/motor oil (equivalent carbon number range of C17 – C32 [aromatic high])
TWA	time-weighted average
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound

D.0 Introduction

This Dust Control and Air Monitoring Plan identifies the measures that will be taken to reduce the potential for particulate emissions and volatile organic compounds (VOCs) associated with soil removal activities at the Sacramento Municipal Utility District (SMUD) 59th Street Corporation Yard (Site). The plan includes air monitoring, dust suppression procedures, and dust control criteria.

Best management practices (BMPs) will be implemented throughout the project. BMPs include wetting active remediation areas, minimizing or ceasing activities during periods of high wind, sweeping or wetting paved areas, wetting unpaved areas, application of dust suppressant materials, application of vapor suppressant foams, and covering stockpiles. This plan provides specific information about the generation and control of dust emissions during the excavation of soil material, stockpiling of these materials and other activities associated with the remediation.

D.1 Air Monitoring and Dust Prevention Team

The Dust Control and Air Monitoring Plan will be implemented and overseen by project personnel who have the authority to implement additional dust control provisions and stop work provisions based on air monitoring results. The project personnel will also revise the plan as needed to reduce the potential for dust emissions during removal activities. All project personnel responsible for calibrating, handling, or interpreting the air monitoring equipment or meter output data will be trained or have sufficient prior training or experience.

D.2 Dust Control and Air Monitoring Plan Objectives and Approach

The objectives of the plan are as follows.

- Provide a plan for preemptively limiting and controlling dust during removal activities.
- Provide a monitoring system to alert project personnel when concentrations of respirable dust in ambient air are approaching action levels due to removal activities.
- Determine whether construction controls are effective in reducing dust emissions to below action levels and make appropriate and necessary adjustments.
- Develop a record that includes results of the real-time air monitoring and BMPs implemented.

D.3 Nature of the Dust

Based on previous investigations, elevated levels of arsenic and lead, up to 330 milligrams per kilogram (mg/kg) and 130 mg/kg, respectively, were detected in soil within portions of the Site. Concentrations of total petroleum hydrocarbons as hydraulic oil/motor oil (equivalent carbon number range of C17 – C32 [aromatic high]) ($TPH_{ho/mo}$) up to 6,000 mg/kg were also detected in a localized area within an area of arsenic-impacted soil. During excavation of the Site soils, the dust will principally contain inorganic constituents, such as arsenic- and lead-containing respirable particulate matter (PM_{10}).

VOCs were detected in Site soil gas. The following VOCs were identified as contaminants of concern (COCs) in soil gas because they were detected at concentrations exceeding human health criteria based on potential exposure via vapor intrusion into indoor air and assuming a vapor attenuation factor (AF) of 0.001.

- Chloroform (detected in soil gas at concentrations up to 1,500 micrograms per cubic meter [$\mu g/m^3$])
- 1,2-Dibromoethane (detected in soil gas at concentrations up to 24 $\mu g/m^3$)
- *cis*-1,2-Dichloroethene (DCE) (detected in soil gas at concentrations up to 53,000 $\mu g/m^3$)

- Tetrachloroethene (PCE) (detected in soil gas at concentrations up to 1,200,000 µg/m^3)
- Trichloroethene (TCE) (detected in soil gas at concentrations up to 18,000 µg/m^3)

When a more conservative 0.03 vapor AF was used, the following VOCs were identified as additional COCs in soil gas:

- Benzene (detected in soil gas at concentrations up to 2,500 µg/m^3)
- Bromodichloromethane (detected in soil gas at concentrations up to 60 µg/m^3)
- 1,2-Dichloropropane (detected in soil gas at concentrations up to 820 µg/m^3)
- Ethylbenzene (detected in soil gas at concentrations up to 220 µg/m^3)
- Naphthalene (detected in soil gas at concentrations up to 70 µg/m^3)
- Toluene (detected in soil gas at concentrations up to 11,000 µg/m^3)

Additionally, total petroleum hydrocarbons as gasoline (TPH_g) were detected in soil gas at concentrations up to 1,900,000 µg/m^3.

D.4 Air Monitoring

Air and meteorological monitoring strategies and methodologies will be implemented during the removal action to achieve several goals:

- Identify and measure the air contaminants generated during the soil removal and decontamination activities to assign the appropriate personal protective equipment and safety measures specified for those activities.
- Provide feedback to Site personnel regarding potential hazards from exposure to hazardous air contaminants generated through excavation activities.
- Identify and measure air contaminants at points outside of the soil removal and decontamination exclusion zones. Air monitoring will be conducted during work activities to measure potential exposure of sensitive receptors (i.e., the community) to Site COCs (i.e., arsenic, lead, and VOCs), as a result of removal activities and to monitor the dust control measures implemented.

The air monitoring program consists of the following:

- Four perimeter air monitoring stations for dust will be deployed around the perimeter of the work zone (one monitoring station each on four sides of the rectangular-shaped property boundary) as shown on Figure 5-1 of the Interim Remedial Action Workplan. Mobilization and air monitoring equipment preparation for the Site will be initiated prior to the start of removal activities. The perimeter air monitoring stations for dust will monitor ambient air continuously while removal activities are being conducted.
- A minimum of one air monitoring station will be located within the work zone to evaluate potential worker exposure. The meter will be placed in the immediate vicinity of the active excavation area.
- Three days of baseline air monitoring conducted at the Site before any removal activities occur.
- A dedicated weather station will be established at the Site and operated to continuously monitor meteorological conditions during the removal activities.

Air quality will be continuously monitored in the work zone for VOCs using either a handheld organic vapor analyzer or a photoionization detector (PID) utilizing a 10.6 electron volt lamp as calibrated with isobutylene. Air quality will be continuously monitored for respirable particulate matter ($PM_{2.5}$) with a minimum of four particulate meters (e.g., DataRAM dust meters) at the perimeter of the work zone and one within the work zone to evaluate potential community and worker exposure to airborne particulate concentrations. Air quality will be monitored with measurements of total particulate concentration, date, time, and wind direction recorded on air monitoring logs or in the field log book. The frequency of the monitoring will depend on the activities being conducted and the predominant wind direction, but no less than every five minutes. The results of the air monitoring will be recorded in a log book and/or electronically recorded and kept as part of the Site documentation.

Instrument calibration will be performed in accordance with the manufacturer's instructions at the beginning of each workday (as applicable). All instrument calibration and maintenance activities, including calibration results, will be documented in the field logs.

D.5 Dust Suppression and Criteria

The remediation contractor will conduct operations and maintain the Site to minimize the creation and dispersion of respirable dust and VOCs. BMPs will be implemented throughout the project. BMPs include wetting active remediation areas, minimizing or ceasing activities during periods of high wind, sweeping or wetting paved areas, wetting unpaved areas, application of dust suppressant materials, and covering stockpiles.

D.5.1 Watering

The primary mechanism for dust control will be the use of water trucks with a spray bar and hose(s). Water will be applied to the Site as necessary to prevent dust during excavation, loading/unloading, stockpiling, and backfilling activities. The watering operations will be applied at a sufficient rate and frequency to control fugitive dust without creating ponding or run-off that travels beyond the Site boundary. As a contingency measure, sediment controls such as wattles or manhole silt screens will be installed as necessary to manage potential run-off.

Non-toxic soil stabilizers may also be applied on unpaved access roads, parking areas, and staging areas at the construction site.

D.5.2 Transfer Points and Trucking

The transfer points refer to any time material is loaded or unloaded during removal activities. For the purposes of this project, the primary transfer points of concern will be the transfer of soil material from the excavator to a waiting truck. The secondary transfer points of concern will be the unloading of the clean soil for use in backfilling the excavated areas. At all transfer points, the following guidelines will be maintained.

- During loading of impacted soil, the material will be sprayed with water during the transfer, and the transfer will only be into a truck trailer or roll-off container located outside of the excavation. The material drop into the trailer or roll-off container will not exceed a vertical distance of 4 feet.
- All trucks entering and leaving the Site will adhere to the posted speed limit, which will be no more than 15 miles per hour (mph). Speed limit signs will be posted at each entrance. If vehicular-caused dust is significant, the speed limit will be reduced and the new speed limit will be posted.
- All loaded truck trailers will be tarped prior to leaving the Site. If the soil is transported in roll-off containers, the containers will be tarped, or if equipped with lids, the lids will be closed.
- At least one foot of freeboard will be maintained above the top of soil in all truck trailers and roll-off containers.
- All trucks leaving unpaved areas to paved areas of the public right-of-way (i.e., sidewalk or street), whether full or empty, will be visually inspected for loose material. Stabilized construction exits (e.g., 3- to 6-inch cobblestone or rip rap placed on top of a geotextile and/or rumble strip) will be used to assist with cleaning of truck tires as the vehicles leave unpaved areas. Any loose material will be removed and placed into the truck trailer or roll-off container.
- All loading of impacted soil will be completed on pavement where possible.

D.5.3 Street Sweeping

In order to keep public roadways clean and free of dust, soil, and rock accumulation, routine street sweeping will be performed during removal activities. The street sweeper will be equipped with a water spray and vacuum system to prevent fugitive dust. Street sweeping will be completed at the end of every day or more frequently as needed.

Other paved areas can be maintained by using a skid steer loader (e.g., Bobcat®) equipped with a power broom, a high efficiency particulate air (HEPA) filter-equipped vacuum device, or manual tools (e.g., push broom, shovels, etc.).

D.5.4 Soil Staging and Stockpiling

Excavated soil may be placed in roll-off containers for transportation to an off-site landfill. Roll-off containers will be covered with tarps or roll-off lids when placement of excavated soil into each container has been completed or at the end of each day if placement of soil into a container continues beyond 1 day.

Soil stockpiles will be covered with plastic sheeting secured with sandbags when inactive and at the end of each workday.

D.5.5 Action Levels

Worker Dust Action Level

The dust action level will be set at 5 milligrams per cubic meter (mg/m^3) for the protection of workers and will be identified in the Health and Safety Plan (HASP). If action levels are exceeded during field activities, additional dust control measures will be implemented. These measures may include, but are not limited to, spraying the excavations or loading areas lightly with water to minimize dust emissions. A stop work will be initiated if additional dust control measures cannot be implemented in a timely manner or are ineffective in reducing dust levels below the action level.

The worker action level is based on Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) for respiratory dust, lead, and arsenic. The OSHA PEL for workplace exposures to respirable dust is not to exceed 5 mg/m^3 (5,000 µg/m^3) of air over an 8-hour time-weighted average (TWA) limit. The required OSHA PEL and the National Institute for Occupational Safety and Health Recommended Exposure Limit (REL) for lead is a TWA of 50 µg/m^3 of air over 8 hours. Based on the maximum lead concentration detected at the Site of 130 mg/kg and an OSHA PEL dust concentration of 5 mg/m^3 during the performance of the work, the predicted maximum airborne concentration of lead in Site-generated dust is 0.65 µg/m^3 which does not exceed the 50 µg/m^3 OSHA PEL threshold for lead. The OSHA PEL for arsenic is 10 µg/m^3 for 8-hour shifts and 40-hour work weeks. Based on the maximum arsenic concentration detected at the Site of 330 mg/kg and a maximum dust concentration of 5,000 µg/m^3 during the performance of the work, the predicted maximum airborne concentration of arsenic in Site-generated dust is 1.65 µg/m^3 which does not exceed the OSHA PEL for arsenic. This calculation is very conservative because the maximum detected concentration was used. The following equation was used to calculate the predicted airborne concentration of arsenic and lead in Site dust:

$$C_{dust}\left(\frac{\mu gCOC}{m^3air}\right) = C_{soil}\left(\frac{mgCOC}{kgsoil}\right) \times 10^{-6}\left(\frac{kg}{mg}\right) \times 5{,}000\left(\frac{\mu gsoil[= dust]}{m^3air}\right)$$

Where:

- C_{dust} = Concentration of a COC in dust
- C_{soil}= Concentration of a COC in soil

- $\mu gCOC$ = micrograms of a COC
- $mgCOC$ = milligrams of a COC
- m^3air = cubic meter of air
- $kgsoil$ = kilogram of soil
- $\mu gsoil$ = microgram of soil

Therefore, a total dust action level of 5 mg/m^3 (5,000 µg/m^3) is protective of workers for respirable dust, and lead and arsenic in Site dust.

VOC Action Level

The VOC action level for worker protection will be set at 1.9 parts per million (ppm) within the Site work zone. Soil vapors released to outdoor air is subject to significant dilution and mixing, such that any downwind concentrations will be insignificant for residents. The action levels posed for worker protection at the construction site will prevent any potential gross releases of soil vapors. Action levels at the Site that are protective of workers are considered protective of downwind off-site residents when considering dilution and mixing.

The VOC action level was calculated for RAE System PIDs using the following equation:

$$AL_{PID} = \frac{AL_{COC}}{CF}$$

Where:

- AL_{PID} = action level for organic vapor measured by PID
- AL_{COC} = action level for a COC
- CF = correction factor to convert a PID concentration (expressed as isobutylene) to a PID concentration expressed as the COC

To allow a direct comparison of the chemical-specific action levels of each VOC to a VOC action level for the PID reading expressed as the calibration gas according to the manufacturer’s instructions, the chemical-specific action levels of each VOC are converted to the VOC action level for the PID. The chemical-specific action levels for each are calculated by assuming that the PID reading is comprised entirely of a single VOC. If real-time monitoring indicates an exceedance of the VOC action level, appropriate response actions will be considered to reduce emissions. The VOC action levels for RAE System PIDs are calculated using general RAE system conversion factors in the table below. The conversion factors may vary depending on the instrument, lamp, and manufacturer.

COC	AL_{COC} (PEL 8-hour)	CF (10.6 eV lamp) RAE System PIDs	AL_{PID} (ppm)
Chloroform	50 ppm (240 mg/m^3)	NA[1]	NA
1,2-Dibromoethane	20 ppm (154 mg/m^3)	1.7	12
cis-1,2-DCE	200 ppm (790 mg/m^3)	0.8	250
PCE	100 ppm (680 mg/m^3)	0.57	175
TCE	50 ppm (540 mg/m^3)	0.54	93
Benzene	1 ppm (3.19 mg/m^3)	0.47	2.1
Bromodichloromethane	NA	NA	NA
1,2-Dichloropropane	75 ppm (359 mg/m^3)	NA[1]	NA
Ethylbenzene	100 ppm (435 mg/m^3)	0.47	213
Naphthalene	10 ppm (50 mg/m^3)	0.42	24
Toluene	200 ppm (mg/m^3)	0.45	444

Notes:

[1] Can be monitored using a PID equipped with an 11.6 eV lamp

AL_{COC} = action level for a contaminant of concern

AL_{PID} = action level for organic vapor measured by PID

CF = conversion factor

mg/m^3 = milligrams per cubic meter

NA = not applicable

PEL = Permissible Exposure Limit

PID = photoionization detector

ppm = parts per million

Community Dust Action Level

The community surrounding the Site includes residential neighborhoods situated to the west and commercial developments situated to the north. The State of California has an established California Ambient Air Quality Standard (CAAQS) for dust of PM_{10} levels to not exceed 50 µg/m^3 averaged over 24 hours when determined by simultaneous air monitoring as the difference between upwind and downwind measurements. The State of California has an established CAAQS for lead. The CAAQS defines the maximum amount of airborne particles that can be present in outdoor air without threatening the public's health. The 30-day average CAAQS for lead is 1.5 µg/m^3.

Based on the maximum lead concentration detected at the Site of 130 mg/kg and CAAQS dust concentration limit of 50 µg/m^3 during the performance of the work, the predicted maximum airborne concentration of lead at the site perimeter project is 0.0065 µg/m^3 which does not exceed the 1.5 µg/m^3 CAAQS threshold for lead. The following equation was used to calculate the predicted airborne concentration of lead in Site dust:

$$C_{dust}\left(\frac{\mu gCOPC}{m^3air}\right) = C_{soil}\left(\frac{mgCOPC}{kgsoil}\right) \times 10^{-6}\left(\frac{kg}{mg}\right) \times 50\left(\frac{\mu gsoil[= dust]}{m^3air}\right)$$

Therefore, a total dust action level of 50 µg/m^3 is protective of the community for respirable dust and lead in Site dust.

The CAAQS, National Ambient Air Quality Standards, and Human Health Risk Assessment Note Number 3, Department of Toxic Substances Control-modified Screening Levels do not have air quality standards or screening levels for inhalation for arsenic. The United States Environmental Protection Agency (USEPA) has a carcinogenic and non-carcinogenic Residential Air Screening Levels of 0.00065 and 0.016 µg/m^3 for arsenic, respectively. However, these screening levels are overly conservative because the levels are calculated for an exposure over 24 hours per day, 350-days per year for 26 years while the project activity will be 9 hours per day, 5 days per week for approximately 8 to 12 weeks. The community action levels were developed using DTSC's Community Air Monitoring Plan (CAMP) Guidance. The exposure duration was revised to 60 days (weekdays for 12 weeks) resulting in a carcinogenic screening level of 0.70 µg/m^3 and non-carcinogenic arsenic screening levels of 0.056 µg/m^3, respectively.

The non-cancer level was calculated using the CAMP Appendix E equation:

$SSAL_{nc} = THQ \times REL \times (AT_{nc} / (ET \times EF \times ED))$. Where,

- $SSAL_{nc}$ = noncancer-based action limit of COC in air (µg/m^3).
- *THQ* = target inhalation noncancer hazard quotient (unitless). The CAMP-recommended THQ value of 1.0 was used.
- *REL* = Arsenic inhalation reference exposure level (per µg/m^3). The 1.5x10^{-02} µg/m^3 arsenic toxicity value from USEPA RSLs May 2022 (same as DTSC's HHRA Note 10 [February 25, 2019]) was used.
- AT_{nc} = averaging time for non-carcinogenic effects (hours). A value of 2016 hours (24 hours/day * 7 days/week * 12 weeks [based on 3-month exposure period]) was used.
- *ET* = Exposure time (hours/day). A project-specific value of 9 hours/day was used.
- *EF* = Exposure frequency (days/week). A project-specific value of 5 days/week was used.
- *ED* = Exposure Duration (weeks). A project-specific value of 12 weeks was used.

The cancer level was calculated using the CAMP Appendix E equation:

$SSAL_c = TR \times (1/IUR) \times (AT_c / (ET \times EF \times ED))$. Where,

- *SSALc* = cancer-based action limit of COC in air (µg/m^3).
- *TR* = target inhalation cancer risk (unitless). The CAMP-recommended TR value of 1.0x10^{-06} was used.
- *IUR* = Arsenic inhalation unit risk (per µg/m^3). The 4.3x10^{-03} µg/m^3 arsenic toxicity value from USEPA RSLs May 2022 (same as DTSC's HHRA Note 10 [February 25, 2019]) was used.
- AT_c = averaging time for carcinogenic effects (hours). A value of 613,200 hours (24 hours/day * 365 days/year * 70 years) was used.
- *ET* = Exposure time (hours/day). A project-specific value of 9 hours/day was used.
- *EF* = Exposure frequency (days/year). A project-specific value of 91 days/year was used. The project is expected to be less than 91 days.
- *ED* = Exposure Duration (years). A project-specific value of 0.25 years was used.

Based on the maximum arsenic concentration detected at the Site of 330 mg/kg and CAAQS dust concentration limit of 50 µg/m^3 during the performance of the work, the predicted maximum airborne concentration of arsenic at the site perimeter project is 0.0165 µg/m^3 which does not exceed the 0.056 µg/m^3 CAAQS non-carcinogenic threshold for arsenic. In addition, work will stop for dust-producing activities when sustained wind speeds exceed 20 mph or visible dust emissions from all earth-moving activities exceed number 1 on the Ringelmann chart for a period, or periods aggregating more than 3 minutes in any hour. The wind speed will be obtained by averaging the measured values over a one-minute period using data from the on-Site meteorological station.

D.6 Reporting

A record of both the dust and VOC control measures implemented as well as the dust and VOC monitoring results will be kept and included in the Removal Action Completion Report.

Appendix E

Sampling and Analysis Plan

Appendix E Sampling and Analysis Plan

SMUD 59th Street Corporation Yard

Prepared for:

Sacramento Municipal Utilities District
Environmental Services
6201 S Street, Mail Stop H201
Sacramento, California 85817

Prepared by:

AECOM Technical Services, Inc.
2020 L Street, Suite 400
Sacramento, California 95811

July 2022

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List of Acronyms and Abbreviations

%R	percent recovery
±	plus or minus
AECOM	AECOM Technical Services, Inc.
APN	Assessor’s Parcel Number
bgs	below ground surface
CCB	continuing calibration blank
CCV	continuing calibration verification
COC	chain of custody
D	second sample value (duplicate value)
DO	data obtained and usable
DOT	Department of Transportation
DP	data planned to be obtained
DQO	data quality objective
DTSC	Department of Toxic Substances Control
DVR	data validation report
e.g.	*exempli gratia*, for example
EMI	electromagnetic induction
etc.	*et cetera*, and other similar things
FD	field duplicate
GPR	ground-penetrating radar
GPS	global positioning system
HASP	health and safety plan
i.e.	*id est*, that is
ICB	initial calibration blank
ICV	initial calibration verification
ID	identification
IDW	investigation-derived waste
LCS	laboratory control sample
LCSD	laboratory control sample duplicate
LUC	land use control
mg/L	milligrams per liter
MS	matrix spike
MSD	matrix spike duplicate
OSHA	Occupation Safety and Health Administration
Pace Analytical®	Pace Analytical® Services, LLC
PARCC	precision, accuracy, representativeness, completeness, and comparability
PCB	polychlorinated biphenyl
PEA	Preliminary Endangerment Assessment
PID	photoionization detector
PM	Project Manager
PPE	personal protective equipment
QA	quality assurance
QC	quality control
RAW	Removal Action Workplan
RCRA	Resource Conservation and Recovery Act
RL	reporting limit
RPD	relative percent difference
S	first sample value (original value)

List of Acronyms and Abbreviations (continued)

SA	spike added
SAP	Sampling and Analysis Plan
Site	59th Street Corporation Yard
SMUD	Sacramento Municipal Utility District
SO	soil
SOP	standard operating procedure
SPLP	synthetic precipitation leaching procedure
SR	sample result
SSR	spiked sample result
SVOC	semi-volatile organic compound
TCLP	toxicity characteristic leaching procedure
USEPA	United States Environmental Protection Agency
VOA	volatile organic analysis
VOC	volatile organic compound
XRF	x-ray fluorescence

1.0 Introduction

This Sampling and Analysis Plan (SAP) provides a project-specific sampling plan that will be used to implement the removal action activities described in the Interim Removal Action Workplan (RAW) at the Sacramento Municipal Utility District (SMUD) 59th Street Corporation Yard (Site), an area encompassing 19.74 acres located at 1708 59th Street in Sacramento, Sacramento County, California, 95819. The primary scope of work includes the implementation of Alternative 2, which consists of soil excavation and off-site disposal, and land use controls (LUCs) in compliance with the *First Amendment to Corrective Action Consent Agreement (CACA)*, Docket HWCA P1-13/14-007 (California Department of Toxic Substances Control [DTSC], 2018).

1.1 Site Name

The SMUD 59th Street Corporation Yard is the Site addressed in this SAP. The DTSC EnviroStor website identifies the Site as the SMUD Corporation Yard (EnviroStor Identification Number 34490015).

1.2 Site Location

The Site address is 1708 59th Street in Sacramento, California, and is approximately 5 miles east of downtown Sacramento. The Site is located on the Sacramento East United States (U.S.) Geological Survey Quadrangle Map in Township 8 North, Range 5 East, Section 9 (Mount Diablo Baseline and Meridian). The Site's approximate coordinates are 121 degrees (˚) 26 minutes (') 18 seconds (") West longitude, 38˚ 33' 22" North latitude.

The Site encompasses 19.74 acres in an area of varied land use. The main portion of the Site is Assessor's Parcel Number (APN) 008-0010-009-0000 (12.89 acres). The wedge shaped portion of the Site situated south of the light rail line and north of U.S. Highway 50 consists of the following 10 parcels listed west to east: APN 011-0073-001-0000 (0.45 acre), APN 011-0073-002-0000 (1.11 acres), APN 011-0073-003-0000 (0.2 acre), APN 011-0073-004-0000 (0.39 acre), APN 011-0073-006-0000 (0.1 acre), APN 011-0073-008-0000 (1.79 acres), APN 011-0081-001-0000 (0.86 acre), APN 011-0081-002-0000 (0.86 acre), APN 011-0081-003-0000 (0.86 acre), APN 011-0081-008-0000 (0.23 acre). The described wedge-shaped area totals 6.85 acres.

1.3 Responsible Agency

Under the *First Amendment to Corrective Action Consent Agreement*, DTSC is the lead regulatory agency and SMUD is the proponent for corrective action at the Site. Under contract with SMUD, AECOM Technical Services, Inc. (AECOM) is responsible for preparing project planning documents. SMUD's selection of contractors to support the interim removal action will be subject to the review and approval of each contractor's qualifications by DTSC.

1.4 Project Organization

Key project personnel, including contact information and project responsibilities, are identified in Table 1.

2.0 Background

2.1 Site Description

Site description information is provided in Section 1.2 of the RAW.

2.2 Site History

Operational history information is provided in Section 1.2.2 of the RAW.

2.3 Previous Investigations

The previous investigations conducted at the Site are summarized in Section 2.2 of the RAW.

2.4 Geological Information

Descriptions of local geology and hydrogeology are presented in Section 2.1 of the RAW.

2.5 Environmental and/or Human Impact

As of December 2021, the Site has been vacant. The Site is not open to public access, so human exposure to on-Site contaminated media would be restricted to SMUD personnel. The Site is considered to be unsuitable habitat for ecological receptors due to its highly developed nature. A preliminary human health exposure assessment was performed for soil and groundwater (AECOM, 2021). A focused baseline Human Health Risk Assessment (HHRA) was performed for the VI exposure pathway. An ecological risk evaluation was not conducted as the Site does not provide suitable habitat for ecological receptors and thus ecological exposure pathways are considered incomplete. Results of the HHRA are discussed in Section 2.5 of the RAW.

3.0 Quality Assurance/Quality Control Plan

3.1 Project Objectives and Problem Definition

Based on the site investigation results presented in the Site Characterization Report Addendum (AECOM, 2021), soil at the Site is impacted with arsenic at concentrations exceeding the 17.53 milligram per kilogram (mg/kg) background concentration and lead and total petroleum hydrocarbons as hydraulic oil/motor oil ($TPH_{ho/mo}$) exceeding the 80 and 2,400 mg/kg residential screening levels (DTSC, 2020), respectively. The nature, source, and extent of contamination at the Site is further discussed in Section 2.4 of the RAW. The estimated lateral extents of elevated arsenic, lead, and $TPH_{ho/mo}$ are shown on Figure 2-2 of the RAW.

Further action is required at the Site due to the elevated concentrations of arsenic, lead, and $TPH_{ho/mo}$. The purpose of the remedial options evaluated in the RAW is to mitigate the onsite exposure risk of arsenic, lead, and $TPH_{ho/mo}$ in soil through inhalation, dermal absorption, and ingestion and reduce volatile organic compound (VOC) concentrations in the soil gas contamination source area. Implementation of the recommended removal action will consist of (1) removing soil from the excavation areas to minimize the potential for direct exposure to contaminants of concern in soils; (2) collecting confirmation samples from the completed soil excavation areas; (3) collecting waste characterization samples; (4) collecting backfill samples, followed by backfilling and restoring the Site; and (5) implementing LUCs until the soil excavation is complete and removal action goals are achieved..

3.2 Data Quality Objectives

Data quality objectives (DQOs) are the basis for the design of the data collection plan and, as such, they specify the type, quality, and quantity of data to be collected, and how the data are to be used to make the appropriate decisions for the project. The DQOs for the removal action were developed to meet the qualitative and quantitative needs of the project.

Together, the DQOs and data measurement objectives provide a means for control and review of the project so that environmentally-related measurements and data collected by the field sampling teams are of known and acceptable quality. The specific DQOs for the removal action are presented in Table 2. These DQOs will be fulfilled by implementing the quality assurance (QA) and quality control (QC) measures described in Sections 3.3 through 3.8.

Every reasonable attempt will be made to obtain an acceptable and high-quality set of usable field measurements and analytical data. If a measurement cannot be obtained or is unusable for any reason, the effect of the missing or invalid data will be evaluated.

3.3 Data Quality Indicators and Measurement Quality Objectives

Precision, accuracy, representativeness, completeness, and comparability (PARCC) are the indicators of data quality. PARCC goals are established to help assess data quality. The following subsections define PARCC parameters associated with this project.

3.3.1 Precision

Data precision is assessed by determining the agreement between replicate measurements of the same sample and/or measurements of duplicate samples. The overall random error component of precision is a function of the sampling and analytical precision, and is assessed by the analysis of field duplicates (FDs). FD samples will be collected to provide a measure of the contribution of field-related sources to overall variability.

The analytical precision is determined by the analysis of FDs by laboratory and by replicate analyses of the same sample. An analytical duplicate is the preferred measure of analytical method precision. When analytes are present in samples at concentrations below or near the reporting limit (RL), precision may be evaluated using duplicate analyses of laboratory-prepared samples, such as laboratory control sample (LCS)/laboratory control sample duplicates (LCSDs) and matrix spike (MS)/matrix spike duplicates (MSDs).

Precision is quantitative, and most often expressed in terms of relative percent difference (RPD). Precision of the laboratory analysis will be assessed by comparing the original and duplicate results. The RPD will be calculated for each pair of duplicate analyses using the following equation:

$$RPD = |S - D| \times 100 / ((S + D) / 2)$$

Where:
S = first sample value (original value)
D = second sample value (duplicate value)

Acceptable RPD limits for FD measurements will be less than or equal to 25 percent for aqueous matrices and less than or equal to 35 percent for soil. Contribution of laboratory-related sources to overall variability is measured through various laboratory QC samples. Acceptable RPD limits for laboratory measurements (i.e., LCSD, MSD, laboratory duplicates) are specified in the source methods and laboratory standard operating procedures (SOPs).

Precision during the project will be determined by field data and laboratory analytical data by the analysis of FDs, laboratory replicates, MS/MSD results, and the evaluation of the RPD for these various paired measurements. The RPD goals for measures of precision associated with the removal action analytical methods are presented in Table 4.

3.3.2 Accuracy

Accuracy is the degree of difference between the measured or calculated value and the true value, and is a measure of the bias in a system. Accuracy is quantitative and usually expressed as the percent recovery (%R) of a sample result. The %R is calculated as follows:

$$\%R = (SSR - SR / SA) \times 100$$

Where:
SSR = spiked sample result
SR = sample result
SA = spike added

Potential sources of systematic errors in accuracy include: improper sample collection methods; physical or chemical instability of samples; interference during sample analysis; incorrect calibration of measurement systems; and sample contamination. Field equipment blanks, ambient blanks, and laboratory blanks may be analyzed to assess artifacts introduced during sampling, transport, and/or analysis that may affect the accuracy of the data. Analytical data will also be evaluated for accuracy. MSs, LCSs, verification standards, and other QC standards will be used, whichever is applicable. Accuracy acceptance criteria are detailed in Table 4.

In addition, initial and continuing calibration verification (ICV and CCV) samples, and initial and continuing calibration blanks (ICBs and CCBs for metal analyses) may be used to verify that the sample concentrations are accurately measured by the analytical instrument throughout the analytical run.

Sampling accuracy during the project will be assessed using calibration verification samples, LCSs or standard reference materials, and MS samples. Accuracy goals for the specific laboratory analytical methods that will be relied on to generate removal action data are summarized in Table 4.

Accuracy and precision may be impacted by contaminants detected in the method or field blanks. Method blanks are contaminant-free water that is processed and analyzed with the associated field samples per matrix and method. Method blank goals will be that blanks contain less than the RL for each target analyte. If an analyte is detected in a field or laboratory blank, any associated positive result less than five times the detected concentration of the blank may be considered undetected.

3.3.3 Representativeness

Representativeness expresses the degree to which sample data accurately and precisely represent the characteristic being measured, parameter variations at a sampling point, and environmental conditions. Representativeness is a qualitative and quantitative parameter that is most concerned with the proper design of the sample plan and the absence of cross-contamination of samples. The representativeness will be assessed qualitatively by reviewing the procedures and design of the sampling event, and quantitatively by reviewing the laboratory QC samples for consistent analytical issues.

Representativeness is addressed by the description of the sampling techniques and the rationale used to select the sampling locations. Sample representativeness is also evaluated using the RPDs for FD and/or MS/MSD results and by review of the results of field blanks (i.e., trip or equipment blanks as appropriate to sampling methods).

Representativeness of individual sample analyses will be described on the basis of results obtained from associated laboratory QC samples. The representativeness of sample analyses will be considered acceptable as long as there are no analytical measurements that deem the data results unusable or analytical procedures that do not meet the method or SAP requirements.

3.3.4 Completeness

Completeness is a measure of the amount of usable data obtained from a measurement system compared with the amount that was expected to be obtained under correct normal conditions. Usability will be determined by evaluation of the PARCC parameters, excluding completeness. Those data that are reviewed and need no qualification, or are qualified as estimated or undetected concentrations, are considered usable with limitations as noted by the USEPA qualifier flags. Rejected data are not considered usable. Completeness will be calculated following data evaluation. Completeness is calculated using the following equation:

Percent Completeness = (DO/DP) x 100

Where:
DO = data obtained and usable
DP = data planned to be obtained

The project’s completeness goals are 90 percent for soil sample analyses.

3.3.5 Comparability

Data comparability is a qualitative parameter. It is defined as the measure of the confidence with which one data set can be compared to another. Data developed under this investigation will be collected and analyzed using standard USEPA analytical methods and QC procedures to ensure comparability of results with other analyses performed in a similar manner. Data resulting from this field investigation may subsequently be compared with other data sets.

Comparability of the data collected for the site characterization will be achieved by following, to the extent possible, the field work procedures described in this SAP for sample collection and analysis. Comparability will be ensured by analyzing samples obtained in accordance with appropriate SOPs and the referenced standard laboratory analysis methods. All data should be calculated and reported in units consistent with standard reporting procedures so that the results of the analyses can be compared with those of other laboratories, if necessary. In general, data will be reported in micrograms per kilogram for organics and milligrams per kilogram (reported in dry weight) for soil.

3.4 Data Review and Validation

All data will be assessed and validated according to the USEPA National Functional Guidelines and this SAP. Each sample delivery group provided by the laboratory will be assessed for accuracy and precision using both the laboratory and field QC samples within the batch. The data will be reviewed for external contamination using method and field blanks, accuracy using percent recoveries from LCSs, MSs, surrogate spikes (organic analyses), and calibration recoveries, and precision from duplicates including field, LCS, and MS.

3.4.1 Batch Quality Control Review

Once laboratory hard copy and electronic versions of data are delivered to the project chemist, he/she will perform a batch QC review for all analytical data provided. This batch QC review is typically referred to as data validation and includes evaluating the QC sample results for groups of samples that were prepared and analyzed together. All analytes will be assessed for accuracy and precision against the limits presented in Table 4. This data validation includes:

- Reviewing chain-of-custody (COC) documentation;
- Checking holding time compliance;
- Determining whether adequate/required batch QC samples were analyzed and reported according to method and project specifications;
- Assessing method blanks;
- Assessing LCS recoveries;
- Reviewing surrogate spike recoveries (organic methods only);
- Assessing MS/MSD recoveries and RPDs; and
- Assessing the initial calibration and CCV recoveries.

3.4.2 Field Quality Control Samples

Influence from field conditions and the assessment of matrix heterogeneity will be evaluated using the following field QC samples:

- Trip blanks;
- Equipment rinsate blanks;
- FD sample results;
- MS recoveries; and
- MS/MSD RPDs.

Field QC samples will be related to field samples by shipment cooler, sampling equipment, location, matrix, or other conditions related to sample collection and handling as appropriate. Temperature blanks should be submitted with each cooler to ensure that the samples were properly preserved during transport.

3.4.3 Data Validation Checklists

Data validation checklists will be completed for each analytical report. Qualifier flags will be applied to sample results that fail to meet the project QA objectives according to USEPA data validation flagging conventions. Circumstances may be encountered that warrant deviations from these flagging conventions. The technical reasoning will be documented with the analytical report or in the data assessment report in these instances. Reanalysis or resampling may be recommended as a corrective action if data are determined to be unacceptable for the intended use. The laboratory data qualifier flags and USEPA data flags will be stored with the data.

3.4.4 Field Screening Data

Field screening data includes data produced by rapid field screening methods that area less precise or qualitative than standard analytical methods, often with less rigorous sample preparation and/or analytical quality control. Screening level methods produce analyte identification, but usually with higher reporting limits. The advantage of using screening data is that a large number of less precise data points can minimize the total error or uncertainty associated with sampling using fewer, more precise results. The field screening data points serve as a real-time guide for identifying the extent of contamination.

3.5 Data Management

The laboratory will provide all analytical data to SMUD and their supporting contractor in two electronic versions: (1) an excel spreadsheet that will be stored with the project files, and (2) a DTSC Envirostor deliverable to be uploaded once the data set is finalized. A review of the electronic data will be performed and compared to the hardcopy package at a minimum frequency of 25 percent.

3.6 Assessment Oversight

Assessments and oversight are necessary to ensure that procedures are followed as required and that deviations from procedures are documented. Oversight of the QA activities may be completed using field and laboratory audits as well as data verification/validation of laboratory data. The SMUD project manager (PM) or designated QA manager will perform an onsite inspection of the field procedures to verify compliance with the SAP. The laboratory participating in the data collection effort will be pre-qualified by the project management team (DTSC-approved laboratory under contract with SMUD). Laboratory pre-qualification and surveillance audits may also be undertaken by DTSC.

Corrective actions will be implemented on a case-by-case basis to correct quality problems as a result of deviations from the field or analytical procedures. All personnel involved in the project are responsible for discovering QA problems or deficiencies in their areas of responsibility. Any such deficiencies must be reported immediately to the SMUD PM. As soon as possible after discovery, the SMUD PM will also propose resolution action in cooperation with personnel in the area where the deficiency was found.

Field teams will note any quality problems in the applicable logbook or other form of documentation. Field teams will notify the PM of any quality problems encountered. The laboratory is responsible for providing a summary of quality issues to the PM with each data report. However, if issues arise prior to or during analysis, the project PM must be notified immediately.

A data validation report (DVR) will be completed by the Project Chemist following each sampling event and provided to the SMUD PM. The DVR will include a discussion of any significant quality problems that were identified and, their effect on the use of the data. Data validation is discussed in Section 3.4.

Quality issues identified by the field team, laboratory, and Project Chemist will be discussed in the Interim Removal Action Completion Report. Any significant quality problems and recommended solutions should be included in the report. Limitations on data usability that were identified during data validation should be highlighted. The results of data assessment should be reconciled with the project objectives. If significant problems are encountered, the party that encountered the problems will report these issues, along with the results of the necessary response actions, to the SMUD PM in a separate memorandum prior to submission of the Interim Removal Action Completion Report.

3.7 Field Quality Control Samples

QC samples collected in the field may include equipment blanks, field duplicates, trip blanks, matrix spike/matrix spike duplicates, and temperature blanks. Each type of QC sample is briefly described in the following subsections.

3.7.1 Field Duplicates

Co-located FD samples will be collected simultaneously with, or immediately after, the corresponding original samples have been collected, depending on the sample type and medium. In all cases, the same sampling protocol is used to collect the original sample and the co-located FD sample. These FDs will be used to assess the sampling and analytical variability of the sampling program. Co-located FD samples are treated in an identical manner during storage, transportation, and analysis. The sample containers are assigned an identification (ID) number in the field such that they cannot be identified (blind duplicate) as duplicate samples by laboratory personnel.

Field duplicate samples will be collected at a frequency of 10 percent. A maximum RPD of 50 percent for soil will be used for evaluation of field duplicate comparability. For samples with low concentrations (e.g., results are less than five times the RL), results should be within plus or minus (±) 2 times the RL for soil.

3.7.2 Trip Blanks

One trip blank will accompany each cooler shipment of samples sent to the laboratory for analysis of VOCs. A trip blank is a set of volatile organic analysis (VOA) vials containing laboratory certified analyte-free water that is prepared in the laboratory, taken to the sampling site, and returned to the laboratory with samples submitted for analysis of VOCs. Trip blanks will not be opened in the field. The trip blank shall be analyzed by the same analytical method as the samples and shall be part of the same preparation batch as the samples.

3.7.3 Temperature Blanks

One temperature blank will accompany each cooler shipment of samples sent to the laboratory for analysis by methods requiring sample preservation by cooling. A temperature blank is a sample bottle containing water, placed in the cooler at the time of sampling, and measured by the laboratory upon receipt to document that the samples were properly preserved from the field to the laboratory.

3.8 Laboratory Quality Control Samples

Soil samples for analyses of VOCs for laboratory QC purposes will be obtained by collecting additional volume of equivalent samples from a co-located location in the same way as the original samples.

The laboratory should be alerted as to which sample is to be used for QC analysis by a notation on the sample container label and the COC record or packing list.

At a minimum, one laboratory QC sample is required per 14 days or one per 20 samples (including blanks and duplicates), whichever is greater. If the sample event lasts longer than 14 days or involves collection of more than 20 samples per matrix, additional QC samples will be designated. The samples designated for laboratory QC purposes will be selected in the field by the sampler. The laboratory QC accuracy and precision limits are provided in Table 4.

3.8.1 Matrix Spike/Matrix Spike Duplicates

MS/MSD samples will be prepared and analyzed at a frequency of 5 percent. The sampler will designate one or more of the samples by noting on the COC that the sample(s) are for MS/MSD (in the remarks column but not on the sample). It is important to provide sufficient volume for MS/MSD analyses. The volume should be three times the volume required for each analyses, or more if specified by the laboratory. Samples designated for MS/MSD analysis should be typical of the matrix and not be highly contaminated in order to minimize MS/MSD imprecision resulting from high levels of environmental contamination. In order to minimize the effects of soil heterogeneity, the laboratory will use a single or adjacent liners.

4.0 Sampling Rationale

A summary of the proposed samples that will be collected as part of the removal effort is provided in Table 5. The proposed confirmation sample locations are shown on Figure 5-2 of the RAW.

4.1 Confirmation Sampling

Confirmation samples will be collected from the excavation areas to determine whether the removal action cleanup goals and RAOs for the Site have been achieved (see Section 3 of the RAW). Prior to excavation completion, x-ray fluorescence (XRF) data will be used as a screening tool to guide excavation extents in the field. A field-portable XRF unit will be used to measure total arsenic concentrations in soil collected from the excavation using sample scoops, direct-push drill rig, hand augers, or the excavator bucket.

Confirmation soil samples will be collected when excavation work has been completed to the depth and extent defined in the RAW. Confirmation sampling for excavations less than 5,000 square feet will be conducted at an approximate frequency of one sample per sidewall and excavation bottom. Confirmation sampling for excavations greater than 5,000 square feet will be conducted at an approximate frequency of one sample per 50 linear feet of sidewall and 2,500 square feet of excavation bottom. The sidewall samples will be collected at a depth halfway between the top and bottom of the sidewall. The excavated volume will approximately be 8,400 bank cubic yards, and it is estimated that 92 confirmation soil samples will be collected from the Site and submitted for laboratory analysis.

Concentrations detected in the confirmation samples will be compared to the removal action cleanup goals established in the RAW. If a soil sample exceeds the cleanup criteria, soil surrounding the soil sample will further be excavated in the area of the soil sample (laterally for sidewall samples and vertically for floor samples). A confirmation sample will be collected from the new excavation limit. The exact confirmation sample locations will be verified in the field in consultation with DTSC, as required. Sample locations and the number of samples collected may be adjusted in the field if necessary. Additional excavation and confirmation sampling will be performed until the cleanup goals are attained.

The confirmation samples for Area #1, #2, #4, #5, #6, #7, and #8 will be analyzed for arsenic by USEPA Method SW6020. Confirmation samples for Area #3 will be analyzed for arsenic and lead by USEPA Method SW6020, lead by synthetic precipitation leaching procedure (SPLP) by USEPA Method 1312, and $\text{TPH}_{\text{ho/mo}}$ by USEPA Method SW8015M. The potential for migration of lead from soil to groundwater will be evaluated by comparing the SPLP data against a cleanup standard of 5 milligrams per liter (mg/L).

The Area #9 excavation bottom (two locations) and sidewalls (four locations) will be evaluated using photoionization detector (PID) readings to determine the source of VOCs at Area #9. If a PID reading of an excavation sidewall exceeds 5 parts per million, the excavation will be expanded to remove additional VOC-impacted soil. The contaminated soil will be excavated until PID readings indicated the contaminated soil has been removed or to the extent practicable.

4.2 Waste Characterization Sampling

Prior to excavation activities, a minimum of one pre-design waste characterization sample may be collected for every 250 cubic yards of proposed excavated soil. Alternatively, a minimum of one four-point composite waste characterization sample for every 250 cubic yards of excavated soil may be collected from soil stockpiled after excavation if pre-design sampling is not conducted. Additional waste characterization samples may be required to be collected depending on landfill acceptance criteria. The excavated soil volume will be approximately 8,400 bank cubic yards, and it is estimated that 38 waste characterization samples will be collected from the Site. The waste characterization samples will be analyzed for the following.

- Title 22 metals by USEPA Methods SW6020 and SW7471
- Toxicity characteristic leaching procedure (TCLP) arsenic and lead by SW-846 Method 1311 (as necessary)
- Waste Extraction Test arsenic, lead, and VOCs by CCR Title 22 (as necessary)
- VOCs by USEPA Method SW8260B
- Semi-volatile organic compounds (SVOCs) by USEPA Method SW8270C
- Organochlorine pesticides by USEPA Method SW8081A
- Chlorinated herbicides by USEPA Method SW8151A
- Polychlorinated biphenyls (PCBs) by USEPA Method SW8082
- Oil-, diesel-, and gasoline-range organics by USEPA Methods SW8015M

The waste characterization sample analytical results may be classified as non-Resource Conservation and Recovery Act (RCRA) hazardous waste based on the potential exceedance of the soluble threshold limit concentration or RCRA-hazardous if the TCLP arsenic concentration exceeds 5 mg/L.

4.3 Backfill Sampling

Excavation side slope material that was removed to slope the excavation sidewalls may be used to backfill the excavation area. This material will be sampled in accordance with DTSC guidance, *Information Advisory, Clean Imported Fill Material* (DTSC, 2001). Up to one four-point composite sample per 250 cubic yards of material will be collected and analyzed for arsenic by USEPA Method SW6020. Excavation side slope material removed from Area #3 will additionally be analyzed for lead by USEPA Method SW6020 and $TPH_{ho/mo}$ by USEPA Method SW8015. The side slope characterization sample results will be provided to DTSC prior to backfilling the excavation areas.

Virgin Class II aggregate base will be used to backfill the excavation area if excavation slide slope material is not used. Recycled aggregate base shall not be used, and the aggregate base will be sourced from rock quarries. After the backfill source site is selected, one four-point composite sample will be collected from the aggregate base source in accordance with DTSC guidance, *Information Advisory, Clean Imported Fill Material* (DTSC, 2001). The composite sample will be analyzed for asbestos by Occupation Safety and Health Administration (OSHA) Method ID-191, and Title 22 metals by USEPA Methods SW6020 and SW7471.

Concentrations detected in the backfill samples will be compared to the screening levels listed in Table 3. If sampling results indicate exceedances of the screening levels, the material source will not be used for backfilling and an alternate source of backfill will be considered. Sampling of new materials will be conducted until a “clean” source of backfill is found for use in the excavation areas. Backfill characterization sample results will be provided to DTSC prior to backfilling the excavation areas.

5.0 Request for Analyses

5.1 Analysis Narrative

A summary of the proposed samples that will be collected and their analyses is provided in Table 5. Container requirements, sample volumes, preservation requirements, and holding times are presented in the Table 6. The analytical methods for the chemical analysis of soil and associated field QC samples will follow standard USEPA testing methods and protocols where applicable. The methods proposed are listed below.

- Arsenic and lead by USEPA Method SW6020
- Title 22 metals by USEPA Methods SW6020 and SW7471
- Asbestos by OSHA Method ID-191
- TCLP arsenic and lead by SW-846 Method 1311
- SPLP lead by Method 1312
- Waste Extraction Test arsenic, lead, and VOCs by CCR Title 22
- VOCs by USEPA Method SW8260B
- SVOCs by USEPA Method SW8270C
- Organochlorine pesticides by USEPA Method SW8081A
- Chlorinated herbicides by USEPA Method SW8151A
- PCBs by USEPA Method SW8082
- Oil-, diesel-, and gasoline-range organics by USEPA Methods SW8015M

Soil samples will be analyzed at a fixed laboratory with a standard 2-week turnaround time for analytical results.

5.2 Analytical Laboratory

Soil samples will be analyzed by Pace Analytical® Services, LLC (Pace Analytical®) of Bakersfield, California. Pace Analytical® is certified by the California Environmental Laboratory Accreditation Program for the methods listed above, except for asbestos; Pace Analytical® will subcontract to LA Testing in South Pasadena, California to analyze soil samples collected for asbestos. The laboratory analytical methods and achievable limits selected for the soil samples for this project are presented in Table 3. The analytical methods were selected to provide data of known quality to meet the project DQOs, and to maintain consistency and comparability with data from the previous sampling events.

Regulatory and risk-based screening level values and laboratory limits are presented in Table 3. For all comparable criteria, the most protective criterion listed for each analyte on these tables will be used for comparison. The cleanup goals established in the RAW will be used for comparison in addition to the risk-based screening levels in Table 3.

6.0 Field Methods and Procedures

6.1 Field Equipment

6.1.1 List of Equipment Needed

The field equipment expected to be utilized for the project includes the following:

- Subsurface utility locating equipment (e.g., magnetometer, ground-penetrating radar)
- Earthmoving equipment (e.g., backhoe, front-end loader)
- Hand auger (aluminum) or direct-push drill rig
- Disposable sample scoops (plastic)
- Samplesmart™ kits
- XRF analyzer
- PID
- Hand-held global positioning system (GPS) unit
- Decontamination supplies (e.g., Alconox®, Type II reagent-grade water, potable water, brush, drums)

6.1.2 Calibration of Field Equipment

Field equipment will be calibrated before the start of work each day. Any instrument drift from prior calibration will be recorded in the field logbook. Calibration will follow procedures and schedules outlined in the particular instrument's operations manual and will be recorded on an *Equipment Calibration Daily Log* (F-1027 included in Attachment 1).

Calibrated equipment will be uniquely identified by using either the manufacturer's serial number or other means. A label with the identification number and the date when the next calibration is due will be physically attached to the equipment. If this is not possible, records traceable to the equipment (e.g., showing the equipment identification) will be readily available for reference. In addition, the results of calibrations and records of repairs will be recorded in the field logbook. Equipment that fails calibration or becomes inoperable during use will be removed from service and either segregated to prevent inadvertent use or tagged to indicate it is out of calibration.

6.1.3 Equipment Maintenance

Field instrument and equipment manuals, provided by the manufacturer, will be maintained with the instruments and equipment for easy access by the field team. Maintenance will be performed on the schedule recommended by the manufacturer, and in accordance with the manuals. Field personnel will record any field service and maintenance information in the field logbooks. Specific preventative maintenance procedures will follow manufacturer recommendations.

Should any of the field equipment become inoperable or fail calibration, it will be removed from service and tagged to indicate that repair, recalibration, or replacement is needed. The field manager will be notified so that prompt service can be completed or substitute equipment can be obtained. Any action of this type will be documented in the field logbook.

6.2 Site Reconnaissance and Preparation

All proposed excavation areas will be marked prior to intrusive field investigations and a ticket will be initiated with Underground Service Alert of Northern/Central California and Nevada. Additionally, a subsurface utility clearance survey will be performed by a subsurface utility survey contractor. The objective of the survey is to locate underground anomalies and avoid underground utilities; therefore, field personnel will work with the SMUD PM to identify and mark any known subsurface utilities or structures.

Geophysical methods are preferred because they are not intrusive, and because they can readily detect buried objects during rapid screening of large areas. Geophysical surveys will be performed using electromagnetic induction (EMI), ground-penetrating radar (GPR), and shallow subsurface magnetic techniques. The three techniques complement each other and will be used to clear the entire excavation footprint (largest potential extent of excavation including side-slopes) plus a 10-foot buffer. Technique effectiveness depends on its ability to contrast the utility against the natural background; depth of utility burial is also a consideration. Ferromagnetic metals are detected by all of the techniques. Non-ferromagnetic metals are not detected by magnetic techniques. Live alternating-current electric lines and communication lines are detected by EMI. Polyvinyl chloride, fiberglass, and ceramic conduits can be detected only by GPR, and not with certainty. If utilities are detected, their location will be marked with easily-identifiable utility marker whiskers secured with nails, plastic flagging, or marking paint.

If pre-design waste characterization samples are collected, all proposed sample locations will be a minimum of five feet away from existing utilities.

6.3 Sample Collection

6.3.1 Field Screening

XRF and PID field screening will be performed during excavation activities to guide excavation extents and segregate soil stockpiles. Field personnel will follow the protocols described in the SOPs for the XRF and PID instruments as provided in Attachment 2 to ensure that they are in good working condition and that field measurements made by different individuals or at different times are consistent and reproducible. Each instrument will be calibrated with standards appropriate for the type of instrument and the linear range established for the analytical method used.

6.3.2 Soil Sampling

The preferred method for collecting soil samples for laboratory analysis is with a disposable scoop. There may be cases where soil samples will be collected using a hand auger, direct-push drill rig, or by using the backhoe bucket for logistical or safety considerations (e.g., where the entry of personnel is not feasible in deeper areas). Soil samples will be analyzed for the analytes listed in Section 4. Proposed soil samples and target intervals are also presented in Table 5.

The soil samples will be collected by scooping the soil directly into laboratory-supplied, glass sample jars. However, soil samples intended for VOC analysis will be collected at the target depth using samplesmart™ kit sampling methodology and preservation, or equivalent. Details regarding the use of samplesmart™ kits are provided in Attachment 2.

If a hand auger is used to collect soil samples, the hand auger will be advanced to the desired depth. The soil will be collected in the bit and emptied directly into the sample jar.

If pre-design waste characterization samples are collected, direct push technology will be used. Direct push technology involves advancing a sampling probe by direct hydraulic pressure or percussion using small diameter rods (generally smaller than four inches in diameter). All drilling activities will conform to state and local requirements and project supervision will be provided by a licensed geologist or engineer. If direct push technology is used, soil will be collected in acetate sleeves at the target depth interval and placed directly into the sample jar.

Data obtained for each soil sample will be recorded in the field on the *Soil/Sediment Sampling Record* form (F-1026 in Attachment 1) to be completed by the geologist at the site.

6.4 Surveying

Sample location coordinates will be determined and recorded using a hand-held GPS unit capable of 100-centimeter resolution. A licensed surveyor will not be utilized.

6.5 Decontamination Procedures

All equipment that comes in contact with potentially contaminated soil will be decontaminated in a designated decontamination area. This includes earth-moving equipment, reusable sampling devices, and instruments. Disposable equipment intended for one-time use will not be decontaminated but will be packaged for appropriate disposal. Decontamination will occur prior to and after each use of a piece of re-usable equipment. Proper decontamination of each piece of equipment and each instrument will be the responsibility of the field personnel.

A portion of the staging area will be designated as an equipment decontamination area. A staging area is any place near the site where equipment and supplies can be stored and not interfere with activities being performed on site. Basic design and content are variable based on the task. Smaller decontamination areas for personnel and portable equipment will be provided as necessary. These locations will include basins or tubs to capture decontamination fluids, which will be transferred to a large accumulation tank as necessary. All equipment that may directly or indirectly contact samples will be decontaminated in the designated decontamination area.

The following procedure will be used to decontaminate large pieces of equipment:

- The external surfaces of equipment will be washed with high-pressure hot water and Alconox® or equivalent laboratory-grade detergent, and if necessary, scrubbed until all visible dirt, grime, grease, oil, loose paint, rust flakes, etc., have been removed
- The equipment will then be rinsed with potable water
- The inside surfaces of the casing, drill rod, and auger flights will also be washed as described

The following procedures will be used to decontaminate reusable sampling equipment:

- Scrub with Alconox®-water solution
- Rinse with copious amounts of potable water
- Rinse again with Type II reagent-grade water
- Allow to air dry prior to further use. If the equipment will not be used immediately, it will be wrapped in oil-free aluminum foil and placed in a plastic bag for storage
- Rinse solutions will be contained in designated drums pending disposal
- Decontamination will be recorded on a *Decontamination Record* form (F-1022 included in Attachment 1)

7.0 Sample Containers, Preservation, Packaging, and Shipping

This section describes the types of containers to be used and the procedures for preserving, packaging, and shipping samples.

7.1 Sample Containers, Sample Volumes, Preservation Requirements

Sample aliquots submitted to Pace Analytical® will be placed in commercial certified pre-cleaned sample containers. Samples will be chilled as soon as possible after collection in the field. Samples will be double-bagged and stored in a manner that prevents submergence of samples in ice melt-water. Container requirements, sample volumes, preservation requirements, and holding times are presented in the Table 6.

7.2 Sample Packaging and Shipping

The following sections contain guidelines for sample packaging and shipping.

7.2.1 Packaging

Samples to be shipped to an off-site laboratory will be packaged in a cooler. Each cooler will be checked for overall integrity and cleanliness. Coolers will be lined with a large plastic bag to prevent melting ice from leaking. Samples will be placed into the cooler in an upright position. Appropriate packing material will be used to prevent breakage of glass sample containers during shipment. Ice contained within sealed plastic bags will be placed around the samples to achieve a storage temperature of ±4 degrees Celsius. The COC form will be placed in a sealed plastic bag and placed either on top of the samples or taped to the inside of the lid. The cooler lid will be secured in the closed position with strapping tape. Custody seals will be affixed to the cooler and lid to ensure the integrity of the samples.

7.2.2 Shipping

The appropriate shipping container will be determined by United States Department of Transportation (DOT) or International Air Transportation Association regulations for the anticipated level of suspected contaminants.

Shipping containers will be custody-sealed for shipment as appropriate. The custody seals will be affixed so that access to the container can be gained only by breaking a seal.

Field personnel will arrange transportation of the samples to the laboratory. When custody is relinquished to a shipper or courier, field personnel or the PM will inform the laboratory sample custodian by telephone or email of the expected arrival time of the sample shipment and advise him or her of any time constraints on sample analysis.

Suggested guidelines for marking and labeling shipping containers are presented below. In all cases, United States DOT or International Air Transportation Association regulations will be consulted for appropriate marking and labeling requirements, which include the following.

- Use abbreviations only where specified.
- The words “This End Up” or “This Side Up” must be printed clearly on the top of the outer package. Upward-pointing arrows should be placed on the sides of the package. After a shipping container is sealed, two COC seals must be place on the container, one on the front and one on the back. To protect the seals from accidental damage, clear strapping tape must be place over them.

8.0 Disposal of Residual Materials

Waste may be classified as non-investigative waste or investigation-derived waste (IDW). Non-investigative waste, such as litter and household garbage, will be collected on an as-needed basis to maintain the site in a clean and orderly manner. This waste will be disposed in a designated collection bin.

IDW management will follow general best management practices in accordance with criteria established in *Management of Investigation-Derived Wastes During Site Inspections* (USEPA, 1991) and guidelines outlined in “Guide to Management of Investigation-Derived Wastes” (USEPA, 1992). Used dedicated sampling equipment and personal protective equipment (PPE) will be rinsed if there is visible evidence of contamination, placed in sturdy plastic bags, taken off-site at the conclusion of the field activities, and disposed of at a municipal sanitary landfill.

IDW will be properly containerized in 5-gallon buckets or 55-gallon drums and temporarily stored on-site at a location determined by SMUD, prior to transportation. The containers will be transported in such a manner to prevent spillage or particulate loss to the atmosphere. The IDW will be segregated at the site according to matrix (solid or liquid) and as to how it was derived (soil cuttings or decontamination fluids). Each container will be properly labeled with site identification, date, sampling point, depth, matrix, and constituents of concern. IDW that is expected to be generated during the investigation includes the following:

- Used sampling equipment
- Decontamination fluids
- Used paper towels
- Used PPE

9.0 Sample Documentation and Shipment

9.1 Field Notes

9.1.1 Field Logbooks and Data Forms

Field logbooks (or daily logs) and data forms are necessary to document daily activities and observations. Documentation will be sufficient to enable reconstruction of events that occurred during the project accurately and objectively at a later time. The PM and field manager are responsible for ensuring that logbook entries provide sufficient information for the completion of an accurate and detailed description of field operations.

A field logbook will be used to summarize the work performed each day, identify individuals involved in performing the work, and describe weather conditions and prominent site features. A site sketch may be included to indicate site features. If applicable, the field logbook will also be used to record information pertaining to monitoring equipment used, identify site visitors, describe photographs taken, and document work plan deviations.

Certain phases of fieldwork may require the use of project-specific data collection forms. The field forms that will be used for this project are provided in Attachment 1.

If corrections to the field logbook or data forms are necessary, they must be made by using a blue or black ink pen, drawing a single line through the original entry in such a manner that it can still be read. Do not erase or render an incorrect notation illegible. The corrected entry should be written beside the incorrect entry, and the correction must be initialed and dated. Most corrected errors will require a footnote explaining the correction.

9.1.2 Photographs

Photographs will be taken as directed by the PM and/or field manager. Documentation of a photograph is crucial to ensure its validity as a representation of an existing situation. After the photographs are taken, they will be documented in the field log book and summarized in captions in the digital photographic log.

9.2 Sample Identification

9.2.1 Sample Numbering

A descriptive ID number will be assigned for data tracking and storage. These ID numbers will be recorded on each sample container and on field data sheets and notebook maintained by field personnel. Sample ID numbers will be designated by a three-part code consisting of an area identifier (A1 for Area 1), location identifier (FL01 for floor samples and SW01 for sidewall samples plus sequential locations, if necessary), and a numerical suffix to indicate the depth of the sample. Proposed sample IDs are presented in Table 5. Field QC samples such as duplicates, trip blanks, and equipment blanks will be assigned sample IDs similar to the non-QC samples so as to not reveal the origin of the sample.

9.2.2 Sample Labeling

All samples collected will be labeled in a clear and precise way for proper identification in the field and for tracking in the laboratory. The samples will have pre-assigned, identifiable, and unique numbers as described in Section 9.2.1. The sample labels will be placed on containers in a manner that will not obscure any container quality assurance/control lot numbers, and sample information will be printed legibly.

To minimize handling of sample containers, labels will be filled out before sample collection with the exception of the sampling date and time, which will be added at the time of sample collection. Each sample label will be written in waterproof ink and attached firmly to the sample containers. At a minimum, the sample labels will contain the following information.

- Sample designation code
- Date and time of collection
- Analysis required
- Preservation (when applicable)

Every sample, including samples collected from a single location but going to separate laboratories, will be assigned a unique sample number.

9.3 Sample Chain-of-Custody Forms and Custody Seals

COC and custody seal procedures are discussed below. An example COC form is provided in Attachment 1.

9.3.1 Chain-of Custody

The primary objective of COC procedures is to provide an accurate written or computerized record that can be used to trace the possession and handling of a sample from collection to completion of all required analyses. A sample is considered to be in custody if it is under one of the conditions listed below:

- In someone's physical possession
- In someone's view
- Locked up
- Kept in a secured area that allows authorized personnel only

COC records document sample collection and shipment to the laboratory. A COC form will be completed for each sampling event. The original copy will be provided to the laboratory with the sample-shipping cooler, and a copy will be retained in the field documentation files. The COC form will identify the contents of each shipment and maintain the custodial integrity of the samples. All COC forms will be signed and dated by the responsible sampling team personnel. The "relinquished by" box will be signed by the responsible sampling team personnel, and the date, time, and air bill number will be noted on the COC form. The laboratory will return the executed copy of the COC with the certified analytical report. The shipping coolers containing the samples will be sealed with a custody seal any time they are not in someone's possession or view before shipping. All custody seals will be signed and dated by the responsible sampling team personnel.

At a minimum, the following information must be documented on the COC form.

- Unique sample ID
- Date and time of sample collection
- Source of sample (including name, location, sample type, and matrix)
- Number of containers
- Designation of MS/MSD
- Preservative used
- Analyses required
- Name of sampler
- Custody transfer signatures and dates and times of sample transfer from the field to transporters and to the laboratory

If samples require rapid laboratory turnaround, the person completing the COC record will note these or similar requirements in the remarks section of the custody record. The relinquishing individual will record pertinent shipping data (e.g., shipping organization, time, and date) on the original custody record, which will be transported with the samples to the laboratory and retained in the laboratory's file. Field personnel will retain a copy of the COC included with the sample shipment. Original custody records with the sample condition upon receipt form, which includes the shipment tracking number, constitute a complete custody record. The field manager will ensure that all records are consistent and that they are made part of the permanent job file.

9.3.1.1 Field Custody Procedures

The sample collector will be responsible for the care and custody of samples until they are transferred to another person. The sample collector will record sample data in the COC form. A sample COC form (F-1000) is included in Attachment 1. When custody is transferred, the individuals relinquishing and receiving them must sign, date, and note the time on the COC record. All shipments will be accompanied by COC records identifying their contents. Shipping containers will be sealed with custody seals for shipment to the laboratory. The method of shipment, name of courier, and other pertinent information will be entered in the COC record.

9.3.1.2 Laboratory Custody Procedures

Once the samples reach the laboratory, they will be checked against information on the COC form for anomalies. The condition, temperature, and appropriate preservation of samples will be checked and documented on the COC or laboratory sample receipt form. The occurrence of any anomalies in the received samples and their resolution will be documented in laboratory records. All sample information will then be entered into a tracking system, and unique analytical sample IDs will be assigned. Internal custody records must be maintained by the laboratory as part of the documentation file for each sample.

9.3.2 Custody Seals

The shipping containers in which samples are stored (usually a sturdy cooler or ice chest) will be sealed with self-adhesive custody seals any time they are not in someone's possession or view before shipping. All custody seals will be signed and dated.

10.0 Field Changes

As conditions in the field may vary, it may become necessary to implement modifications to sampling as presented in this SAP. For minor modifications that do not affect the ability to meet DQOs and do not have significant cost or schedule impacts, the individual performing the task is required to use his/her judgement as to the best approach toward satisfactory completion of the task and when appropriate will consult with the field manager or PM prior to implementing the change. For major modifications that may lead to significant cost or schedule impacts, the field manager will notify the SMUD PM prior to implementing the change. For major modifications that affect the ability to meet DQOs, regardless of whether there are potential cost or schedule impacts, the SMUD PM will obtain approval from the DTSC PM prior to implementing the change. A discussion of all implemented field changes will be included in the Interim Removal Action Completion Report.

11.0 Field Health and Safety Procedures

All field work will be performed in accordance with the health and safety procedures outlined in the Health and Safety Plan (HASP). The HASP provides information regarding anticipated site health and safety hazards, and establishes policies and procedures adequate to protect site workers, the public, and the environment from the anticipated site hazards for field activities being conducted by the prime contractor and its subcontractors. In the event that conditions at the site are different from those anticipated, the HASP will be modified accordingly in coordination with and approved by the project health and safety manager.

12.0 References

AECOM Technical Services, Inc. (AECOM). 2021. *Site Characterization Report Addendum, SMUD 59th Street Corporation Yard, 1708 59th Street, Sacramento, California 95819.* May.

California Department of Toxic Substances Control (DTSC). 2001. *Information Advisory, Clean Imported Fill Material*. October.

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San Francisco Bay Regional Water Quality Control Board. 2019. *ESL Summary Tables, 2019 (Rev. 2)*. July 25.

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______. 2021. *Regional Screening Level (RSL) Summary Table (TR=1E-06, HQ=1) November 2021*. Available at https://semspub.epa.gov/work/HQ/400750.pdf. November.

Tables

Table 1
Key Project Personnel Contact Information and Responsibilities
(Page 1 of 1)

Title	Name	Phone Number Email Address	Responsibilities
California DTSC			
Project Manager	Peter Ruttan	Office: (916) 255-3777 Peter.Ruttan@dtsc.ca.gov	Regulatory review and oversight.
SMUD			
Project Manager	Keegan George, PE	Office: (916) 732-5548 Mobile: (916) 847-3086 Keegan.George@smud.org	Compliance review and oversight.
AECOM			
Project Manager	Andrew Shepard	Office: (916) 361-6425 Mobile: (916) 296-3943 andy.shepard@aecom.com	Confirmation and waste characterization management.
Project Chemist / Quality Assurance Manager	Stacy Louie	Office: (916) 361-6429 stacy.louie@aecom.com	Quality and chemistry oversight.
SH&E Manager	Shannon Couch, CSP	Mobile: (510) 277-5369 shannon.couch@aecom.com	Safety oversight.
Field Manager	Andrew Archuleta	Mobile: (916) 208-2639 andrew.archuleta@aecom.com	Confirmation and waste characterization sampling.
Pace Analytical®			
Project Manager	Kaylee Mayall	Office: (661) 852-4215 kaylee.mayall@pacelabs.com	Analytical laboratory and reporting.

Notes:

CSP = Certified Safety Professional
DTSC = Department of Toxic Substances Control
Pace Analytical® = Pace Analytical® Services, LLC
PE = Professional Engineer
SH&E = Safety, Health, and Environment
SMUD = Sacramento Municipal Utilities District

Table 2
Data Quality Objectives
(Page 1 of 2)

Step	Data Quality Objectives
1. State the Problem	1. Arsenic is present in soil at concentrations above background levels. 2. Lead and $TPH_{ho/mo}$ are present in soil at concentrations above their respective screening levels. 3. Elevated concentrations of VOCs are present in soil gas in the soil gas source area.
2. Identify the Goal of the Study	1. Mitigate the onsite exposure risk through inhalation, dermal absorption, and ingestion by excavating and disposing of onsite soil exceeding removal action cleanup goals. 2. Upon completion of the removal action, restore the onsite area to a condition to that which existed prior to the removal action. 3. Monitor compliance with the LUC restrictions until the removal action cleanup goals are achieved.
3. Identify the Information Inputs	1. Analytical results from waste characterization samples. 2. Analytical results from soil confirmation samples. 3. Analytical results from backfill samples. 4. XRF field screening data. 5. PID field screening data. 6. Field parameters (dust monitor and PID readings) measured during excavation and soil handling activities. 7. Survey coordinates corresponding to excavation activities.
4. Define the Study Boundaries	1. The study will be conducted at the SMUD 59th Street Corporation Yard and is limited to the onsite portion of the yard, north of the Sacramento Regional Transit Light Rail line. 2. The excavation will be limited to the upper 15 feet of soil within the contaminated onsite area, excluding the Warehouse Building/loading dock footprints, or to the extents verified by XRF/PID field screening data and confirmation sample results. 3. The excavated soil will be disposed of at appropriate offsite disposal facilities.
5. Develop the Analytic Approach	1. If soil confirmation sample analytical results exceed the cleanup goals established in the Interim RAW, then additional excavation will be conducted. 2. If XRF field screening data indicate concentrations exceed the cleanup goals established in the Interim RAW, then additional excavation will be conducted. 3. If PID field screening data indicate VOC concentrations exceed 5 parts per million, then additional excavation will be conducted. 4. Waste characterization sample results will be compared to the total threshold limit concentration and the screening values for both STLC and TCLP, where applicable. If any of the limits are exceeded, additional analyses may need to be performed to determine the classification of the waste for disposal (i.e., non-hazardous, non-RCRA hazardous, or RCRA hazardous). 5. If the excavation side slope sample results exceed the cleanup goals established in the Interim RAW, then the material will not be considered “clean” and therefore not used as backfill. 6. If virgin Class II aggregate base sample results exceed DTSC residential SLs (DTSC, 2020), USEPA residential RSLs (USEPA, 2021), or San Francisco Bay RWQCB groundwater protection ESLs (RWQCB, 2019), then the material will not be considered “clean” and therefore not used as backfill.
6. Specify Performance or Acceptance Criteria	1. Field data must meet all requirements of the SAP, including the sample documentation requirements in Section 9.0. A PID and XRF analyzer will be utilized for field screening soils to determine the preliminary extents of excavation. 2. Laboratory data must meet all requirements of the SAP, including the laboratory accuracy and precision limits in Table 4 and the laboratory method-specific quality control acceptance criteria. Laboratory data will be utilized to confirm if removal objectives have been met.

Table 2
Data Quality Objectives
(Page 2 of 2)

Step	Data Quality Objectives
7. Develop the Plan for Obtaining Data	1. Field work will be performed in accordance with this SAP to ensure consistency. 2. Collect field screening data utilizing a PID and XRF analyzer during excavation activities from excavation floors and sidewalls. 3. Collect floor and sidewall confirmation soil samples from excavation Areas 1 through 9. 4. Collect four-point composite samples from backfill sources in accordance with DTSC guidance. 5. Collect four-point composite pre-design waste characterization soil samples prior to excavation activities or four-point composite waste characterization soil samples after excavation activities. 6. Analyze samples for contaminants of concern using a certified laboratory and approved analytical methods.

Notes:

DTSC = California Department of Toxic Substances Control
ESL = environmental screening level
i.e. = *id est*, that is
LUC = land use covenant
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
PID = photoionization detector
RAW = Remedial Action Workplan
RCRA = Resource Conservation and Recovery Act
RSL = regional screening level
RWQCB = Regional Water Quality Control Board
SAP = Sampling and Analysis Plan
SL = screening level
SMUD = Sacramento Municipal Utility District
STLC = soluble threshold limit concentration
TCLP = toxicity characteristic leaching procedure
$TPH_{ho/mo}$ = total petroleum hydrocarbons as hydraulic oil/motor oil
USEPA = United States Environmental Protection Agency
VOC = volatile organic compound
XRF = x-ray fluorescence

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
(Page 1 of 8)

Laboratory Measurement	Pace Analytical® (2022)			Soil (mg/kg)	
	Method	MDL[a] (mg/kg)	PQL[a] or MRL[a] (mg/kg)	DTSC SLs [b]	RWQCB ESLs[c]
				Residential	Groundwater Protection (drinking water) (Table S-3)
Antimony	SW6010	0.33	5.0	**31**	-
Arsenic		0.40	1.0	**0.11**[d]	-
Barium		0.18	0.50	**15,000**	-
Beryllium		0.047	0.50	**1,600**	-
Cadmium		0.052	0.50	**910**	-
Chromium		0.05	0.50	-	-
Cobalt		0.098	2.5	**23**	-
Copper		0.05	1.0	**3,100**	-
Lead		0.28	2.5	***80***	-
Molybdenum		0.05	2.5	**390**	-
Nickel		0.15	0.50	**15,000**	-
Selenium		0.98	1.0	**390**	-
Silver		0.067	0.50	**390**	-
Thallium		0.64	5.0	**0.78**	-
Vanadium		0.11	0.50	**390**	-
Zinc		0.087	2.5	**23,000**	-
Arsenic (in mg/L)	STLC 6010	0.12	0.5	-	-
Lead (in mg/L)		0.13	0.5	-	-
Arsenic (in mg/L)	TCLP 6010	0.083	0.2	-	-
Lead (in mg/L)		0.03	0.5	-	-
Lead (in mg/L)	SPLP 6010	0.03	0.5	-	-
Antimony	SW6020	0.16	1.0	**31**	-
Arsenic		0.17	0.5	**0.11**[d]	-
Barium		0.054	0.25	**15,000**	-
Beryllium		0.041	0.25	**1,600**	-
Cadmium		0.048	0.25	**910**	-
Chromium		0.25	0.75	-	-
Cobalt		0.049	0.25	**23**	-
Copper		0.099	0.5	**3,100**	-
Lead		0.12	0.25	***80***	-
Molybdenum		0.045	0.25	**390**	-
Nickel		0.11	0.5	**15,000**	-
Selenium		0.11	0.5	**390**	-
Silver		0.051	0.25	**390**	-
Thallium		0.049	0.25	**0.78**	-
Vanadium		0.27	0.75	**390**	-
Zinc		0.5	1.3	**23,000**	-
Arsenic (in mg/L)	STLC 6020	-	-	-	-
Lead (in mg/L)		-	-	-	-
Arsenic (in mg/L)	TCLP 6020	-	-	-	-
Lead (in mg/L)		-	-	-	-
Mercury	SW7471	0.016	0.16	***1.0***	-
Gasoline Range Organics	SW8015	0.22	1.0	**82**	1,100
Diesel Range Organics		1.3	10	**97**	1,100
Motor Oil		6.5	20	**2,400**	-

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
(Page 2 of 8)

Laboratory Measurement	Pace Analytical® (2022)			Soil (mg/kg)	
				DTSC SLs (b)	RWQCB ESLs(c)
	Method	MDL(a) (mg/kg)	PQL(a) or MRL(a) (mg/kg)	Residential	Groundwater Protection (drinking water) (Table S-3)
Aldrin	SW8081A	0.000018	0.0010	**0.039**	8.4
alpha-BHC		0.000038	0.0010	**0.086**	-
beta-BHC		0.000048	0.0020	**0.3**	-
delta-BHC		0.000037	0.0010	-	-
gamma-BHC (Lindane)		0.000018	0.0010	0.57	**0.0074**
alpha-Chlordane		0.000062	0.0010	36	**23 (e)**
gamma-Chlordane		0.00008	0.0010	36	**23 (e)**
Chlordane (Technical)		0.0010	0.10	**1.7**	23 (e)
4,4'-DDD		0.000064	0.0010	**2.3**	65
4,4'-DDE		0.000095	0.0010	**2.0**	29
4,4'-DDT		0.00004	0.0010	**1.9**	5.6
Dieldrin		0.000036	0.0010	0.034	**0.00046**
Endosulfan I		0.00002	0.0010	*450*	**0.0098 (f)**
Endosulfan II		0.000034	0.0010	*450*	**0.0098 (f)**
Endosulfan sulfate		0.000026	0.0010	***380***	-
Endrin		0.000065	0.0010	*19*	**0.0076**
Endrin aldehyde		0.000018	0.0010	-	-
Endrin ketone		0.000065	0.0010	-	-
Heptachlor		0.000086	0.0010	**0.13**	44
Heptachlor epoxide		0.000017	0.0010	0.07	**0.00018**
Methoxychlor		0.000094	0.0010	*320*	**0.013**
Toxaphene		0.0014	0.010	**0.45**	250
PCB-1016	SW8082A	0.0023	0.020	**6.6**	-
PCB-1221		0.0033	0.020	**0.20**	-
PCB-1232		0.0026	0.020	**0.17**	-
PCB-1242		0.0015	0.020	**0.23**	-
PCB-1248		0.0021	0.020	**0.23**	-
PCB-1254		0.0016	0.020	**0.24**	-
PCB-1260		0.0018	0.020	**0.24**	-
PCB-1262		0.0023	0.020	-	-
PCB-1268		0.0036	0.020	-	-
Total PCBs		0.0050	0.020	**0.23**	330
2,4-D	SW8151A	0.0030	0.040	***700***	-
2,4-DB		0.0067	0.080	***1,900***	-
Dalapon		0.0068	0.020	***1,900***	-
Dicamba		0.00057	0.0040	***1,900***	-
Dichloroprop		0.0037	0.040	-	-
Dinoseb		0.0020	0.010	***63***	-
Pentachlorophenol		0.00040	0.0020	1.0	**0.098**
2,4,5-T		0.0011	0.0060	***630***	-
2,4,5-TP (Silvex)		0.00073	0.0060	***510***	-
1,1,1,2-Tetrachloroethane	SW8260B	0.00095	0.0050	2.0	**0.017**
1,1,1-Trichloroethane		0.00067	0.0050	*1,700*	**7.0**
1,1,2,2-Tetrachloroethane		0.00084	0.0050	0.6	**0.018**
1,1,2-Trichloro-1,2,2-trifluoroethane		0.001	0.0050	***6,700***	-
1,1,2-Trichloroethane		0.00094	0.0050	1.1	**0.076**

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
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Laboratory Measurement	**Pace Analytical® (2022)**			**Soil (mg/kg)**	
				DTSC SLs (b)	**RWQCB ESLs(c)**
	Method	**MDL(a) (mg/kg)**	**PQL(a) or MRL(a) (mg/kg)**	**Residential**	**Groundwater Protection (drinking water) (Table S-3)**
1,1-Dichloroethane	SW8260B	0.00064	0.0050	3.6	**0.20**
1,1-Dichloroethene		0.0011	0.0050	*83*	**0.54**
1,1-Dichloropropene		0.00067	0.0050	-	-
1,2,3-Trichlorobenzene		0.0015	0.0050	***40***	-
1,2,3-Trichloropropane		0.0019	0.0050	0.0015	**0.00011**
1,2,4-Trichlorobenzene		0.0014	0.0050	7.8	**1.2**
1,2,4-Trimethylbenzene		0.0008	0.0050	**300**	-
1,2-Dibromo-3-chloropropane		0.00096	0.0050	0.0043	**0.00059**
1,2-Dibromoethane		0.00082	0.0050	0.036	**0.00053**
1,2-Dichlorobenzene		0.00079	0.0050	1,800	**1.0**
1,2-Dichloroethane		0.00073	0.0050	0.46	**0.0070**
1,2-Dichloropropane		0.0008	0.0050	2.5	**0.065**
1,3,5-Trimethylbenzene		0.00066	0.0050	**270**	-
1,3-Dichlorobenzene		0.00073	0.0050	-	**7.4**
1,3-Dichloropropane		0.00067	0.0050	***410***	-
1,4-Dichlorobenzene		0.00073	0.0050	2.6	**0.20**
1,4-Dioxane		0.052	0.30	5.3	**0.00017**
2,2-Dichloropropane		0.00067	0.0050	-	-
2-Chlorotoluene		0.00087	0.0050	***470***	-
2-Hexanone		0.0032	0.010	**200**	-
4-Chlorotoluene		0.0007	0.0050	***440***	-
Acetone		0.009	0.020	61,000	**0.92**
Acrolein		0.0053	0.050	**0.14**	-
Acrylonitrile		0.002	0.020	**0.25**	-
Benzene		0.00067	0.0050	0.33	**0.025**
Bromobenzene		0.00087	0.0050	**290**	-
Bromochloromethane		0.00081	0.0050	**150**	-
Bromodichloromethane		0.00078	0.0050	0.29	**0.016**
Bromoform		0.0007	0.0050	19	**0.69**
Bromomethane		0.0017	0.0050	6.8	**0.36**
Carbon disulfide		0.0005	0.0050	**770**	-
Carbon tetrachloride		0.00078	0.0050	0.65	**0.076**
Chlorobenzene		0.00077	0.0050	280	**1.4**
Chloroethane		0.0011	0.0050	14,000	**1.2**
Chloroform		0.0009	0.0050	0.32	**0.023**
Chloromethane		0.0011	0.0050	110	**11**
cis-1,2-Dichloroethene		0.00054	0.0050	*18*	**0.19**
cis-1,3-Dichloropropene		0.00058	0.0050	1.8 (g)	**0.017 (g)**
Dibromochloromethane		0.0008	0.0050	0.94	**0.35**
Dibromomethane		0.0014	0.0050	**0.036**	-
Dichlorodifluoromethane		0.00079	0.0050	**87**	-
Diisopropyl ether		0.00057	0.0050	**2,200**	-
Ethyl t-butyl ether		0.0005	0.0050	-	-
Ethylbenzene		0.00069	0.0050	5.8	**0.43**
Hexachlorobutadiene		0.00067	0.0050	1.2	**0.028**
Isopropylbenzene		0.0008	0.0050	**1,900**	-

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
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Laboratory Measurement	Pace Analytical® (2022)			Soil (mg/kg)	
				DTSC SLs [b]	RWQCB ESLs[c]
	Method	MDL[a] (mg/kg)	PQL[a] or MRL[a] (mg/kg)	Residential	Groundwater Protection (drinking water) (Table S-3)
Methyl ethyl ketone	SW8260B	0.0025	0.010	27,000	**6.1**
Methyl isobutyl ketone		0.005	0.050	33,000	**0.36**
Methyl t-butyl ether		0.00056	0.0050	47	**0.028**
Methylene chloride		0.0011	0.010	2.2	**0.12**
Naphthalene		0.00099	0.0050	2.0	**0.042**
n-Butylbenzene		0.00076	0.0050	**3,900**	-
n-Propylbenzene		0.00071	0.0050	**3,800**	-
o-Xylene		0.00093	0.0050	**650**	-
p- & m-Xylenes		0.0015	0.0050	**550**	-
p-Isopropyltoluene		0.00059	0.0050	-	-
sec-Butylbenzene		0.00071	0.0050	***2,200***	-
Styrene		0.00062	0.0050	*5,600*	**0.92**
t-Amyl Methyl ether		0.0005	0.0050	-	-
t-Butyl alcohol		0.012	0.050	-	**0.075**
tert-Butylbenzene		0.00085	0.0050	***2,200***	-
Tetrachloroethene		0.00097	0.0050	0.59	**0.080**
Toluene		0.00069	0.0050	*1,100*	**3.2**
Total 1,2-Dichloroethene		0.0043	0.010	-	-
Total 1,3-Dichloropropene		0.0013	0.010	**1.8** [g]	**0.017**
Total Purgeable Petroleum Hydrocarbons		0.058	0.20	**82**	-
Total Xylenes		0.0025	0.010	580	**2.1**
trans-1,2-Dichloroethene		0.0037	0.0050	*130*	**0.65**
trans-1,3-Dichloropropene		0.00066	0.0050	1.8 [g]	**0.17** [g]
Trichloroethene		0.00074	0.0050	0.94	**0.085**
Trichlorofluoromethane		0.0015	0.0050	***1,200***	-
Vinyl chloride		0.00059	0.0050	0.0082	**0.0015**
2,2-Dichloro-1,1,1-trifluoroethane	STLC SW8260	0.00010	0.00050	-	-
Benzene		0.000083	0.00050	-	-
Bromobenzene		0.00013	0.00050	-	-
Bromochloromethane		0.00024	0.00050	-	-
Bromodichloromethane		0.00014	0.00050	-	-
Bromoform		0.00027	0.00050	-	-
Bromomethane		0.00025	0.0010	-	-
n-Butylbenzene		0.00011	0.00050	-	-
sec-Butylbenzene		0.00015	0.00050	-	-
tert-Butylbenzene		0.00013	0.00050	-	-
Carbon tetrachloride		0.00018	0.00050	-	-
Chlorobenzene		0.000093	0.00050	-	-
Chloroethane		0.00014	0.00050	-	-
Chloroform		0.00012	0.00050	-	-
Chloromethane		0.00014	0.00050	-	-
2-Chlorotoluene		0.00020	0.00050	-	-
4-Chlorotoluene		0.00015	0.00050	-	-
Dibromochloromethane		0.00013	0.00050	-	-
1,2-Dibromo-3-chloropropane		0.00044	0.0010	-	-
1,2-Dibromoethane		0.00016	0.00050	-	-

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
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Laboratory Measurement	Pace Analytical® (2022)			Soil (mg/kg)	
	Method	MDL[(a)] (mg/kg)	PQL[(a)] or MRL[(a)] (mg/kg)	DTSC SLs [(b)]	RWQCB ESLs[(c)]
				Residential	Groundwater Protection (drinking water) (Table S-3)
Dibromomethane	STLC SW8260	0.00024	0.00050	-	-
1,2-Dichlorobenzene		0.000072	0.00050	-	-
1,3-Dichlorobenzene		0.00015	0.00050	-	-
1,4-Dichlorobenzene		0.000062	0.00050	-	-
Dichlorodifluoromethane		0.000099	0.00050	-	-
1,1-Dichloroethane		0.00011	0.00050	-	-
1,2-Dichloroethane		0.00017	0.00050	-	-
1,1-Dichloroethene		0.00018	0.00050	-	-
cis-1,2-Dichloroethene		0.000085	0.00050	-	-
trans-1,2-Dichloroethene		0.00015	0.00050	-	-
Total 1,2-Dichloroethene		0.00023	0.0010	-	-
1,2-Dichloropropane		0.00013	0.00050	-	-
1,3-Dichloropropane		0.000086	0.00050	-	-
2,2-Dichloropropane		0.00013	0.00050	-	-
1,1-Dichloropropene		0.000085	0.00050	-	-
cis-1,3-Dichloropropene		0.00014	0.00050	-	-
trans-1,3-Dichloropropene		0.000079	0.00050	-	-
Total 1,3-Dichloropropene		0.00021	0.0010	-	-
Ethylbenzene		0.000098	0.00050	-	-
Hexachlorobutadiene		0.00017	0.00050	-	-
Isopropylbenzene		0.00014	0.00050	-	-
p-Isopropyltoluene		0.00012	0.00050	-	-
Methylene chloride		0.00048	0.0010	-	-
Methyl t-butyl ether		0.00011	0.00050	-	-
Naphthalene		0.00036	0.00050	-	-
n-Propylbenzene		0.00011	0.00050	-	-
Styrene		0.000068	0.00050	-	-
1,1,1,2-Tetrachloroethane		0.00018	0.00050	-	-
1,1,2,2-Tetrachloroethane		0.00017	0.00050	-	-
Tetrachloroethene		0.00013	0.00050	-	-
Toluene		0.000093	0.00050	-	-
1,2,3-Trichlorobenzene		0.00016	0.00050	-	-
1,2,4-Trichlorobenzene		0.00019	0.00050	-	-
1,1,1-Trichloroethane		0.00011	0.00050	-	-
1,1,2-Trichloroethane		0.00016	0.00050	-	-
Trichloroethene		0.000085	0.00050	-	-
Trichlorofluoromethane		0.00013	0.00050	-	-
1,2,3-Trichloropropane		0.00024	0.0010	-	-
1,1,2-Trichloro-1,2,2-trifluoroethane		0.00015	0.00050	-	-
1,2,4-Trimethylbenzene		0.00012	0.00050	-	-
1,3,5-Trimethylbenzene		0.00012	0.00050	-	-
Vinyl chloride		0.00012	0.00050	-	-
Total Xylenes		0.00036	0.0010	-	-
Total Trihalomethanes		0.00063	0.0020	-	-
Acetone		0.0046	0.010	-	-
Acetonitrile		0.0055	0.010	-	-

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
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Laboratory Measurement	Pace Analytical® (2022)			Soil (mg/kg)	
	Method	MDL[a] (mg/kg)	PQL[a] or MRL[a] (mg/kg)	DTSC SLs [b]	RWQCB ESLs[c]
				Residential	Groundwater Protection (drinking water) (Table S-3)
Acrolein	STLC SW8260	0.0079	0.020	-	-
Acrylonitrile		0.0012	0.0050	-	-
Allyl chloride		0.00080	0.0050	-	-
t-Amyl Methyl ether		0.00025	0.00050	-	-
Benzyl chloride		0.00060	0.0050	-	-
t-Butyl alcohol		0.0094	0.010	-	-
Carbon disulfide		0.00038	0.0010	-	-
2-Chloroethyl vinyl ether		0.0024	0.010	-	-
1-Chlorohexane		0.0020	0.0050	-	-
Chloroprene		0.00037	0.0050	-	-
Cyclohexane		0.00015	0.00050	-	-
Cyclohexanone		0.014	0.20	-	-
trans-1,4-Dichloro-2-butene		0.0014	0.0050	-	-
Diisopropyl ether		0.00023	0.00050	-	-
1,4-Dioxane		0.042	0.10	-	-
Ethanol		0.050	0.25	-	-
Ethyl methacrylate		0.00097	0.0040	-	-
Ethyl t-butyl ether		0.00018	0.00050	-	-
Hexane		0.00023	0.00050	-	-
2-Hexanone		0.0034	0.010	-	-
Isobutanol		0.0077	0.020	-	-
Isopropyl alcohol		0.0093	0.10	-	-
Methacrylonitrile		0.0017	0.010	-	-
Methylcyclohexane		0.00025	0.00050	-	-
Methyl ethyl ketone		0.0025	0.010	-	-
Methyl iodide		0.00047	0.0020	-	-
Methyl isobutyl ketone		0.0021	0.010	-	-
Methyl methacrylate		0.0015	0.0050	-	-
Pentachloroethane		0.00043	0.0020	-	-
Propionitrile		0.0042	0.020	-	-
Tetrahydrofuran		0.0052	0.020	-	-
Vinyl acetate		0.0018	0.010	-	-
p- & m-Xylenes		0.00028	0.00050	-	-
o-Xylene		0.000082	0.00050	-	-
Total Purgeable Petroleum Hydrocarbons		0.0072	0.050	-	-
1,2,4-Trichlorobenzene	SW8270C	0.0067	0.20	7.8	**1.2**
1,2-Dichlorobenzene		0.0067	0.20	1,800	**1.0**
1,3-Dichlorobenzene		0.0067	0.20	-	**7.4**
1,4-Dichlorobenzene		0.0067	0.20	2.6	**0.20**
1-Chloronaphthalene		0.0067	0.20	-	-
2,3,4,6-Tetrachlorophenol		0.020	1.0	***1,900***	-
2,4,5-Trichlorophenol		0.011	0.40	*6,300*	**2.9**
2,4,6-Trichlorophenol		0.0067	0.40	7.8	**0.040**
2,4-Dichlorophenol		0.0067	0.20	*190*	**0.0075**
2,4-Dimethylphenol		0.0067	0.20	*1,300*	**8.1**
2,4-Dinitrophenol		0.0067	1.0	*130*	**3.0**

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
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Laboratory Measurement	Pace Analytical® (2022)			Soil (mg/kg)	
	Method	MDL[a] (mg/kg)	PQL[a] or MRL[a] (mg/kg)	DTSC SLs [b]	RWQCB ESLs[c]
				Residential	Groundwater Protection (drinking water) (Table S-3)
2,4-Dinitrotoluene	SW8270C	0.0085	0.20	1.7	**0.023**
2,6-Dichlorophenol		0.0085	1.0	-	-
2,6-Dinitrotoluene		0.0067	0.20	**0.36**	-
2-Chloronaphthalene		0.0067	0.20	**4,100**	-
2-Chlorophenol		0.0067	0.20	340	**0.012**
2-Methylnaphthalene		0.0067	0.20	190	**0.88**
2-Methylphenol		0.0067	0.20	**3,200**	-
2-Nitroaniline		0.0067	0.20	**630**	-
2-Nitrophenol		0.0067	0.20	-	-
3- & 4-Methylphenol		0.014	0.40	**3,200/6,300**	-
3,3-Dichlorobenzidine		0.0067	0.40	0.45	**0.025**
3-Nitroaniline		0.0067	0.20	-	-
4,6-Dinitro-2-methylphenol		0.0067	1.0	***5.1***	-
4-Bromophenyl phenyl ether		0.0067	0.20	-	-
4-Chloro-3-methylphenol		0.0067	0.40	***6,300***	-
4-Chloroaniline		0.015	0.20	2.7	**0.0067**
4-Chlorophenyl phenyl ether		0.0067	0.20	-	-
4-Nitroaniline		0.011	0.40	**27**	-
4-Nitrophenol		0.018	0.40	-	-
Acenaphthene		0.0067	0.20	*3,300*	**12**
Acenaphthylene		0.0067	0.20	-	**6.4**
Aniline		0.011	0.40	**95**	-
Anthracene		0.0067	0.20	*17,000*	**1.9**
Benzidine		0.0093	6.0	**0.00024**	-
Benzo[a]anthracene		0.0077	0.20	**1.1**	10
Benzo[a]pyrene		0.0067	0.20	**0.11**	5.7
Benzo[b]fluoranthene		0.0067	0.20	**1.1**	5.4
Benzo[g,h,i]perylene		0.013	0.20	-	**27**
Benzo[k]fluoranthene		0.0082	0.20	11	**4.8**
Benzyl alcohol		0.0067	0.20	***6,300***	-
Benzyl butyl phthalate		0.0067	0.20	***290***	-
bis(2-Chloroethoxy)methane		0.0067	0.20	***190***	-
bis(2-Chloroethyl) ether		0.0097	0.20	0.1	**0.000034**
bis(2-Ethylhexyl)phthalate		0.0067	0.40	**39**	190
Carbazole		0.0067	0.20	-	-
Chrysene		0.0067	0.20	110	**2.2**
Dibenzo[a,h]anthracene		0.0067	0.20	**0.028**	29
Dibenzofuran		0.0067	0.20	***66***	-
Diethyl phthalate		0.0067	0.20	*51,000*	**0.025**
Dimethyl phthalate		0.0067	0.20	7,800	**0.035**
Di-n-butyl phthalate		0.0067	0.20	***6,300***	-
Di-n-octyl phthalate		0.0067	0.20	***630***	-
Fluoranthene		0.0067	0.20	*2,400*	**86**
Fluorene		0.0067	0.20	*2,300*	**6.0**
Hexachlorobenzene		0.0067	0.20	0.19	**0.00080**
Hexachlorobutadiene		0.0067	0.20	1.2	**0.028**
Hexachlorocyclopentadiene		0.015	0.20	**1.8**	-

Table 3
Achievable Laboratory Limits and Risk-Based Screening Values, Soil Parameters
(Page 8 of 8)

Laboratory Measurement	**Pace Analytical® (2022)**			**Soil (mg/kg)**	
	Method	**MDL[a] (mg/kg)**	**PQL[a] or MRL[a] (mg/kg)**	**DTSC SLs [b]**	**RWQCB ESLs[c]**
				Residential	**Groundwater Protection (drinking water) (Table S-3)**
Hexachloroethane	SW8270C	0.0067	0.20	1.8	**0.019**
Indeno[1,2,3-cd]pyrene		0.0069	0.20	**1.1**	16
Isophorone		0.0067	0.20	**570**	-
Naphthalene		0.0067	0.2	2.0	**0.042**
Nitrobenzene		0.0067	0.20	***5.1***	-
N-Nitrosodimethylamine		0.040	0.20	***0.0020***	-
N-Nitrosodi-N-propylamine		0.0067	0.20	**0.078**	-
N-Nitrosodiphenylamine		0.0067	0.20	**110**	-
Pentachlorophenol		0.017	0.40	1.0	**0.098**
Phenanthrene		0.0067	0.20	-	**11**
Phenol		0.0067	0.20	*19,000*	**0.16**
Pyrene		0.0067	0.20	*1,800*	**45**
Pyridine		0.065	1.0	***58***	-
Asbestos	OSHA ID-191	NA	NA	-	-

Notes:

Bold indicates the lowest comparable regulatory or screening value for each analyte.

¯ = No value

DTSC = Department of Toxic Substances Control

ESL = Environmental Screening Level

MDL = method detection limit

mg/kg = milligrams per kilogram

mg/L - milligrams per liter

MRL = method reporting limit

NE = not established

PQL = practical quantitation limit

RWQCB = Regional Water Quality Control Board

SL = screening level

SPLP = synthetic precipitation leaching procedure

STLC = soluble threshold limit concentration (also referred to as CAWET)

TCLP = toxicity characteristic leaching procedure

(a) Specific methods, MRLs/PQLs and MDLs are subject to change based on the laboratory capabilities at the time of sample submittal. Values are from Pace Analytical® Services, LLC.

(b) Residential SLs from *Human and Ecological Risk Office Human Health Risk Assessment Note 3; DTSC-modified Screening Levels* (California DTSC, 2020b). Cancer Endpoint (*non-cancer endpoint*).

Where DTSC values were not established, the default values used are residential USEPA RSLs (USEPA, 2021).

(c) Groundwater protection (drinking water) ESLs from *Summary of Soil ESLs* (San Francisco Bay RWQCB, 2019).

(d) Confirmation samples and side slope backfill material will be compared to the arsenic cleanup level of 17.53 mg/kg, and Virgin Class II aggregate base will be compared to an arsenic concentration of 11 mg/kg.

(e) Based on Chlordane

(f) Based on Endosulfan

(g) Based on 1,3-Dichloropropene

Table 4
Accuracy and Precision Limits
(Page 1 of 5)

Method	Parameter	Soil Samples		
		LCS Percent Recovery	MS/MSD Percent Recovery	RPDs
SW6010	Antimony	79-114	79-114	20
	Arsenic	82-111	82-111	20
	Barium	83-113	83-113	20
	Beryllium	83-113	83-113	20
	Cadmium	82-113	82-113	20
	Chromium	85-113	85-113	20
	Coblat	85-112	85-112	20
	Copper	81-117	81-117	20
	Lead	81-112	81-112	20
	Molybdenum	82-116	82-116	20
	Nickel	83-113	83-113	20
	Selenium	78-111	78-111	20
	Silver	82-112	82-112	20
	Thallium	83-111	83-111	20
	Vanadium	82-114	82-114	20
	Zinc	82-113	82-113	20
STLC SW6010	Arsenic	85-115	75-125	20
	Lead	85-115	75-125	20
TCLP SW6010	Arsenic	85-115	75-125	20
	Lead	85-115	75-125	20
SPLP SW6010	Lead	85-115	75-125	20
SW6020	Antimony	72-124	72-124	20
	Arsenic	82-118	82-118	20
	Barium	86-116	86-116	20
	Beryllium	80-120	80-120	20
	Cadmium	84-116	84-116	20
	Chromium	83-119	83-119	20
	Coblat	84-115	84-115	20
	Copper	84-119	84-119	20
	Lead	84-118	84-118	20
	Molybdenum	83-114	83-114	20
	Nickel	84-119	84-119	20
	Selenium	80-119	80-119	20
	Silver	83-118	83-118	20
	Thallium	83-118	83-118	20
	Vanadium	82-116	82-116	20
	Zinc	82-119	82-119	20
STLC SW6020	Arsenic	NA	NA	NA
	Lead	NA	NA	NA
TCLP SW6020	Arsenic	75-125	75-125	20
	Lead	75-125	75-125	20
SW7471	Mercury	80-124	80-124	20
SW8015 GRO	Gasoline Range Organics	79-122	79-122	30
SW8015 DRO/MRO	Diesel	38-132	38-132	30
	Motor Oil	-	-	-
SW8081A	Aldrin	45-136	45-136	30
	alpha-BHC	45-137	45-137	30
	beta-BHC	50-136	50-136	30
	delta-BHC	47-139	47-139	30
	gamma-BHC (Lindane)	49-135	49-135	30

Table 4
Accuracy and Precision Limits
(Page 2 of 5)

Method	Parameter	Soil Samples		
		LCS Percent Recovery	MS/MSD Percent Recovery	RPDs
SW8081A	alpha-Chlordane	54-133	54-133	30
	gamma-Chlordane	53-135	53-135	30
	Chlordane (Technical)	-	-	-
	4,4'-DDD	56-139	56-139	30
	4,4'-DDE	56-134	56-134	30
	4,4'-DDT	50-141	50-141	30
	Dieldrin	53-132	53-132	30
	Endosulfan I	53-132	53-132	30
	Endosulfan II	53-134	53-134	30
	Endosulfan sulfate	55-136	55-136	30
	Endrin	57-140	57-140	30
	Endrin aldehyde	35-137	35-137	30
	Endrin ketone	55-136	55-136	30
	Heptachlor	47-136	47-136	30
	Heptachlor epoxide	52-136	52-136	30
	Methoxychlor	52-143	52-143	30
	Toxaphene	-	-	-
SW8082A	PCB-1016	47-134	47-134	30
	PCB-1221	-	-	-
	PCB-1232	-	-	-
	PCB-1242	-	-	-
	PCB-1248	-	-	-
	PCB-1254	-	-	-
	PCB-1260	53-140	53-140	30
	PCB-1262	-	-	-
	PCB-1268	-	-	-
SW8151A	2,4-D	28-144	28-144	30
	2,4-DB	34-142	34-142	30
	Dalapon	10-160	10-160	30
	Dicamba	38-132	38-132	30
	Dichloroprop	28-155	28-155	30
	Dinoseb	5-130	5-130	30
	Pentachlorophenol	20-150	20-150	30
	2,4,5-T	31-138	31-138	30
	2,4,5-TP (Silvex)	43-129	43-129	30
SW8260B	1,1,1,2-Tetrachloroethane	78-125	78-125	20
	1,1,1-Trichloroethane	73-130	73-130	20
	1,1,2,2-Tetrachloroethane	70-124	70-124	20
	1,1,2-Trichloro-1,2,2-trifluoroethane	66-136	66-136	20
	1,1,2-Trichloroethane	78-121	78-121	20
	1,1-Dichloroethane	76-125	76-125	20
	1,1-Dichloroethene	70-131	70-131	20
	1,1-Dichloropropene	76-125	76-125	20
	1,2,3-Trichlorobenzene	66-130	66-130	20
	1,2,3-Trichloropropane	73-125	73-125	20
	1,2,4-Trichlorobenzene	67-129	67-129	20
	1,2,4-Trimethylbenzene	75-123	75-123	20
	1,2-Dibromo-3-chloropropane	61-132	61-132	20
	1,2-Dibromoethane	78-122	78-122	20
	1,2-Dichlorobenzene	78-121	78-121	20

Table 4
Accuracy and Precision Limits
(Page 3 of 5)

Method	Parameter	Soil Samples		
		LCS Percent Recovery	MS/MSD Percent Recovery	RPDs
SW8260B	1,2-Dichloroethane	73-128	73-128	20
	1,2-Dichloropropane	76-123	76-123	20
	1,3,5-Trimethylbenzene	73-124	73-124	20
	1,3-Dichlorobenzene	77-121	77-121	20
	1,3-Dichloropropane	77-121	77-121	20
	1,4-Dichlorobenzene	75-120	75-120	20
	1,4-Dioxane	55-138	55-138	20
	2,2-Dichloropropane	67-133	67-133	20
	2-Chlorotoluene	75-122	75-122	20
	2-Hexanone	53-145	53-145	20
	4-Chlorotoluene	72-124	72-124	20
	Acetone	36-164	36-164	20
	Acrolein	47-155	47-155	20
	Acrylonitrile	65-134	65-134	20
	Benzene	77-121	77-121	20
	Bromobenzene	78-121	78-121	20
	Bromochloromethane	78-125	78-125	20
	Bromodichloromethane	75-127	75-127	20
	Bromoform	67-132	67-132	20
	Bromomethane	53-143	53-143	20
	Carbon disulfide	63-132	63-132	20
	Carbon tetrachloride	70-135	70-135	20
	Chlorobenzene	79-120	79-120	20
	Chloroethane	59-139	59-139	20
	Chloroform	78-123	78-123	20
	Chloromethane	50-136	50-136	20
	cis-1,2-Dichloroethene	77-123	77-123	20
	cis-1,3-Dichloropropene	74-126	74-126	20
	Dibromochloromethane	74-126	74-126	20
	Dibromomethane	78-125	78-125	20
	Dichlorodifluoromethane	29-149	29-149	20
	Diisopropyl ether	69-127	69-127	20
	Ethyl t-butyl ether	72-126	72-126	20
	Ethylbenzene	76-122	76-122	20
	Hexachlorobutadiene	61-135	61-135	20
	Isopropylbenzene	68-134	68-134	20
	Methyl ethyl ketone	51-148	51-148	20
	Methyl isobutyl ketone	65-135	65-135	20
	Methyl t-butyl ether	73-125	73-125	20
	Methylene chloride	70-128	70-128	20
	Naphthalene	62-129	62-129	20
	n-Butylbenzene	70-128	70-128	20
	n-Propylbenzene	73-125	73-125	20
	o-Xylene	77-123	77-123	20
	p- & m-Xylenes	77-124	77-124	20
	p-Isopropyltoluene	73-127	73-127	20
	sec-Butylbenzene	73-126	73-126	20
	Styrene	76-124	76-124	20
	t-Amyl Methyl ether	73-126	73-126	20
	t-Butyl alcohol	68-133	68-133	20

Table 4
Accuracy and Precision Limits
(Page 4 of 5)

Method	Parameter	Soil Samples		
		LCS Percent Recovery	MS/MSD Percent Recovery	RPDs
SW8260B	tert-Butylbenzene	73-125	73-125	20
	Tetrachloroethene	73-128	73-128	20
	Toluene	77-121	77-121	20
	Total 1,2-Dichloroethene	-	-	-
	Total 1,3-Dichloropropene	-	-	-
	Total Purgeable Petroleum Hydrocarbons	-	-	-
	Total Xylenes	78-124	78-124	20
	trans-1,2-Dichloroethene	74-125	74-125	20
	trans-1,3-Dichloropropene	71-130	71-130	20
	Trichloroethene	77-123	77-123	20
	Trichlorofluoromethane	62-140	62-140	20
	Vinyl chloride	56-135	56-135	20
STLC SW8260	Benzene	70-130	70-130	20
	Bromodichloromethane	70-130	70-130	20
	Chlorobenzene	70-130	70-130	20
	Chloroethane	70-130	70-130	20
	1,4-Dichlorobenzene	70-130	70-130	20
	1,1-Dichloroethane	70-130	70-130	20
	1,1-Dichloroethene	70-130	70-130	20
	Toluene	70-130	70-130	20
	Trichloroethene	70-130	70-130	20
SW8270C	1,2,4-Trichlorobenzene	34-118	34-118	20
	1,2-Dichlorobenzene	33-117	33-117	20
	1,3-Dichlorobenzene	30-115	30-115	20
	1,4-Dichlorobenzene	31-115	31-115	20
	1-Chloronaphthalene	48-115	48-115	20
	2,3,4,6-Tetrachlorophenol	44-125	44-125	20
	2,4,5-Trichlorophenol	41-124	41-124	20
	2,4,6-Trichlorophenol	39-126	39-126	20
	2,4-Dichlorophenol	40-122	40-122	20
	2,4-Dimethylphenol	30-127	30-127	20
	2,4-Dinitrophenol	15-130	15-130	20
	2,4-Dinitrotoluene	48-126	48-126	20
	2,6-Dichlorophenol	47-117	47-117	20
	2,6-Dinitrotoluene	46-124	46-124	20
	2-Chloronaphthalene	41-114	41-114	20
	2-Chlorophenol	34-121	34-121	20
	2-Methylnaphthalene	38-122	38-122	20
	2-Methylphenol	32-122	32-122	20
	2-Nitroaniline	44-127	44-127	20
	2-Nitrophenol	36-123	36-123	20
	3- & 4-Methylphenol	34-119	34-119	20
	3,3-Dichlorobenzidine	22-121	22-121	20
	3-Nitroaniline	33-119	33-119	20
	4,6-Dinitro-2-methylphenol	29-132	29-132	20
	4-Bromophenyl phenyl ether	46-124	46-124	20
	4-Chloro-3-methylphenol	45-122	45-122	20
	4-Chloroaniline	17-106	17-106	20
	4-Chlorophenyl phenyl ether	45-121	45-121	20
	4-Nitroaniline	35-115	35-115	20

Table 4
Accuracy and Precision Limits
(Page 5 of 5)

Method	Parameter	Soil Samples		
		LCS Percent Recovery	MS/MSD Percent Recovery	RPDs
SW8270C	4-Nitrophenol	30-132	30-132	20
	Acenaphthene	40-123	40-123	20
	Acenaphthylene	32-132	32-132	20
	Aniline	10-130	10-130	20
	Anthracene	47-123	47-123	20
	Benzidine	1-130	1-130	20
	Benzo[a]anthracene	49-126	49-126	20
	Benzo[a]pyrene	45-129	45-129	20
	Benzo[b]fluoranthene	45-132	45-132	20
	Benzo[g,h,i]perylene	43-134	43-134	20
	Benzo[k]fluoranthene	47-132	47-132	20
	Benzyl alcohol	29-122	29-122	20
	Benzyl butyl phthalate	48-132	48-132	20
	bis(2-Chloroethoxy)methane	36-121	36-121	20
	bis(2-Chloroethyl) ether	31-120	31-120	20
	bis(2-Ethylhexyl)phthalate	51-133	51-133	20
	Carbazole	50-123	50-123	20
	Chrysene	50-124	50-124	20
	Dibenzo[a,h]anthracene	45-134	45-134	20
	Dibenzofuran	44-120	44-120	20
	Diethyl phthalate	50-124	50-124	20
	Dimethyl phthalate	48-124	48-124	20
	Di-n-butyl phthalate	51-128	51-128	20
	Di-n-octyl phthalate	45-140	45-140	20
	Fluoranthene	50-127	50-127	20
	Fluorene	43-125	43-125	20
	Hexachlorobenzene	45-122	45-122	20
	Hexachlorobutadiene	32-123	32-123	20
	Hexachlorocyclopentadiene	30-130	30-130	20
	Hexachloroethane	28-117	28-117	20
	Indeno[1,2,3-cd]pyrene	45-133	45-133	20
	Isophorone	30-122	30-122	20
	Naphthalene	35-123	35-123	20
	Nitrobenzene	34-122	34-122	20
	N-Nitrosodimethylamine	23-120	23-120	20
	N-Nitrosodi-N-propylamine	36-120	36-120	20
	N-Nitrosodiphenylamine	38-127	38-127	20
	Pentachlorophenol	25-133	25-133	20
	Phenanthrene	50-121	50-121	20
	Phenol	34-121	34-121	20
	Pyrene	47-127	47-127	20
	Pyridine	-	-	-
OSHA ID-191	Asbestos	-	-	-

Notes:

- = no limit
LCS = laboratory control sample
MS =matrix spike
MSD = matrix spike duplicate
NA = not applicable
RPD = relative percent difference
SPLP = synthetic precipitation leaching procedure
STLC = soluble threshold limit concentration
TCLP = toxicity charachteristic leaching procedure

Table 5
Summary of Proposed Samples
(Page 1 of 2)

Location ID	Field Sample ID	# of Samples	Matrix	Depth (feet bgs)	Location Description	Title 22 Metals (SW6020/SW7471)	Arsenic (SW6020)	Lead (SW6020)	SPLP Lead (1312)	TCLP Arsenic and Lead (1311)	VOCs (SW8260B)	SVOCs (SW8270C)	Organochlorine Pesticides (SW8081A)	Chlorinated Herbicides (SW8151A)	Polychlorinated Biphenyls (SW8082)	Oil-, Diesel-, and Gasoline-Range Organics (SW8015M/SW8020)	Asbestos (OSHA ID-191)	PID
Confirmation Samples																		
A1	A1-FL01-2.5 and A1-FL02-2.5	2	Soil	2.5-3.0	Area #1 Floor		X											
A1	A1-SW01-1.25 through A1-SW04-1.25	4	Soil	1.25-1.75	Area #1 Sidewall		X											
A2	A2-FL01-3.0 through A1-FL07-3.0	11	Soil	3.0-3.5	Area #2 Floor		X											
A2	A2-SW01-1.5 through A2-SW12-1.5	12	Soil	1.5-2.0	Area #2 Sidewall		X											
A3	A3-FL01-3.0	1	Soil	6.0-6.5	Area #3 Floor		X	X	X							X		
A3	A3-SW01-3.1 through A3-SW04-3.0	4	Soil	3.0-3.5	Area #3 Sidewall		X	X	X							X		
A4	A4-FL01-2.5 through A4-FL05-2.5	5	Soil	2.5-3.0	Area #4 Floor		X											
A4	A4-SW01-1.25 through A4-SW08-1.25	8	Soil	1.25-1.75	Area #4 Sidewall		X											
A5	A5-FL01-6.5	1	Soil	6.5-7.0	Area #5 Floor		X											
A5	A5-SW01-3.25 through A5-SW04-3.25	4	Soil	3.25-3.75	Area #5 Sidewall		X											
A6	A6-FL01-2.5	1	Soil	2.5-3.0	Area #6 Floor		X											
A6	A6-SW01-1.25 through A6-SW04-1.25	4	Soil	1.25-1.75	Area #6 Sidewall		X											
A7	A7-FL01-3.0 through A7-FL08-3.0	8	Soil	3.0-3.5	Area #7 Floor		X											
A7	A7-SW01-1.5 through A7-SW13-1.5	13	Soil	1.5-2.0	Area #7 Sidewall		X											
A8	A8-FL01-6.0 through A8-FL04-6.0	4	Soil	6.0-6.5	Area #8 Floor		X											
A8	A8-SW01-3.0 through A8-SW09-3.0	9	Soil	3.0-3.5	Area #8 Sidewall		X											
A9	A9-FL01-15.0 and A9-FL02-15.0	2	Soil	15.0-15.5	Area #9 Floor													X
A9	A9-SW01-7.5 through A9-SW04-7.5	4	Soil	7.5-8.0	Area #9 Sidewall													X
Waste Characterization Samples[1]																		
A1[1]	A1-WC-01	1	Soil	5.0-5.5	Area #1	X				X	X	X	X	X	X	X		
A2[1]	A2-WC-01 through A9-WC-13	13	Soil	5.0-5.5	Area #2	X				X	X	X	X	X	X	X		
A3[1]	A3-WC-01	1	Soil	7.5-8.0	Area #3	X				X	X	X	X	X	X	X		

Table 5
Summary of Proposed Samples
(Page 2 of 2)

Location ID	Field Sample ID	# of Samples	Matrix	Depth (feet bgs)	Location Description	Title 22 Metals (SW6020/SW7471)	Arsenic (SW6020)	Lead (SW6020)	SPLP Lead (1312)	TCLP Arsenic and Lead (1311)	VOCs (SW8260B)	SVOCs (SW8270C)	Organochlorine Pesticides (SW8081A)	Chlorinated Herbicides (SW8151A)	Polychlorinated Biphenyls (SW8082)	Oil-, Diesel-, and Gasoline-Range Organics (SW8015M/SW8020)	Asbestos (OSHA ID-191)	PID
A4[1]	A4-WC-01 and A4-WC-02	2	Soil	7.5-8.0	Area #4	X				X	X	X	X	X	X	X		
A5[1]	A5-WC-01 and A5-WC-02	2	Soil	10.0-10.5	Area #5	X				X	X	X	X	X	X	X		
A6[1]	A6-WC-01	1	Soil	10.0-10.5	Area #6	X				X	X	X	X	X	X	X		
A7[1]	A7-WC-01 through A7-WC-07	7	Soil	2.5-3.0	Area #7	X				X	X	X	X	X	X	X		
A8[1]	A8-WC-01 through A8-WC-07	7	Soil	2.5-3.0	Area #8	X				X	X	X	X	X	X	X		
A9[1]	A9-WC-01 through A9-WC-04	4	Soil	2.5-3.0	Area #9	X				X	X	X	X	X	X	X		
Backfill Samples[1]																		
Backfill-SS[2]	Backfill-SS-01	1	Soil	NA	Excavation Side Slope Material	X												
Backfill-IMP[2]	Backfill-IMP-01	1	Soil	NA	Imported Fill (Virgin Class II Aggregate Base)	X											X	

Notes:

[1] Will be collected as four-point samples and analyzed as one composite sample.

# = number
bgs = below ground surface
ID = identification
OSHA = Occupational Safety and Health Administration
PID = photoionization detector
SPLP = synthetic precipitation leaching procedure
SVOC = semi-volatile organic compound
TCLP = toxicity characteristic leaching procedure
VOC = volatile organic compound

Table 6
Sample Container, Preservation, and Holding Times

Parameter	Matrix	Preparation Method	Analytical Method	Container Quantity	Container Size	Container Type	Preservation	Holding Time
Title 22 Metals	Soil	SW3005A	SW6010B or SW6020	1	4 oz	Glass Jar, Stainless Steel or Brass Sleeve	None	180 days
STLC arsenic and lead	Soil	CA WET	SW6010B/ SW6020	1	8 oz	Glass Jar, Stainless Steel or Brass Sleeve	None	180 days
TCLP arsenic and lead	Soil	1311	SW6010B/ SW6020	1	8 oz	Glass Jar, Stainless Steel or Brass Sleeve	None	180 days
SPLP lead	Soil	1312	SW6010B	1	32 oz	Glass Jar	None	180 days
VOCs	Soil	SW5035	SW8260B	3-4	40 mL	samplesmart kit (or equivalent)*	Sodium Bisulfite or Methanol and/ or water* Cool to ≤ 6°C	14 days, if preserved
STLC VOCs	Soil	STLC	SW8260B	1	8 oz	Jar with Teflon lined lid	Cool to ≤ 6°C	14 days
SVOCs	Soil	SW3550	SW8370C	1	4 oz	Glass Jar, Stainless Steel or Brass Sleeve	Cool to ≤ 6°C	14 days to extraction
Organochlorine Pesticides	Soil	SW3550	SW8081A	1	4 oz	Glass Jar, Stainless Steel or Brass Sleeve	Cool to ≤ 6°C	14 days to extraction
Chlorinated Herbicides	Soil	SW3550	SW8151A	1	4 oz	Glass Jar, Stainless Steel or Brass Sleeve	Cool to ≤ 6°C	14 days to extraction
PCBs	Soil	SW3550	SW8082	1	4 oz	Glass Jar, Stainless Steel or Brass Sleeve	Cool to ≤ 6°C	1 year
Gasoline-Range Organics	Soil	SW5035	SW8015	1	40 mL	samplesmart kit (or equivalent), Teflon™ Vial with Teflon™-lined septum	Cool to ≤ 6°C	14 days. If preserved
Oil-, and Diesel-, Range Organics	Soil	SW3550	SW8015	1	4 oz	Glass Jar, Stainless Steel or Brass Sleeve	Cool to ≤ 6°C	14 days to extraction
Asbestos	Soil	NA	OSHA ID-191	1	4 oz	Jar	None	NA

Notes:

*Soil analysis for VOCs and gasoline requires multiple 40 mL vials, with water or other preservatives. Check with laboratory prior to sampling.

°C = degrees Celsius
< = less than
≤ = less than or equal to
cc = cubic centimeter
mL = milliliters
oz = ounces
NA = not applicable
PCB = polychlorinated biphenyl
SPLP = synthetic precipitation leaching procedure
STLC = soluble threshold limit concentration
SVOC = semi-volatile organic compound
TCLP = toxicity characteristic leaching procedure
VOC = volatile organic compound

Attachment 1

Example Field Forms

Chain of Custody Record

Lab job no.: ____________

Date ____________

Page ______ of ______

Laboratory ____________
Address ____________
____
____

Client ____________
Address ____________
____

Project Name ____________
Project Number ____________

Method of Shipment ____________
Shipment No. ____________
Airbill No. ____________
Cooler No. ____________
Project Manager ____________
Telephone No. ____________
Fax. No. ____________
Samplers: (Signature) ____________

Field Sample ID	Matrix	Sample Depth Interval	Sampling Date	Sampling Time	Type/Size of Container	Preservation		Filtered	No. of Containers	Analysis Required								Remarks
						Temp.	Chemical											
		/																
		/																
		/																
		/																
		/																
		/																
		/																

Relinquished by:
Signature ____________
Printed ____________
Company ____________
Reason ____________
Date
Time

Received by:
Signature ____________
Printed ____________
Company ____________
Date
Time

Relinquished by:
Signature ____________
Printed ____________
Company ____________
Reason ____________
Date
Time

Received by:
Signature ____________
Printed ____________
Company ____________
Date
Time

Comments: ____________
____
____

Relinquished by:
Signature ____________
Printed ____________
Company ____________
Reason ____________
Date
Time

Received by:
Signature ____________
Printed ____________
Company ____________
Date
Time

DISTRIBUTION: White to Project File, Canary to Laboratory, Pink to Courier, Goldenrod to Field File

F-1000
04/11

AECOM

Decontamination Record

Project Name

Project Number

Recorded By

Site

Date

Time

Checked By

Date

Decontamination after borehole/well/sampling point

Equipment	Use	Steam/Hot Water	Detergent/Water	Potable Water	Deionized Water	Type II Water	Other Water	Methanol	Hexane	HNO_3 (Dilution)			Equip. Blank No.
Drill Rig I.D.													
Drill Rods													
Augers													
Soil Sampler I.D.													
Pump I.D.Type													
Bailer I.D.													
Drill Bit													
Hand Auger I.D.													
Drive Casing													
Well Casing (if required)													
Other:													

Use key : GS - Groundwater Sampling, SS - Soil Sampling, WP - Well Purging

Comments (e.g. initial decon, between which locations, or if last decon for the day)

Soil / Sediment Sampling Record

Project Name ______________________ Project Number ______________

Location ______________________ Sample Number ______________

Site ______________________ Duplicate Number ______________

Date ______________________ Checked by ______________

Recorded By ______________________ Date ______________

Sampling Equipment ______________________

Sample Type: ☐ Soil ☐ Sediment ☐ Rock

Sample Type Description

USCS Soil Type ______________________

Color ______________________

Odor ______________________

Depth ______________________

Number of Samples ______________________

Comments ______________________

____

Sampling Point (sketch):

Decontamination

Equipment: ☐ Hand auger

Type ____________

☐ Trowel

☐ Other ____________

Decontamination Fluids: ______________________

☐ Steam/Hot Water	☐ Methanol
☐ Detergent/ Water	☐ Hexane
☐ Potable Water	☐ HNO_3 ; dilution
☐ Deionized Water	☐ Other ____________

Equipment Calibration Daily Log

Water Equipment

Project Name ____________________ Date: ____________________

Project No. ____________________ Location ____________________ Time: AM ____________________

PM ____________________

pH Meter

Model ____________________ Serial No. ____________________

	AM	Adjustment	PM
pH 7.00 Buffer Solution: pH			
pH 4.00 Buffer Solution: pH			
pH 10.00 Buffer Solution: pH			

Exp. Date ____________________ Lot # ____________________

Exp. Date ____________________ Lot # ____________________

Exp. Date ____________________ Lot # ____________________

Temperature ____________________ (AM) ____________________ (PM) Comments ____________________

Operator Signature ____________________ (AM) ____________________ (PM) ____________________

Conductivity Meter

Model ____________________ Serial No. ____________________

Calibration Solution ____________________ Exp. Date ____________________ Lot # ____________________

	AM	Adjustment	PM
mS/cm Reading			

Comments ____________________

Temperature ____________________ (AM) ____________________ (PM) ____________________

Operator Signature ____________________ (AM) ____________________ (PM) ____________________

Turbidimeter

Model ____________________ Serial No. ____________________

Calibration Blank	AM	Adjustment	PM

Comments ____________________

Operator Signature ____________________ (AM) ____________________ (PM) ____________________

Dissolved Oxygen Meter

Model ____________________ Serial No. ____________________

Calibration Method ____________________ Temp. __________ (AM) __________ (PM) __________

Precalibration (mg/L) ____________________ (AM) ____________________ (PM) Comments ____________________

Post-calibration (mg/L) ____________________ (AM) ____________________ (PM) ____________________

Operator Signature ____________________ (AM) ____________________ (PM) ____________________

Oxidation/Reduction Potential Meter

Model ____________________ Serial No. ____________________

Calibration Solution Expiration Date ____________________ Calibration Solution Lot No. ____________________

	Temp.(Calibration Solution)	Expected Reading	Actual Reading
AM			
PM			

Operator Signature ____________________ (AM) ____________________ (PM)

Checked By ____________________ Date ____________________

Equipment Calibration Daily Log

Gas Detectors

Project Name ______

Project No. ______ Location ______

Date: ______

Time: AM ______

PM ______

Combustible Gas Indicator

Model ______ Serial No. ______

Ambient Air Readings

	AM	Adjustment	PM
O_2 (%)		(span)	
CO (ppm)		(zero)	
H_2S (ppm)		(zero)	
LEL (%)		(zero)	

Comments ______

Operator Signature ______ (AM) ______ (PM)

Photo-Ionization Detector

Model ______ Serial No. ______

Bulb Type
☐ 10.6 meV (56 ppm baseline)
☐ 11.7 meV (66 ppm baseline)
☐ Other ______

Post warm-up background ______ (ppm)

Comments ______

Calibration Gas:

100 ppm isobutylene

______

AM	Adjustment	PM

Operator Signature ______ (Begin) ______ (End)

Organic Vapor Analyzer

Model ______ Serial No. ______

Gas Select ______

Calibration Gas: ______ (______ ppm)

	AM	Adjustment	PM
Reading			
Background			

Comments ______

Operator Signature ______ (AM) ______ (PM)

Checked by ______ Date ______

F-1027B
04/11

AECOM

Unified Soil Classification System

Major Divisions			Group Symbols	Typical Names
Coarse Grained Soils (More than 50% of material is larger than No. 200 sieve size)	**Gravels** (More than 50% of coarse fraction is larger than the No. 4 sieve size)	**Clean Gravels** (Little or no fines)	▒ GW	Well graded gravels, gravel-sand mixtures, little or no fines
			░ GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
		Gravels with Fines (Appreciable amount of fines)	░ GM	Silty gravels, gravel-sand-silt mixtures.
			▒ GC	Clayey gravels, gravel-sand-clay mixtures.
	Sands (More than 50% of coarse fraction is smaller than the No. 4 sieve size)	**Clean Sands** (Little or no fines)	⁘ SW	Well graded sands, gravelly sands, little or no fines
			░ SP	Poorly graded sands, gravelly sands, little or no fines
		Sands with Fines (Appreciable amount of fines)	▤ SM	Silty sands, sand-silt mixtures.
			▤ SC	Clayey sands, sand-clay mixtures.
Fine Grained Soils (More than 50% of material is smaller than No. 200 sieve size)	**Silts and Clays** (Liquid limit less than 50)		▤ ML	Inorganic silts and very fine sands. Rock flour, silty or clayey fine sands or clayey silts with slight plasticity.
			▤ CL	Inorganic clays of low to medium plasticity. Gravelly clays, sandy clays, silty clays, lean clays
			▤ OL	Organic silts and organic silty clays of low plasticity.
	Silts and Clays (Liquid limit greater than 50)		▥ MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils. Elastic silts
			■ CH	Inorganic clays of high plasticity. Fat clays
			▧ OH	Organic clays of medium to high plasticity. Organic silts
Highly Organic Soils			▥ PT	Peat and other highly organic soils
Fill			▒ AF	Artificial Fill material

Particle Size Limits - U.S. Standard Sieve Size

Silt or Clay	Sand			Gravel		Cobbles	Boulders
	Fine	Medium	Coarse	Fine	Coarse		

No. 200 No. 40 No.10 No. 4 3/4 in 3 in 12 in

NOTE: WHEN SOILS POSSESS CHARACTERISTICS OF TWO GROUPS THEY SHOULD BE DESIGNATED BY USING BOTH GROUP SYMBOLS

AECOM

General Rock Syntax

Rock Syntax

Type: color (#); weathering; hardness; original texture; mineralogy

e.g. – Quartz Monzonite; light gray(2.5Y N7); completely weathered; soft; phaneritic (1-3 mm); 20% qtz/ 25% kspar / 25% plag / 20% clay / 10% mica; dry

Degree of Weathering

Term	Description
Fresh	No visible sign of weathering.
Faintly Weathered	Weathering limited to the surface of major discontinuities.
Slightly Weathered	Penetrative weathering developed on open discontinuity surfaces but only slight weathering of rock material.
Moderately Weathered	Weathering extends throughout the rock mass but the rock material is not friable.
Highly Weathered	Weathering extends throughout the rock mass and the rock material is partially friable.
Completely Weathered	Rock is wholly decomposed and in a friable condition but the rock texture and structure are preserved.
Residual Soil	A soil material with the original texture, structure, and mineralogy of the rock completely destroyed.

Overall Hardness of Rock

Term	Description
Very Hard	Cannot be scratched with knife or sharp pick. Breaking of hand specimens requires several hard blows from a hammer or pick.
Hard	Can be scratched with knife or pick only with difficulty. Hard blow of hammer required to detach a hand specimen.
Moderately Hard	Can be scratched with knife or pick. Gouges or grooves of 1/4 in. deep can be excavated by hard blow with the point of a pick. Hand specimens can be detached by a moderate blow.
Medium Hard	Can be grooved or gouged 1/4 in. deep by firm pressure on knife or pick point. Can be excavated in small chips to pieces approx. 1 in. maximum size by hard blows with the point of a pick.
Soft	Can be gouged or grooved readily with knife or pick point. Can be excavated in chips to pieces several inches in size by moderate blows with the pick point. Small, thin pieces can be broken by finger pressure.
Very Soft	Can be carved with a knife. Can be excavated readily with the pick point. Pieces of 1 in. or more in thickness can be broken by finger pressure. Readily scratched with fingernail.

Fracture Syntax

Item, dip, spacing, smoothness/planarity, void width, weathering penetration, filling minerals or stain (thickness)

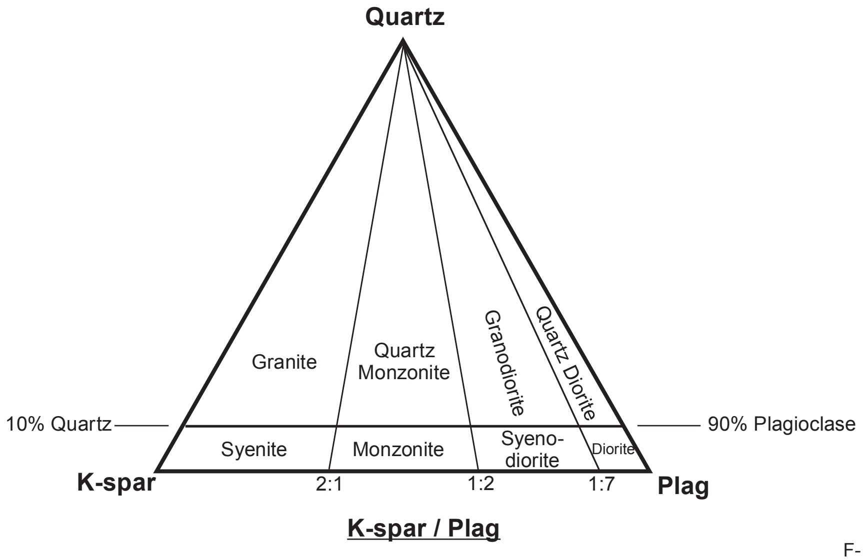
e.g. – fractures, 65° dip, spaced 3 to 5 inches, smooth/planar, open 1 mm, fresh, iron stained.

Descriptive Terms for Surface Roughness

Designation	Description
Very Rough	Near vertical steps and ridges occur on the discontinuity.
Rough	Some ridges and side-angle steps are evident; asperities are clearly visible; surface feels very abrasive.
Slightly Rough	Asperities on the discontinuity surfaces are distinguishable and can be felt.
Smooth	Surface appears smooth and feels smooth to the touch.
Slickensided	Visual evidence of polishing and movement are visible.

Descriptive Terms for Surface Planarity

Designation	Description
Wavy	A moderately undulating surface, with no sharp breaks or steps.
Planar	A flat surface.
Stepped	A surface with asperities or steps. The height of the asperity should be estimated or measured.



AECOM

Soil Descriptions

Size Gradation for Gravel and Sand Fractions

"the 90% rule"

≥ 90% coarse = coarse
≥ 90% medium and coarse = medium to coarse
≥ 90% medium = medium
≥ 90% fine and medium = fine to medium
≥ 90% fine = fine
≥10% each; fine, medium, and coarse = fine to coarse

Hardness of Soils

Correlations for density of sand/gravel

Description	Relative density D, (approx)	N-value (approx)
Very loose		5
Loose	40	10
Medium dense	70	30
Dense	90	50
Very dense	>90	>50

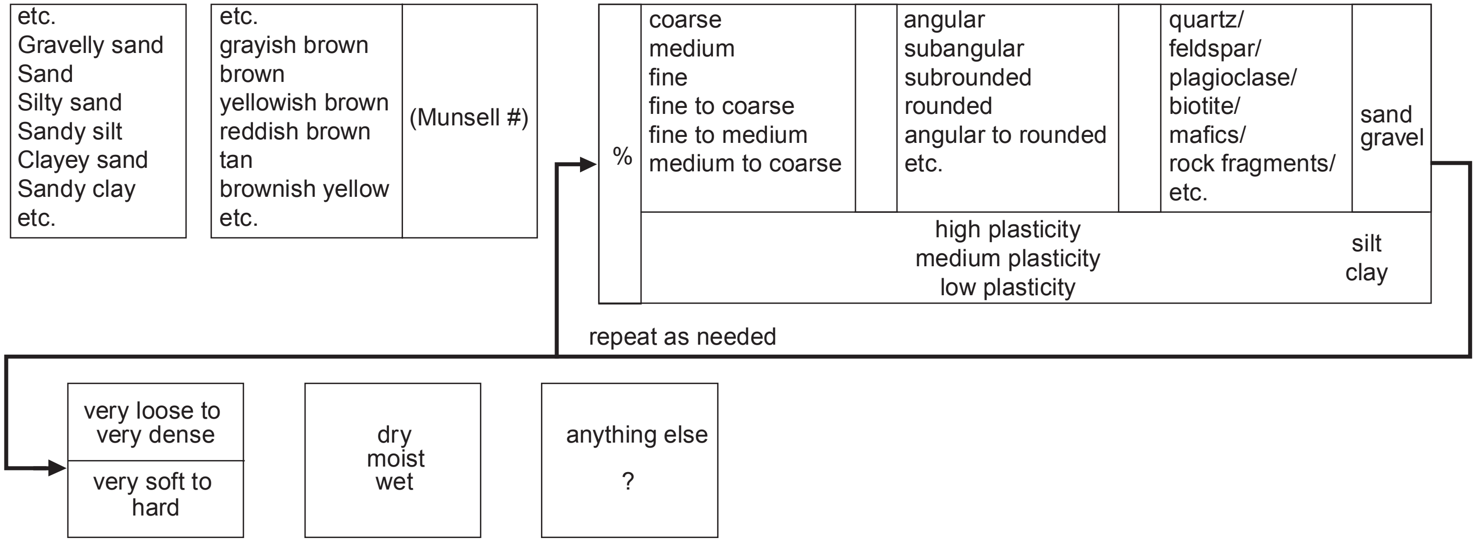
Correlations for Stiffness of Silt/Clay

Description	qu (tsf)	N-value (approx)		Field identification
		Low Pi	High Pi	
Very soft	>0.25	1-3	1	Squeezes between fingers when fist is closed
Soft	0.25-0.5	3-6	1-2	Easily molded by fingers
Firm	0.5-1.0	6-12	4-8	Molded by strong finger pressure
Stiff	1.0-2.0	12-24	4-8	Dented by strong finger pressure
Very stiff	2.0-4.0	24-50	8-15	Dented only slightly by finger pressure
Hard	>4.0	>50	>15	Dented only slightly by pencil point

Grading

Change in existing component = Grading to 25% sand
Add new component = Grading with trace med. plast. clay
Delete old component = Grading without gravel
Change color or density = Color changes to olive brown (2.5Y 3/3)

Mnemonic for Soil Logging



etc.
Gravelly sand
Sand
Silty sand
Sandy silt
Clayey sand
Sandy clay
etc.

etc.
grayish brown
brown
yellowish brown
reddish brown
tan
brownish yellow
etc.

(Munsell #)

%

coarse
medium
fine
fine to coarse
fine to medium
medium to coarse

angular
subangular
subrounded
rounded
angular to rounded
etc.

quartz/
feldspar/
plagioclase/
biotite/
mafics/
rock fragments/
etc.

sand
gravel

high plasticity
medium plasticity
low plasticity

silt
clay

repeat as needed

very loose to very dense

very soft to hard

dry
moist
wet

anything else

?

e.g. Ð Silty sand; light yellowish brown (2.5Y 6/3); 80% fine to medium, subangular, quartz/feldspar sand; 15% low plasticity silt; trace fine, subangular, rock fragments; gravel; dense; dry

e.g. Ð Sandy clay; strong brown (7.5YR 5/6); 85% low plasticity clay; 15% fine, angular, quartz sand; stiff; moist

Attachment 2

Standard Operating Procedures

A GUIDELINE FOR PID INSTRUMENT RESPONSE

CORRECTION FACTORS AND IONIZATION ENERGIES*

RAE Systems by Honeywell PIDs can be used for the detection of a wide variety of gases that exhibit different responses. In general, any compound with ionization energy (IE) lower than that of the lamp photons can be measured.* The best way to calibrate a PID to different compounds is to use a standard of the gas of interest. However, correction factors have been determined that enable the user to quantify a large number of chemicals using only a single calibration gas, typically isobutylene. In our PIDs, correction factors can be used in one of three ways:

1. Calibrate the monitor with isobutylene in the usual fashion to read in isobutylene equivalents. Manually multiply the reading by the correction factor (CF) to obtain the concentration of the gas being measured.
2. Calibrate the unit with isobutylene in the usual fashion to read in isobutylene equivalents. Call up the correction factor from the instrument memory or download it from a personal computer and then call it up. The monitor will then read directly in units of the gas of interest.
3. Calibrate the unit with isobutylene, but input an equivalent, "corrected" span gas concentration when prompted for this value. The unit will then read directly in units of the gas of interest.

Example 1:

With the unit calibrated to read isobutylene equivalents, the reading is 10 ppm with a 10.6 eV lamp. The gas being measured is butyl acetate, which has a correction factor of 2.6. Multiplying 10 by 2.6 gives an adjusted butyl acetate value of 26 ppm. Similarly, if the gas being measured were trichloroethylene (CF = 0.54), the adjusted value with a 10 ppm reading would be 5.4 ppm.

Example 2:

With the unit calibrated to read isobutylene equivalents, the reading is 100 ppm with a 10.6 eV lamp. The gas measured is m-xylene (CF = 0.43). After downloading this factor, the unit should read about 43 ppm when exposed to the same gas, and thus read directly in m-xylene values.

Example 3:

The desired gas to measure is ethylene dichloride (EDC). The CF is 0.6 with an 11.7 eV lamp. During calibration with 100 ppm isobutylene, insert 0.6 times 100, or 60 at the prompt for the calibration gas concentration. The unit then reads directly in EDC values.

Conversion to mg/m^3

To convert from ppm to mg/m^3, use the following formula:

$$\text{Conc. (mg/m}^3\text{)} = \frac{\text{[Conc.(ppmv) x mol. wt. (g/mole)]}}{\text{molar gas volume (L)}}$$

For air at 25°C (77°F), the molar gas volume is 24.4 L/mole and the formula reduces to:

$$\text{Conc.(mg/m}^3\text{)} = \text{Conc.(ppmv) x mol. wt. (g/mole) x 0.041}$$

** The term "ionization energy" is more scientifically correct and replaces the old term "ionization potential." High-boiling ("heavy") compounds may not vaporize enough to give a response even when their ionization energies are below the lamp photon energy. Some inorganic compounds like H_2O_2 and NO_2 give weak response even when their ionization energies are well below the lamp photon energy.*

For example, if the instrument is calibrated with a gas standard in ppmv, such as 100 ppm isobutylene, and the user wants the display to read in mg/m^3 of hexane, whose m.w. is 86 and CF is 4.3, the overall correction factor would be 4.3 x 86 x 0.041 equals 15.2.

Correction Factors for Mixtures

The correction factor for a mixture is calculated from the sum of the mole fractions Xi of each component divided by their respective correction factors CFi:

$$CFmix = 1 / (X_1/CF_1 + X_2/CF_2 + X_3/CF_3 + ... Xi/CFi)$$

Thus, for example, a vapor phase mixture of 5% benzene and 95% n-hexane would have a CFmix of CFmix = 1 / (0.05/0.53 + 0.95/4.3) = 3.2. A reading of 100 would then correspond to 320 ppm of the total mixture, comprised of 16 ppm benzene and 304 ppm hexane.

For a spreadsheet to compute the correction factor and TLV of a mixture see the appendix at the end of the CF table.

TLVs and Alarm Limits for Mixtures

The correction factor for mixtures can be used to set alarm limits for mixtures. To do this one first needs to calculate the exposure limit for the mixture. The Threshold Limit Value (TLV) often defines exposure limits. The TLV for the mixture is calculated in a manner similar to the CF calculation:

$$TLV\ mix = 1 / (X_1/TLV_1 + X_2/TLV_2 + X_3/TLV_3 + ... Xi/TLVi)$$

In the above example, the 8-h TLV for benzene is 0.5 ppm and for n-hexane 50 ppm. Therefore the TLV of the mixture is TLVmix = 1 / (0.05/0.5 + 0.95/50) = 8.4 ppm, corresponding to 8.0 ppm hexane and 0.4 ppm benzene. For an instrument calibrated on isobutylene, the reading corrsponding to the TLV is:

$$Alarm\ Reading = TLVmix / CFmix = 8.4 / 3.2 = 2.6\ ppm$$

A common practice is to set the lower alarm limit to half the TLV, and the higher limit to the TLV. Thus, one would set the alarms to 1.3 and 2.6 ppm, respectively.

CALIBRATION CHARACTERISTICS

A. Flow Configuration. PID response is essentially independent of gas flow rate as long as it is sufficient to satisfy the pump demand. Four main flow configurations are used for calibrating a PID:

1. **Pressurized gas cylinder (Fixed-flow regulator):** The flow rate of the regulator should match the flow demand of the instrument pump or be slightly higher.
2. **Pressurized gas cylinder (Demand-flow regulator):** A demand-flow regulator better matches pump speed differences, but results in a slight vacuum during calibration and thus slightly high readings.
3. **Collapsible gas bag:** The instrument will draw the calibration gas from the bag at its normal flow rate, as long as the bag valve is large enough. The bag should be filled with enough gas to allow at least one minute of flow (~ 0.6 L for a MiniRAE, ~0.3 L for MultiRAE).
4. **T (or open tube) method:** The T method uses a T-junction with gas flow higher than the pump draw. The gas supply is connected to one end of the T, the instrument inlet is connected to a second end of the T, and excess gas flow escapes through the third, open end of the T. To prevent ambient air mixing, a long tube should be connected to the open end, or a high excess rate should be used. Alternatively, the instrument probe can be inserted into an open tube slightly wider than the probe. Excess gas flows out around the probe.

The first two cylinder methods are the most efficient in terms of gas usage, while the bag and T methods give slightly more accurate results because they match the pump flow better.

B. Pressure. Pressures deviating from atmospheric pressure affect the readings by altering gas concentration and pump characteristics. It is best to calibrate with the instrument and calibration gas at the same pressure as each other and the sample gas. (Note that the cylinder pressure is not relevant because the regulator reduces the pressure to ambient.) If the instrument is calibrated at atmospheric pressure in one of the flow configurations described above, then 1) pressures slightly above ambient are acceptable but high pressures can damage the pump and 2) samples under vacuum may give low readings if air leaks into the sample train.

C. Temperature. Because temperature effects gas density and concentration, the temperature of the calibration gas and instrument should be as close as possible to the ambient temperature where the unit will be used. We recommend that the temperature of the calibration gas be within the instrument's temperature specification (typically 14° to 113° F or -10° to 45° C). Also, during actual measurements, the instrument should be kept at the same or higher temperature than the sample temperature to avoid condensation in the unit.

D. Matrix. The matrix gas of the calibration compound and VOC sample is significant. Some common matrix components, such as methane and water vapor can affect the VOC signal.

PIDs are most commonly used for monitoring VOCs in air, in which case the preferred calibration gas matrix is air. For a MiniRAE, methane, methanol, and water vapor reduce the response by about 20% when their concentration is 15,000 ppm and by about 40% at 30,000 ppm. Despite earlier reports of oxygen effects, RAE PID responses with 10.6 eV lamps are independent of oxygen concentration, and calibration gases in a pure nitrogen matrix can be used. H_2 and CO_2 up to 5 volume % also have no effect.

E. Concentration. Although RAE Systems PIDs have electronically linearized output, it is best to calibrate in a concentration range close to the actual measurement range. For example, 100 ppm standard gas for anticipated vapors of 0 to 250 ppm, and 500 ppm standard for expected concentrations of 250 to 1000 ppm. The correction factors in this table were typically measured at 50 to 100 ppm and apply from the ppb range up to about 1000 ppm. Above 1000 ppm the CF may vary and it is best to calibrate with the gas of interest near the concentration of interest.

F. Filters. Filters affect flow and pressure conditions and therefore all filters to be used during sampling should also be in place during calibration. Using a water trap (hydrophobic filter) greatly reduces the chances of drawing water aerosols or dirt particles into the instrument. Regular filter replacements are recommended because dirty filters can adsorb VOCs and cause slower response time and shifts in calibration.

G. Instrument Design. High-boiling ("heavy") or very reactive compounds can be lost by reaction or adsorption onto materials in the gas sample train, such as filters, pumps and other sensors. Multi-gas meters, including EntryRAE, MultiRAE and AreaRAE have the pump and other sensors upstream of the PID and are prone to these losses. Compounds possibly affected by such losses are shown in green in the table, and may give slow response, or in extreme cases, no response at all. In many cases the multi-gas meters can still give a rough indication of the relative concentration, without giving an accurate, quantitative reading. The ppbRAE and MiniRAE series instruments have inert sample trains and therefore do not exhibit significant loss; nevertheless, response may be slow for the very heavy compounds and additional sampling time up to a minute or more should be allowed to get a stable reading.

TABLE ABBREVIATIONS

CF = Correction Factor (multiply by reading to get corrected value for the compound when calibrated to isobutylene)

NR = No Response

IE = Ionization Energy (values in parentheses are not well established)

C = Confirmed Value indicated by "+" in this column; all others are preliminary or estimated values and are subject to change

ne = Not Established ACGIH 8-hr. TWA

C## = Ceiling value, given where 8-hr.TWA is not available

DISCLAIMER

TN-106 is a general guideline for Correction Factors (CF) for use with PID instruments manufactured by RAE Systems. The CF may vary depending on instrument and operation conditions. For the best accuracy, RAE Systems recommends calibrating the instrument to target gas. Actual readings may vary with age and cleanliness of lamp, relative humidity, and other factors as well. For accurate work, the instrument should be calibrated regularly under the operating conditions used. The factors in this table on the following pages were measured in dry air (40 to 50% RH) at room temperature, typically at 50 to 100 ppm. CF values may vary above about 1000 ppm.

Updates

The values in this table on the following pages are subject to change as more or better data become available. Watch for updates of this table on the Internet at **http://www.raesystems.com.**

IE data are taken from the CRC Handbook of Chemistry and Physics, 73rd Edition, D.R. Lide (Ed.), CRC Press (1993) and NIST Standard Ref. Database 19A, NIST Positive Ion Energetics, Vers. 2.0, Lias, et.al., U.S. Dept. Commerce (1993). Exposure limits (8-h TWA and Ceiling Values) are from the 2005 ACGIH Guide to Occupational Exposure Values, ACGIH, Cincinnati, OH 2005. Equations for exposure limits for mixtures of chemicals were taken from the 1997 TLVs and BEIs handbook published by the ACGIH (1997).

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Acetaldehyde		75-07-0	C_2H_4O	NR	+	6	+	3.3	+	10.23	C25
Acetic acid	Ethanoic Acid	64-19-7	$C_2H_4O_2$	NR	+	22	+	2.6	+	10.66	10
Acetic anhydride	Ethanoic Acid Anhydride	108-24-7	$C_4H_6O_3$	NR	+	6.1	+	2.0	+	10.14	5
Acetone	2-Propanone	67-64-1	C_3H_6O	1.2	+	0.9	+	1.4	+	9.71	500
Acetone cyanohydrin	2-Hydroxyisobutyronitrile	75-86-5	C_4H_7NO					4	+	11.1	C5
Acetonitrile	Methyl cyanide, Cyanomethane	75-05-8	C_2H_3N					100		12.19	40
Acetylene	Ethyne	74-86-2	C_2H_2					2.1	+	11.40	ne
Acrolein	Propenal	107-02-8	C_3H_4O	42	+	3.9	+	1.4	+	10.10	0.1
Acrylic acid	Propenoic Acid	79-10-7	$C_3H_4O_2$			12	+	2.0	+	10.60	2
Acrylonitrile	Propenenitrile	107-13-1	C_3H_3N			NR	+	1.2	+	10.91	2
Allyl alcohol		107-18-6	C_3H_6O	4.5	+	2.4	+	1.6	+	9.67	2
Allyl chloride	3-Chloropropene	107-05-1	C_3H_5Cl			4.3		0.7		9.9	1
Ammonia		7664-41-7	NH_3	NR	+	10.9	+	5.7	+	10.16	25
Amyl acetate	mix of n-Pentyl acetate & 2-Methylbutyl acetate	628-63-7	$C_7H_{14}O_2$	11	+	2.3	+	0.95	+	<9.9	100
Amyl alcohol	1-Pentanol	75-85-4	$C_5H_{12}O$			5				10.00	ne
Aniline	Aminobenzene	62-53-3	C_6H_7N	0.50	+	0.5	+	0.47	+	7.72	2
Anisole	Methoxybenzene	100-66-3	C_7H_8O	0.89	+	0.58	+	0.56	+	8.21	ne
Arsine	Arsenic trihydride	7784-42-1	AsH_3			1.9	+			9.89	0.05
Benzaldehyde		100-52-7	C_7H_6O					1		9.49	ne
Benzene		71-43-2	C_6H_6	0.55	+	0.47	+	0.6	+	9.25	0.5
Benzonitrile	Cyanobenzene	100-47-0	C_7H_5N			1.6				9.62	ne
Benzyl alcohol	α-Hydroxytoluene, Hydroxymethylbenzene, Benzenemethanol	100-51-6	C_7H_8O	1.4	+	0.8	+	0.9	+	8.26	ne
Benzyl chloride	α-Chlorotoluene, Chloromethylbenzene	100-44-7	C_7H_7Cl	0.7	+	0.6	+	0.5	+	9.14	1
Benzyl formate	Formic acid benzyl ester	104-57-4	$C_8H_8O_2$	0.9	+	0.73	+	0.66	+		ne
Boron trifluoride		7637-07-2	BF_3	NR		NR		NR		15.5	C1
Bromine		7726-95-6	Br_2	NR	+	1.30	+	0.74	+	10.51	0.1
Bromobenzene		108-86-1	C_6H_5Br			0.25		0.5		8.98	ne
2-Bromoethyl methyl ether		6482-24-2	C_3H_7OBr			0.84	+			~10	ne
Bromoform	Tribromomethane	75-25-2	$CHBr_3$	NR	+	1.6	+	0.5	+	10.48	0.5
Bromopropane,1-	n-Propyl bromide	106-94-5	C_3H_7Br	150	+	1.5	+	0.6	+	10.18	ne
Butadiene	1,3-Butadiene, Vinyl ethylene	106-99-0	C_4H_6	0.8		0.6	+	1.1		9.07	2
Butadiene diepoxide, 1,3-	1,2,3,4-Diepoxybutane	298-18-0	$C_4H_6O_2$	25	+	3.5	+	1.2		~10	ne
Butane		106-97-8	C_4H_{10}			67	+	1.2		10.53	800
Butanol, 1-	Butyl alcohol, n-Butanol	71-36-3	$C_4H_{10}O$	70	+	4.7	+	1.4	+	9.99	20
Butanol, t-	tert-Butanol, t-Butyl alcohol	75-65-0	$C_4H_{10}O$	6.9	+	2.9	+			9.90	100
Butene, 1-	1-Butylene	106-98-9	C_4H_8			0.9				9.58	ne
Butoxyethanol, 2-	Butyl Cellosolve, Ethylene glycol monobutyl ether	111-76-2	$C_6H_{14}O_2$	1.8	+	1.2	+	0.6	+	<10	25
Butoxyethyl Acetate, 2-	2-Butoxyethyl acetate; 2-Butoxyethanol acetate; Butyl Cellosolve acetate; Butyl glycol acetate; EGBEA; Ektasolve EB acetate	112-07-2	$C_8H_{16}O_3$			1.27	+				20
Butyl acetate, n-		123-86-4	$C_6H_{12}O_2$			2.6	+			10	150
Butyl acrylate, n-	Butyl 2-propenoate, Acrylic acid butyl ester	141-32-2	$C_7H_{12}O_2$			1.6	+	0.6	+		10
Butylamine, n-		109-73-9	$C_4H_{11}N$	1.1	+	1.1	+	0.7	+	8.71	C5
Butyl cellosolve see 2-Butoxyethanol		111-76-2									
Butyl hydroperoxide, t-		75-91-2	$C_4H_{10}O_2$	2.0	+	1.6	+			<10	1

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Butyl mercaptan	1-Butanethiol	109-79-5	$C_4H_{10}S$	0.55	+	0.52	+			9.14	0.5
Butyraldehyde	Butanal	123-72-8	C_4H_8O			1.87	+			9.82	20
Camelinal HRJ						1.1	+	0.32	+		
Camelinal HRJ/JP-8 50/50						0.89	+	0.41	+		
CamelinalHRJ						1.15	+				
CamelinalHRJ/JP-8						1.07	+				
Carbon disulfide		75-15-0	CS_2	4	+	1.2	+	0.44		10.07	10
Carbon tetrachloride	Tetrachloromethane	56-23-5	CCl_4	NR	+	NR	+	1.7	+	11.47	5
Carbonyl sulfide	Carbon oxysulfide	463-58-1	COS							11.18	
Cellosolve see 2-Ethoxyethanol											
CFC-14 see Tetrafluoromethane											
CFC-113 see 1,1,2-Trichloro-1,2,2-trifluoroethane											
Chlorine		7782-50-5	Cl_2					1.0	+	11.48	0.5
Chlorine dioxide		10049-04-4	ClO_2	NR	+	NR	+	NR	+	10.57	0.1
Chlorobenzene	Monochlorobenzene	108-90-7	C_6H_5Cl	0.44	+	0.3	+	0.39	+	9.06	10
Chlorobenzotrifluoride, 4-	PCBTF, OXSOL 100 p-Chlorobenzotrifluoride	98-56-6	$C_7H_4ClF_3$	0.74	+	0.63	+	0.55	+	<9.6	
Chloro-1,3-butadiene, 2-	Chloroprene	126-99-8	C_4H_5Cl			3					10
Chloro-1,1-difluoroethane, 1-	HCFC-142B, R-142B	75-68-3	$C_2H_3ClF_2$	NR		NR		NR		12.0	ne
Chlorodifluoromethane	HCFC-22, R-22	75-45-6	$CHClF_2$	NR		NR		NR		12.2	1000
Chloroethane	Ethyl chloride	75-00-3	C_2H_5Cl	NR	+	NR	+	1.1	+	10.97	100
Chloroethanol	Ethylene chlrohydrin	107-07-3	C_2H_5ClO							10.52	C1
Chloroethanol, 2-	2-Chloroethanol; 2-Chloroethyl alcohol; Ethylene chlorhydrin	107-07-3	C_2H_5ClO			2.88	+			10.5	5
Chloroethyl ether, 2-	bis (2-chloroethyl) ether	111-44-4	$C_4H_8Cl_2O$	8.6	+	3.0	+				5
Chloroethyl methyl ether, 2-	Methyl 2-chloroethyl ether	627-42-9	C_3H_7ClO			3					ne
Chloroform	Trichloromethane	67-66-3	$CHCl_3$	NR	+	NR	+	3.5	+	11.37	10
Chloro-2-methylpropene, 3-	Methallyl chloride, Isobutenyl chloride	563-47-3	C_4H_7Cl	1.4	+	1.2	+	0.63	+	9.76	ne
Chloropicrin		76-06-2	CCl_3NO_2	NR	+	~400	+	7	+		0.1
Chlorotoluene, o-	o-Chloromethylbenzene	95-49-8	C_7H_7Cl			0.5		0.6		8.83	50
Chlorotoluene, p-	p-Chloromethylbenzene	106-43-4	C_7H_7Cl					0.6		8.69	ne
Chlorotrifluoroethene	CTFE, Chlorotrifluoroethylene Genetron 1113	79-38-9	C_2ClF_3	6.7	+	3.9	+	1.2	+	9.76	5
Chlorotrimethylsilane		75-77-4	C_3H_9ClSi	NR		NR		0.82	+	10.83	ne
Cresol, m-	m-Hydroxytoluene, 3-Methylphenol	108-39-4	C_7H_8O	0.57	+	0.50	+	0.57	+	8.29	5
Cresol, o-	ortho-Cresol; 2-Cresol; o-Cresylic acid; 1-Hydroxy-2-methylbenzene; 2-Hydroxytoluene; 2-Methyl phenol	95-48-7	C_7H_8O			1	+			8.14	5
Cresol, p-	para-Cresol; 4-Cresol; p-Cresylic acid; 1-Hydroxy-4-methylbenzene; 4-Hydroxytoluene; 4-Methyl phenol	106-44-5	C_7H_8O			1.4	+			8.34	5
Crotonaldehyde	trans-2-Butenal	123-73-9 4170-30-3	C_4H_6O	1.5	+	1.1	+	1.0	+	9.73	2
Cumene	Isopropylbenzene	98-82-8	C_9H_{12}	0.58	+	0.54	+	0.4	+	8.73	50
Cyanogen bromide		506-68-3	CNBr	NR		NR		NR		11.84	ne
Cyanogen chloride		506-77-4	CNCl	NR		NR		NR		12.34	C0.3
Cyclohexane		110-82-7	C_6H_{12}	3.3	+	1.4	+	0.64	+	9.86	300
Cyclohexanol	Cyclohexyl alcohol	108-93-0	$C_6H_{12}O$	1.5	+	0.9	+	1.1	+	9.75	50
Cyclohexanone		108-94-1	$C_6H_{10}O$	1.0	+	0.9	+	0.7	+	9.14	25

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Cyclohexene		110-83-8	C_6H_{10}			0.8	+			8.95	300
Cyclohexylamine		108-91-8	$C_6H_{13}N$			2.2				8.62	10
Cyclopentane 85% 2,2-dimethylbutane 15%		287-92-3	C_5H_{10}	NR	+	15	+	1.1		10.33	600
Cyclopropylamine	Aminocyclpropane	765-30-0	C_3H_7N	1.1	+	0.7	+	0.9	+		ne
Decamethylcyclopentasiloxane		541-02-6	$C_{10}H_{30}O_5Si_5$	0.16	+	0.13	+	0.12	+		ne
Decamethyltetrasiloxane		141-62-8	$C_{10}H_{30}O_3Si_4$	0.17	+	0.13	+	0.12	+	<10.2	ne
Decane		124-18-5	$C_{10}H_{22}$	4.0	+	1.4	+	0.35	+	9.65	ne
Diacetone alcohol	4-Methyl-4-hydroxy-2-pentanone	123-42-2	$C_6H_{12}O_2$			0.7					50
Dibromochloromethane	Chlorodibromomethane	124-48-1	$CHBr_2Cl$	NR	+	3.5	+	0.7	+	10.59	ne
Dibromo-3-chloropropane, 1,2-	DBCP	96-12-8	$C_3H_5Br_2Cl$	NR	+	1.7	+	0.43	+		0.001
Dibromoethane, 1,2-	EDB, Ethylene dibromide, Ethylene bromide	106-93-4	$C_2H_4Br_2$	NR	+	1.7	+	0.6	+	10.37	ne
Dichlorobenzene, o-	1,2-Dichlorobenzene	95-50-1	$C_6H_4Cl_2$	0.54	+	0.45	+	0.38	+	9.08	25
Dichlorodifluoromethane	CFC-12	75-71-8	CCl_2F_2			NR	+	NR	+	11.75	1000
Dichlorodimethylsilane		75-78-5	$C_2H_6Cl_2Si$	NR		NR		1.1	+	>10.7	ne
Dichloroethane, 1,2-	EDC, 1,2-DCA, Ethylene dichloride	107-06-2	$C_2H_4Cl_2$			NR	+	0.6	+	11.04	10
Dichloroethene, 1,1-	1,1-DCE, Vinylidene chloride	75-35-4	$C_2H_2Cl_2$			0.82	+	0.8	+	9.79	5
Dichloroethene, c-1,2-	c-1,2-DCE, *cis*-Dichloroethylene	156-59-2	$C_2H_2Cl_2$			0.8				9.66	200
Dichloroethene, t-1,2-	t-1,2-DCE, *trans*-Dichloroethylene	156-60-5	$C_2H_2Cl_2$			0.45	+	0.34	+	9.65	200
Dichloro-1-fluoroethane, 1,1-	R-141B	1717-00-6	$C_2H_3Cl_2F$	NR	+	NR	+	2.0	+		ne
Dichloromethane see Methylene chloride											
Dichloropentafluoropropane	AK-225, mix of ~45% 3,3-dichloro-1,1,1,2,2-pentafluoropropane (HCFC-225ca) & ~55% 1,3-Dichloro-1,1,2,2,3-pentafluoropropane (HCFC-225cb)	442-56-0 507-55-1	$C_3HCl_2F_5$	NR	+	NR	+	25	+		ne
Dichloropropane, 1,2-		78-87-5	$C_3H_6Cl_2$					0.7		10.87	75
Dichloro-1-propene, 1,3-		542-75-6	$C_3H_4Cl_2$	1.3	+	0.96	+			<10	1
Dichloro-1-propene, 2,3-		78-88-6	$C_3H_4Cl_2$	1.9	+	1.3	+	0.7	+	<10	ne
Dichloro-1,1,1- trifluoroethane, 2,2-	R-123	306-83-2	$C_2HCl_2F_3$	NR	+	NR	+	10.1	+	11.5	ne
Dichloro-2,4,6- trifluoropyridine, 3,5-	DCTFP	1737-93-5	$C_5Cl_2F_3N$	1.1	+	1	+	0.8	+		ne
Dichlorvos**	Vapona; O,O-dimethyl O-dichlorovinyl phosphate	62-73-7	$C_4H_7Cl_2O_4P$			0.9	+			<9.4	0.1
Dicyclopentadiene	DCPD, Cyclopentadiene dimer	77-73-6	$C_{10}H_{12}$	0.57	+	0.47	+	0.43	+	8.8	5
Diesel Fuel**		68334-30-5	m.w. 226			0.9	+				11
Diesel Fuel #2 (Automotive)**		68334-30-5	m.w. 216	1.3		0.7	+	0.4	+		11
Diethylamine		109-89-7	$C_4H_{11}N$			1.6	+			8.01	5
Diethylaminopropylamine, 3-		104-78-9	$C_7H_{18}N_2$			1.9					ne
Diethylbenzene see Dowtherm J											
Diethyl ether	Diethyl ether; Diethyl oxide; Ethyl oxide; Ether; Solvent ether	60-29-7	$C_4H_{10}O$			1.74	+			9.51	400
Diethylene glycol butyl ether	2-(2-Butoxyethoxy)ethanol, BDG, Butyldiglycol, DB Solvent	112-34-5	$C_8H_{18}O_3$			4.6	+				5
Diethylene glycol monobutyl ether acetate	Butyldiglycol acetate, DB Acetate, Diethylene glycol monobutyl ether acetate	124-17-4	$C_{10}H_{20}O_4$			5.62	+				ne
Diethylmaleate		141-05-9	$C_8H_{12}O_4$			4					ne
Diethyl sulfide see Ethyl sulfide											
Diglyme see Methoxyethyl ether		111-96-6	$C_6H_{14}O_3$								

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Diisobutyl ketone	DIBK, 2,2-dimethyl-4-heptanone	108-83-8	$C_9H_{18}O$	0.71	+	0.61	+	0.35	+	9.04	25
Diisopropylamine		108-18-9	$C_6H_{15}N$	0.84	+	0.74	+	0.5	+	7.73	5
Diisopropylcarbodiimide,N,N'-	DIPC	693-13-0	$C_7H_{14}N_2$			0.42	+				ne
Diisopropylethylamine	'Hünig's base', *N*-Ethyldiisopropylamine, DIPEA, Ethyldiisopropylamine	7087-68-5	$C_8H_{19}N$			0.7	+				ne
Diketene	Ketene dimer	674-82-8	$C_4H_4O_2$	2.6	+	2.0	+	1.4	+	9.6	0.5
Dimethylacetamide, N,N-	DMA	127-19-5	C_4H_9NO	0.87	+	0.8	+	0.8	+	8.81	10
Dimethylamine		124-40-3	C_2H_7N			1.5				8.23	5
Dimethyl carbonate	Carbonic acid dimethyl ester	616-38-6	$C_3H_6O_3$	NR	+	~70	+	1.7	+	~10.5	ne
Dimethyl disulfide	DMDS	624-92-0	$C_2H_6S_2$	0.2	+	0.20	+	0.21	+	7.4	ne
Dimethyl ether see Methyl ether											
Dimethylethylamine	DMEA	598-56-1	$C_4H_{11}N$	1.1	+	1.0	+	0.9	+	7.74	~3
Dimethylformamide, N,N-	DMF	68-12-2	C_3H_7NO	0.7	+	0.7	+	0.8	+	9.13	10
Dimethylhydrazine, 1,1-	UDMH	57-14-7	$C_2H_8N_2$			0.8	+	0.8	+	7.28	0.01
Dimethyl methylphosphonate	DMMP, methyl phosphonic acid dimethyl ester	756-79-6	$C_3H_9O_3P$	NR	+	4.3	+	0.74	+	10.0	ne
Dimethyl sulfate		77-78-1	$C_2H_6O_4S$	~23		~20	+	2.3	+		0.1
Dimethyl sulfide see Methyl sulfide											
Dimethyl sulfoxide	DMSO, Methyl sulfoxide	67-68-5	C_2H_6OS			1.4	+			9.10	ne
Dioxane, 1,4-		123-91-1	$C_4H_8O_2$			1.3				9.19	25
Dioxolane, 1,3-	Ethylene glycol formal	646-06-0	$C_3H_6O_2$	4.0	+	2.3	+	1.6	+	9.9	20
Dowtherm A see Therminol®**											
Dowtherm J (97% Diethylbenzene)**		25340-17-4	$C_{10}H_{14}$			0.5					
DS-108F Wipe Solvent	Ethyl lactate/Isopar H/ Propoxypropanol ~7:2:1	97-64-3 64742-48-9 1569-01-3	m.w. 118	3.3	+	1.6	+	0.7	+		ne
Epichlorohydrin	ECH Chloromethyloxirane, 1-chloro2,3-epoxypropane	106-89-8	C_2H_5ClO	~200	+	8.5	+	1.4	+	10.2	0.5
Ethane		74-84-0	C_2H_6			NR	+	15	+	11.52	ne
Ethanol	Ethyl alcohol	64-17-5	C_2H_6O			7.9	+	3.1	+	10.47	1000
Ethanolamine**	MEA, Monoethanolamine	141-43-5	C_2H_7NO	5.6	+	21.9	+			8.96	3
Ethene	Ethylene	74-85-1	C_2H_4			9	+	4.5	+	10.51	ne
Ethoxyethanol, 2-	Ethyl cellosolve, Ethylene glycol monoethyl ether	110-80-5	$C_4H_{10}O_2$			1.3				9.6	5
Ethyl acetate	Acetic ester; Acetic ether; Ethyl ester of acetic acid; Ethyl ethanoate	141-78-6	$C_4H_8O_2$			3.2	+	2.18	+	10.01	400
Ethyl acetoacetate		141-97-9	$C_6H_{10}O_3$	1.4	+	1.2	+	1.0	+	<10	ne
Ethyl acrylate		140-88-5	$C_5H_8O_2$			2.4	+	1.0	+	<10.3	5
Ethylamine		75-04-7	C_2H_7N			0.8				8.86	5
Ethylbenzene		100-41-4	C_8H_{10}	0.52	+	0.47	+	0.51	+	8.77	100
Ethyl caprylate	Ethyl octanoate	106-32-1	$C_{10}H_{20}O_2$		+	0.52	+	0.51	+		
Ethylenediamine	1,2-Ethanediamine; 1,2-Diaminoethane	107-15-3	$C_2H_8N_2$	0.9	+	1.35	+	1.0	+	8.6	10
(Ethylenedioxy)diethanethiol, 2,2'-	1,2-Bis(2-mercaptoethoxy)ethane, 3,6-Dioxa-1,8-octane-dithiol	14970-87-7	$C_6H_{14}O_2S_2$			1.3	+				ne
Ethylene glycol**	1,2-Ethanediol	107-21-1	$C_2H_6O_2$			16	+	6	+	10.16	C100
Ethylene glycol, Acrylate**	2-hydroxyethyl Acrylate	818-61-1	$C_5H_8O_3$			8.2				≤10.6	
Ethylene glycol dimethyl ether	1,2-Dimethoxyethane, Monoglyme	110-71-4	$C_4H_{10}O_2$	1.1		0.85		0.7		9.2	ne
Ethylene glycol monobutyl ether acetate	1,2-Dimethoxyethane, Monoglyme	110-71-4	$C_4H_{10}O_2$	1.1		1.1		0.7		9.2	ne

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Ethylene glycol, monothio		60-24-2	C_2H_6OS			1.5				9.65	
Ethylene oxide	Oxirane, Epoxyethane	75-21-8	C_2H_4O			13	+	3.5	+	10.57	1
Ethyl ether	Diethyl ether	60-29-7	$C_4H_{10}O$			1.1	+			9.51	400
Ethyl 3-ethoxypropionate	EEP	763-69-9	$C_7H_{14}O_3$	1.2	+	0.75	+				ne
Ethyl formate		109-94-4	$C_3H_6O_2$					1.9		10.61	100
Ethyl-1-hexanol, 2-	Isooctyl alcohol	104-76-7	$C_8H_{18}O$			1.9	+				ne
Ethyl hexyl acrylate, 2-	Acrylic acid 2-ethylhexyl ester	103-11-7	$C_{11}H_{20}O_2$			1.1	+	0.5	+		ne
Ethylidenenorbornene	5-Ethylidene bicyclo(2,2,1) hept-2-ene	16219-75-3	C_9H_{12}	0.4	+	0.39	+	0.34	+	≤8.8	ne
Ethyl (S)-(-)-lactate see also DS-108F	Ethyl lactate, Ethyl (S)-(-)-hydroxypropionate	687-47-8 97-64-3	$C_5H_{10}O_3$	13	+	3.2	+	1.6	+	~10	ne
Ethyl mercaptan	Ethanethiol	75-08-1	C_2H_6S	0.60	+	0.56	+			9.29	0.5
Ethyl sulfide	Diethyl sulfide	352-93-2	$C_4H_{10}S$			0.5	+			8.43	ne
Formaldehyde	Formalin	50-00-0	CH_2O	NR	+	NR	+	1.6	+	10.87	C0.3
Formamide		75-12-7	CH_3NO			6.9	+	4		10.16	10
Formic acid		64-18-6	CH_2O_2	NR	+	NR	+	9	+	11.33	5
Furfural	2-Furaldehyde	98-01-1	$C_5H_4O_2$			0.7	+	0.8	+	9.21	2
Furfuryl alcohol		98-00-0	$C_5H_6O_2$			0.80	+			<9.5	10
Gasoline #1		8006-61-9	m.w. 72			0.9	+				300
Gasoline #2, 92 octane		8006-61-9	m.w. 93	1.3	+	1.0	+	0.5	+		300
Glutaraldehyde	1,5-Pentanedial, Glutaric dialdehyde	111-30-8	$C_5H_8O_2$	1.1	+	0.8	+	0.6	+		C0.05
Glycidyl methacrylate	2,3-Epoxypropyl methacrylate	106-91-2	$C_7H_{10}O_3$	2.6	+	1.2	+	0.9	+		0.5
Halothane	2-Bromo-2-chloro-1,1,1-trifluoroethane	151-67-7	$C_2HBrClF_3$					0.6		11.0	50
HCFC-22 see Chlorodifluoromethane											
HCFC-123 see 2,2-Dichloro-1,1,1-trifluoroethane											
HCFC-141B see 1,1-Dichloro-1-fluoroethane											
HCFC-142B see 1-Chloro-1,1-difluoroethane											
HCFC-134A see 1,1,1,2-Tetrafluoroethane											
HCFC-225 see Dichloropentafluoropropane											
Heptane, n-		142-82-5	C_7H_{16}	45	+	2.8	+	0.60	+	9.92	400
Heptanol, 4-	Dipropylcarbinol	589-55-9	$C_7H_{16}O$	1.8	+	1.3	+	0.5	+	9.61	ne
Hexamethyldisilazane, 1,1,1,3,3,3-**	HMDS	999-97-3	$C_6H_{19}NSi_2$			0.39	+	0.39	+	~8.6	ne
Hexamethyldisiloxane	HMDSx	107-46-0	$C_6H_{18}OSi_2$	0.33	+	0.34	+	0.34	+	9.64	ne
Hexane, n-		110-54-3	C_6H_{14}	350	+	5.1	+	0.51	+	10.13	50
Hexanol, 1-	Hexyl alcohol	111-27-3	$C_6H_{14}O$	9	+	2.5	+	0.55	+	9.89	ne
Hexene, 1-		592-41-6	C_6H_{12}			0.8				9.44	30
HFE-7100 see Methyl nonafluorobutyl ether											
Histoclear (Histo-Clear)	Limonene/corn oil reagent		m.w. ~136	0.5	+	0.4	+	0.3	+		ne
Hydrazine**		302-01-2	H_4N_2	>8	+	2.6	+	2.1	+	8.1	0.01
Hydrazoic acid	Hydrogen azide		HN_3							10.7	
Hydrogen	Synthesis gas	1333-74-0	H_2	NR	+	NR	+	NR	+	15.43	ne
Hydrogen cyanide	Hydrocyanic acid	74-90-8	HCN	NR	+	NR	+	NR	+	13.6	C4.7
Hydrogen iodide**	Hydriodic acid	10034-85-2	HI			~0.6				10.39	
Hydrogen peroxide		7722-84-1	H_2O_2	NR	+	NR	+	NR	+	10.54	1
Hydrogen sulfide		7783-06-4	H_2S	NR	+	3.3	+	1.5	+	10.45	10
Hydroxyethyl acrylate, 2-	Ethylene glycol monoacrylate	818-61-1	$C_5H_8O_3$			8.2	+				ne
Hydroxypropyl methacrylate		27813-02-1 923-26-2	$C_7H_{12}O_3$	9.9	+	2.3	+	1.1	+		ne

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Iodine**		7553-56-2	I_2	0.1	+	0.1	+	0.1	+	9.40	C0.1
Iodomethane	Methyl iodide	74-88-4	CH_3I	0.21	+	0.22	+	0.26	+	9.54	2
Isoamyl acetate	Isopentyl acetate	123-92-2	$C_7H_{14}O_2$	10.1		2.1		1.0		<10	100
Isobutane	2-Methylpropane	75-28-5	C_4H_{10}			100	+	1.2	+	10.57	ne
Isobutanol	2-Methyl-1-propanol	78-83-1	$C_4H_{10}O$	19	+	3.8	+	1.5		10.02	50
Isobutene	Isobutylene, Methyl butene	115-11-7	C_4H_8	1.00	+	1.00	+	1.00	+	9.24	ne
Isobutyl acetate	2-methylpropyl ethanoate, β-methylpropyl acetate	110-19-0	$C_6H_{12}O_2$			2.1	+			9.97	150
Isobutyl acrylate	Isobutyl 2-propenoate, Acrylic acid Isobutyl ester	106-63-8	$C_7H_{12}O_2$			1.5	+	0.60	+		ne
Isoflurane	1-Chloro-2,2,2-trifluoroethyl difluoromethyl ether, forane	26675-46-7	$C_3H_2ClF_5O$	NR	+	NR	+	48	+	~11.7	ne
Isooctane	2,2,4-Trimethylpentane	540-84-1	C_8H_{18}			1.2				9.86	ne
Isopar E Solvent	Isoparaffinic hydrocarbons	64741-66-8	m.w. 121	1.7	+	0.8	+				ne
Isopar G Solvent	Photocopier diluent	64742-48-9	m.w. 148			0.8	+				ne
Isopar K Solvent	Isoparaffinic hydrocarbons	64742-48-9	m.w. 156	0.9	+	0.5	+	0.27	+		ne
Isopar L Solvent	Isoparaffinic hydrocarbons	64742-48-9	m.w. 163	0.9	+	0.5	+	0.28	+		ne
Isopar M Solvent	Isoparaffinic hydrocarbons	64742-47-8	m.w. 191			0.7	+	0.4	+		ne
Isopentane	2-Methylbutane	78-78-4	C_5H_{12}			8.2					ne
Isophorone		78-59-1	$C_9H_{14}O$					3		9.07	C5
Isoprene	2-Methyl-1,3-butadiene	78-79-5	C_5H_8	0.69	+	0.63	+	0.60	+	8.85	ne
Isopropanol	Isopropyl alcohol, 2-propanol, IPA	67-63-0	C_3H_8O	500	+	4.2	+	2.7		10.12	200
Isopropyl acetate		108-21-4	$C_5H_{10}O_2$			2.6				9.99	100
Isopropyl ether	Diisopropyl ether	108-20-3	$C_6H_{14}O$			0.8				9.20	250
Jet fuel JP-4	Jet B, Turbo B, F-40 Wide cut type aviation fuel	8008-20-6 + 64741-42-0	m.w. 115			1.0	+	0.4	+		ne
Jet fuel JP-5	Jet 5, F-44, Kerosene type aviation fuel	8008-20-6 + 64747-77-1	m.w. 167			0.6	+	0.5	+		29
Jet fuel JP-8	F-34, Kerosene type aviation fuel	8008-20-6 + 64741-77-1	m.w. 165			0.94	+	0.3	+		30
Jet fuel A-1	F-34, Kerosene type aviation fuel	8008-20-6 + 64741-77-1	m.w. 145			0.6					34
Jet Fuel TS	Thermally Stable Jet Fuel, Hydrotreated kerosene fuel	8008-20-6 + 64742-47-8	m.w. 165	0.9	+	0.6	+	0.3	+		30
JP-10						0.7	+	0.5	+		
JP5, Petroleum/camelinal						1.05	+				
JP5/Petroleum						0.98	+				
Limonene, D-	(R)-(+)-Limonene	5989-27-5	$C_{10}H_{16}$			0.33	+			~8.2	ne
Kerosene C10-C16 petro.distillate	see Jet Fuels	8008-20-6									
MDI see 4,4'-Methylenebis (phenylisocyanate)											
Maleic anhydride	2,5-Furandione	108-31-6	$C_4H_2O_3$							~10.8	0.1
Mercapto-2-ethanol	β-Mercaptoethanol, 2-Hydroxyethylmercaptan, BME, Thioethylene glycol	60-24-2	C_2H_6OS			1.5	+			9.65	0.2
Mesitylene	1,3,5-Trimethylbenzene	108-67-8	C_9H_{12}	0.36	+	0.35	+	0.3	+	8.41	25
Methallyl chloride see 3-Chloro-2-methylpropene											
Methane	Natural gas	74-82-8	CH_4	NR	+	NR	+	NR	+	12.61	ne
Methanol	Methyl alcohol, carbinol	67-56-1	CH_4O	NR	+	NR	+	2.5	+	10.85	200
Methoxyethanol, 2-	Methyl cellosolve, Ethylene glycol monomethyl ether	109-86-4	$C_3H_8O_2$	4.8	+	2.4	+	1.4	+	10.1	5

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Methoxyethoxyethanol, 2-	2-(2-Methoxyethoxy)ethanol Diethylene glycol monomethyl ether	111-77-3	$C_5H_{12}O_3$	2.3	+	1.2	+	0.9	+	<10	ne
Methoxyethyl ether, 2-	bis(2-Methoxyethyl) ether, Diethylene glycol dimethyl ether, Diglyme	111-96-6	$C_6H_{14}O_3$	0.64	+	0.54	+	0.44	+	<9.8	ne
Methyl acetate		79-20-9	$C_3H_6O_2$	NR	+	6.6	+	1.4	+	10.27	200
Methyl acrylate	Methyl 2-propenoate, Acrylic acid methyl ester	96-33-3	$C_4H_6O_2$			3.7	+	1.2	+	(9.9)	2
Methylamine	Aminomethane	74-89-5	CH_5N			1.2				8.97	5
Methyl amyl ketone	MAK, 2-Heptanone, Methyl pentyl ketone	110-43-0	$C_7H_{14}O$	0.9	+	0.85	+	0.5	+	9.30	50
Methylaniline, N-	MA; (Methylamino) benzene; N-Methyl aniline; Methylphenylamine; N-Phenylmethylamin	100-61-8	C_7H_9N			0.58	+			7.32	2
Methyl bromide	Bromomethane	74-83-9	CH_3Br	110	+	1.7	+	1.3	+	10.54	1
Methyl-2-butanol, 2-	*tert*-Amyl alcohol, *tert*-Pentyl alcohol	75-85-4	$C_5H_{12}O$			1.62	+			10.16	100
Methyl t-butyl ether	MTBE, tert-Butyl methyl ether	1634-04-4	$C_5H_{12}O$			0.9	+			9.24	40
Methyl cellosolve see 2-Methoxyethanol											
Methyl chloride	Chloromethane	74-87-3	CH_3Cl	NR	+	NR	+	0.74	+	11.22	50
Methylcyclohexane		107-87-2	C_7H_{14}	1.6	+	0.97	+	0.53	+	9.64	400
Methylene bis (phenyl-isocyanate), 4,4'-**	MDI, Mondur M		$C_{15}H_{10}N_2O_2$	Very slow ppb level response							0.005
Methylene chloride	Dichloromethane	75-09-2	CH_2Cl_2	NR	+	NR	+	0.89	+	11.32	25
Methyl ether	Dimethyl ether	115-10-6	C_2H_6O	4.8	+	3.1	+	2.5	+	10.03	ne
Methyl ethyl ketone	MEK, 2-Butanone	78-93-3	C_4H_8O	0.86	+	0.8	+	1.1	+	9.51	200
Methylhydrazine	Monomethylhydrazine, Hydrazomethane	60-34-4	$C_2H_6N_2$	1.4	+	2.5	+	1.3	+	7.7	0.01
Methyl isoamyl ketone	MIAK, 5-Methyl-2-hexanone	110-12-3	$C_7H_{14}O$	0.8	+	0.76	+	0.5	+	9.28	50
Methyl isobutyl ketone	MIBK, 4-Methyl-2-pentanone	108-10-1	$C_6H_{12}O$	0.9	+	0.8	+	0.6	+	9.30	50
Methyl isocyanate		624-83-9	C_2H_3NO	NR	+	4.6	+	1.5		10.67	0.02
Methyl isothiocyanate		551-61-6	C_2H_3NS	0.5	+	0.45	+	0.4	+	9.25	ne
Methyl mercaptan	Methanethiol	74-93-1	CH_4S	0.65		0.54		0.66		9.44	0.5
Methyl methacrylate		80-62-6	$C_5H_8O_2$	2.7	+	1.5	+	1.2	+	9.7	100
Methyl nonafluorobutyl ether	HFE-7100DL	163702-08-7, 163702-07-6	$C_5H_3F_9O$			NR	+	~35	+		ne
Methyl-1,5-pentanediamine, 2- (coats lamp)**	Dytek-A amine, 2-Methyl pentamethylenediamine	15520-10-2	$C_6H_{16}N_2$			~0.6	+			<9.0	ne
Methyl propyl ketone	MPK, 2-Pentanone	107-87-9	$C_5H_{12}O$			0.93	+	0.79	+	9.38	200
Methyl-2-pyrrolidinone, N-	NMP, N-Methylpyrrolidone, 1-Methyl-2-pyrrolidinone, 1-Methyl-2-pyrrolidone	872-50-4	C_5H_9NO	1.0	+	0.8	+	0.9	+	9.17	ne
Methyl salicylate**	Methyl 2-hydroxybenzoate	119-36-8	$C_8H_8O_3$	1.3	+	0.9	+	0.9	+	~9	ne
Methylstyrene, α-	2-Propenylbenzene	98-83-9	C_9H_{10}			0.5				8.18	50
Methyl sulfide	DMS, Dimethyl sulfide	75-18-3	C_2H_6S	0.49	+	0.44	+	0.46	+	8.69	ne
Methyl vinyl ketone	MVK, 3-Buten-2-one	78-94-4	C_4H_6O			0.93	+			9.65	ne
Methyltetrahydrofuran	2-MeTHF, Tetrahydro-2-methylfuran, Tetrahydrosilvan	96-47-9	$C_5H_{10}O$			2.44	+			9.22	ne
Mineral spirits	Stoddard Solvent, Varsol 1, White Spirits	8020-83-5 8052-41-3 68551-17-7	m.w. 144	1.0		0.69	+	0.38	+		100
Mineral Spirits	Viscor 120B Calibration Fluid, b.p. 156-207°C	8052-41-3	m.w. 142	1.0	+	0.7	+	0.3	+		100

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Monoethanolamine see Ethanolamine											
Mustard	HD, Bis (2-chloroethyl) sulfide	505-60-2 39472-40-7 68157-62-0	$C_4H_8Cl_2S$			0.6					0.0005
Naphtha see VM & P Naphtha											
Naphthalene	Mothballs	91-20-3	$C_{10}H_8$	0.45	+	0.42	+	0.40	+	8.13	10
Nickel carbonyl (in CO)	Nickel tetracarbonyl	13463-39-3	C_4NiO_4			0.18				<8.8	0.001
Nicotine	3-(1-Methyl-2-pyrrolidyl)pyridine	54-11-5	$C_{10}H_{14}N_2$			1.98	+				ne
Nitric oxide		10102-43-9	NO	~6		5.0	+	2.8	+	9.26	25
Nitrobenzene		98-95-3	$C_6H_5NO_2$	2.6	+	1.6	+	1.6	+	9.81	1
Nitroethane		79-24-3	$C_2H_5NO_2$					3		10.88	100
Nitrogen dioxide		10102-44-0	NO_2	23	+	16	+	6	+	9.75	3
Nitrogen trifluoride		7783-54-2	NF_3	NR		NR		NR		13.0	10
Nitromethane		75-52-5	CH_3NO_2					4		11.02	20
Nitropropane, 2-		79-46-9	$C_3H_7NO_2$					2.6		10.71	10
Nonane		111-84-2	C_9H_{20}			1.4				9.72	200
Norpar 12	n-Paraffins, mostly C_{10}-C_{13}	64771-72-8	m.w. 161	3.2	+	1.1	+	0.28	+		ne
Norpar 13	n-Paraffins, mostly C_{13}-C_{14}	64771-72-8	m.w. 189	2.7	+	1.0	+	0.3	+		ne
Octamethylcyclotetrasiloxane		556-67-2	$C_8H_{24}O_4Si_4$	0.21	+	0.17	+	0.14	+		ne
Octamethyltrisiloxane		107-51-7	$C_8H_{24}O_2Si_3$	0.23	+	0.16	+	0.17	+	<10.0	ne
Octane, n-		111-65-9	C_8H_{18}	13	+	1.8	+			9.82	300
Octene, 1-		111-66-0	C_8H_{16}	0.9	+	0.75	+	0.4	+	9.43	75
Pentachloropropane	1,1,1,3,3-pentachloropropane	23153-23-3	$C_3H_3Cl_5$					1.25	+		0.1
Pentane		109-66-0	C_5H_{12}	80	+	9.0	+	0.7	+	10.35	600
Peracetic acid**	Peroxyacetic acid, Acetyl hydroperoxide	79-21-0	$C_2H_4O_3$	NR	+	NR	+	2.3	+		ne
Peracetic/Acetic acid mix**	Peroxyacetic acid, Acetyl hydroperoxide	79-21-0	$C_2H_4O_3$			50	+	2.5	+		ne
Perchloroethene	PCE, Perchloroethylene, Tetrachloroethylene	127-18-4	C_2Cl_4	0.69	+	0.57	+	0.31	+	9.32	25
Propylene glycol methyl ether, 1-Methoxy-2-propanol	PGME	107-98-2	$C_6H_{12}O_3$	2.4	+	1.2	+	1.1	+		100
Propylene glycol methyl ether acetate, 1-Methoxy-2-acetoxypropane, 1-Methoxy-2-propanol acetate	PGMEA	108-65-6	$C_6H_{12}O_3$	1.65	+	1.0	+	0.8	+		ne
Phenol	Hydroxybenzene	108-95-2	C_6H_6O	1.0	+	1.6	+	0.9	+	8.51	5
Phosgene	Dichlorocarbonyl	75-44-5	CCl_2O	NR	+	NR	+	8.5	+	11.2	0.1
Phosgene in Nitrogen	Dichlorocarbonyl	75-44-5	CCl_2O	NR	+	NR	+	6.8	+	11.2	0.1
Phosphine (coats lamp)		7803-51-2	PH_3	28		3.9	+	1.1	+	9.87	0.3
Photocopier Toner	Isoparaffin mix					0.5	+	0.3	+		ne
Picoline, 3-	3-Methylpyridine	108-99-6	C_6H_7N			0.9				9.04	ne
Pinene, α-		2437-95-8	$C_{10}H_{16}$			0.31	+	0.47		8.07	ne
Pinene, β-		18172-67-3	$C_{10}H_{16}$	0.38	+	0.37	+	0.37	+	~8	100
Piperylene, isomer mix	1,3-Pentadiene	504-60-9	C_5H_8	0.76	+	0.69	+	0.64	+	8.6	100
Propane		74-98-6	C_3H_8			NR	+	1.8	+	10.95	2500
Propanol, n-	Propyl alcohol	71-23-8	C_3H_8O			5.1		1.7		10.22	200
Propene	Propylene	115-07-1	C_3H_6	1.5	+	1.4	+	1.6	+	9.73	ne
Propionaldehyde	Propanal	123-38-6	C_3H_6O			1.9				9.95	ne
Propyl acetate, n-		109-60-4	$C_5H_{10}O_2$			3.5				10.04	200
Propyl acetate	Propylacetate; n-Propyl ester of acetic acid	109-60-4	$C_5H_{10}O_2$			2.27	+			10.04	200

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Propylamine, n-	1-Propylamine, 1-Aminopropane	107-10-8	C_3H_9N	1.1	+	1.1	+	0.9	+	8.78	ne
Propylene carbonate[**]		108-32-7	$C_4H_6O_3$			62	+	1	+	10.5	ne
Propylene glycol	1,2-Propanediol	57-55-6	$C_3H_8O_2$	18		4.0	+	1.6	+	<10.2	ne
Propylene glycol propyl ether	1-Propoxy-2-propanol	1569-01-3	$C_6H_{14}O_2$	1.3	+	1.0	+	1.6	+		ne
Propylene oxide	Methyloxirane	75-56-9 16088-62-3 15448-47-2	C_3H_6O	~240		6.6	+	2.9	+	10.22	20
Propyleneimine	2-Methylaziridine	75-55-8	C_3H_7N	1.5	+	1.3	+	1.0	+	9.0	2
Propyl mercaptan, 2-	2-Propanethiol, Isopropyl mercaptan	75-33-2	C_3H_8S	0.64	+	0.66	+			9.15	ne
Pyridine		110-86-1	C_5H_5N	0.78	+	0.7	+	0.7	+	9.25	5
Pyrrolidine (coats lamp)	Azacyclohexane	123-75-1	C_4H_9N	2.1	+	1.3	+	1.6	+	~8.0	ne
RR7300 (PGME/PGMEA)	70:30 PGME:PGMEA (1-Methoxy-2-propanol: 1-Methoxy-2-acetoxypropane)	107-98-2	$C_4H_{10}O_2$/ $C_6H_{12}O_3$			1.4	+	1.0	+		ne
Sarin	GB, Isopropyl methylphosphonofluoridate	107-44-8 50642-23-4	$C_4H_{10}FO_2P$			~3					
Shell SPK						1.26	+				
Shell SPK						1.29	+	0.4	+		
Shell SPK 50/50						1.02	+	0.41	+		
Shell SPK/JP-8						1.11	+				
Stoddard Solvent see Mineral Spirits		8020-83-5									
Styrene		100-42-5	C_8H_8	0.45	+	0.43	+	0.4	+	8.43	20
Sulfur dioxide		7446-09-5	SO_2	NR		NR	+	NR	+	12.32	2
Sulfur hexafluoride		2551-62-4	SF_6	NR		NR		NR		15.3	1000
Sulfuryl fluoride	Vikane	2699-79-8	SO_2F_2	NR		NR		NR		13.0	5
Tabun[**]	Ethyl N, N-dimethylphosphoramidocyanidate	77-81-6	$C_5H_{11}N_2O_2P$			0.8					15ppt
Tallow HRJ						1.09	+				
Tallow HRJ						0.95	+	0.36	+		
Tallow HRJ/JP-8						1.14	+				
Tallow HRJ/JP-8 50/50						0.9	+	0.39	+		
Tetrachloroethane, 1,1,1,2-		630-20-6	$C_2H_2Cl_4$					1.3		~11.1	ne
Tetrachloroethane, 1,1,2,2-		79-34-5	$C_2H_2Cl_4$	NR	+	NR	+	0.60	+	~11.1	1
Tetrachlorosilane		10023-04-7	$SiCl_4$	NR		NR		15	+	11.79	ne
Tetraethyllead	TEL	78-00-2	$C_8H_{20}Pb$	0.4		0.3		0.2		~11.1	0.008
Tetraethyl orthosilicate	Ethyl silicate, TEOS	78-10-4	$C_8H_{20}O_4Si$			0.7	+	0.2	+	~9.8	10
Tetrafluoroethane, 1,1,1,2-	HFC-134A	811-97-2	$C_2H_2F_4$			NR		NR			ne
Tetrafluoroethene	TFE, Tetrafluoroethylene, Perfluoroethylene	116-14-3	C_2F_4			~15				10.12	ne
Tetrafluoromethane	CFC-14, Carbon tetrafluoride	75-73-0	CF_4			NR	+	NR	+	>15.3	ne
Tetrahydrofuran	THF	109-99-9	C_4H_8O	1.9	+	1.7	+	1.0	+	9.41	200
Tetramethyl orthosilicate	Methyl silicate, TMOS	681-84-5	$C_4H_{12}O_4Si$	10	+	1.3	+			~10	1
Therminol® D-12[**]	Hydrotreated heavy naphtha	64742-48-9	m.w. 160	0.8	+	0.51	+	0.33	+		ne
Therminol® VP-1[**]	Dowtherm A, 3:1 Diphenyl oxide: Biphenyl	101-84-8 92-52-4	$C_{12}H_{10}O$ $C_{12}H_{10}$			0.4	+				1
Toluene	Methylbenzene	108-88-3	C_7H_8	0.54	+	0.45	+	0.51	+	8.82	50
Tolylene-2,4-diisocyanate	TDI, 4-Methyl-1,3-phenylene-2,4-diisocyanate	584-84-9	$C_9H_6N_2O_2$	1.4	+	1.4	+	2.0	+		0.002
Trichlorobenzene, 1,2,4-	1,2,4-TCB	120-82-1	$C_6H_3Cl_3$	0.7	+	0.45	+			9.04	C5
Trichloroethane, 1,1,1-	1,1,1-TCA, Methyl chloroform	71-55-6	$C_2H_3Cl_3$			NR	+	1	+	11	350

Compound Name	Synonym/Abbreviation	CAS No.	Formula	9.8	C	10.6	C	11.7	C	IE (eV)	TWA
Trichloroethane, 1,1,2-	1,1,2-TCA	79-00-5	$C_2H_3Cl_3$	NR	+	NR	+	0.9	+	11.0	10
Trichloroethene	TCE, Trichoroethylene	79-01-6	C_2HCl_3	0.62	+	0.54	+	0.43	+	9.47	50
Trichloromethylsilane	Methyltrichlorosilane	75-79-6	CH_3Cl_3Si	NR		NR		1.8	+	11.36	ne
Trichlorotrifluoroethane, 1,1,2-	CFC-113	76-13-1	$C_2Cl_3F_3$			NR		NR		11.99	1000
Triethylamine	TEA	121-44-8	$C_6H_{15}N$	0.95	+	0.97	+	0.65	+	7.3	1
Triethyl borate	TEB; Boric acid triethyl ester, Boron ethoxide	150-46-9	$C_6H_{15}O_3B$			2.2	+	1.1	+	~10	ne
Triethyl phosphate	Ethyl phosphate	78-40-0	$C_6H_{15}O_4P$	~50	+	3.1	+	0.60	+	9.79	ne
Trifluoroethane, 1,1,2-		430-66-0	$C_2H_3F_3$					34		12.9	ne
Trimethylamine		75-50-3	C_3H_9N			0.97				7.82	5
Trimethylbenzene, 1,3,5- see Mesitylene		108-67-8									25
Trimethyl borate	TMB; Boric acid trimethyl ester, Boron methoxide	121-43-7	$C_3H_9O_3B$			5.1	+	1.2	+	10.1	ne
Trimethyl phosphate	Methyl phosphate	512-56-1	$C_3H_9O_4P$			9.2	+	1.3	+	9.99	ne
Trimethyl phosphite	Methyl phosphite	121-45-9	$C_3H_9O_3P$			1.6	+		+	8.5	2
Turpentine	Pinenes (85%) + other diisoprenes	8006-64-2	$C_{10}H_{16}$	0.37	+	0.3	+	0.29	+	~8	20
Undecane		1120-21-4	$C_{11}H_{24}$			2				9.56	ne
Varsol see Mineral Spirits											
Vinyl actetate		108-05-4	$C_4H_6O_2$	1.5	+	1.2	+	1.0	+	9.19	10
Vinyl bromide	Bromoethylene	593-60-2	C_2H_3Br			0.4				9.80	5
Vinyl chloride	Chloroethylene, VCM	75-01-4	C_2H_3Cl			2.0	+	0.6	+	9.99	5
Vinyl-1-cyclohexene, 4-	Butadiene dimer, 4-Ethenylcyclohexene	100-40-3	C_8H_{12}	0.6	+	0.56	+			9.83	0.1
Vinylidene chloride see 1,1-Dicholorethene											
Vinyl-2-pyrrolidinone, 1-	NVP, N-vinylpyrrolidone, 1-ethenyl-2-pyrrolidinone	88-12-0	C_6H_9NO	1.0	+	0.8	+	0.9	+		ne
Viscor 120B see Mineral Spirits—Viscor 120B Calibration Fluid											
V. M. & P. Naphtha	Ligroin; Solvent naphtha; Varnish maker's & painter's naphtha	64742-89-8	m.w. 111 (C_8-C_9)	1.7	+	0.97	+				300
Xylene, m-	1,3-Dimethylbenzene	108-38-3	C_8H_{10}	0.50	+	0.44	+	0.40	+	8.56	100
Xylene, o-	1,2-Dimethylbenzene	95-47-6	C_8H_{10}	0.56	+	0.45	+	0.43		8.56	100
Xylene, p-	1,4-Dimethylbenzene	106-42-3	C_8H_{10}	0.48	+	0.39	+	0.38	+	8.44	100

* The term "ionization energy" is more scientifically correct and replaces the old term "ionization potential." High-boiling ("heavy") compounds may not vaporize enough to give a response even when their ionization energies are below the lamp photon energy. Some inorganic compounds like H_2O_2 and NO_2 give weak response even when their ionization energies are well below the lamp photon energy.

** Compounds indicated in green can be detected using a MiniRAE 3000, UltraRAE 3000 or ppbRAE 3000 with slow response, but may be lost by adsorption on a MultiRAE, EntryRAE and AreaRAE. Response on multi-gas meters can give an indication of relative concentrations, but may not be quantitative and for some chemicals no response is observed.

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MiniRAE 3000
ppbRAE 3000

Basic Operation
Pocket Reference

PN: 059-4030-000-D
Rev. B August 2010

MiniRAE 3000/ppbRAE 3000 Pocket Reference

Read Before Operating

This Pocket Reference is intended as a quick guide to basic use and calibration of your instrument. It does not cover advanced features. Information on advanced features and other operation modes is included in the User's Guide.

The User's Guide must be carefully read by all individuals who have or will have the responsibility of using, maintaining, or servicing this product. The product will perform as designed only if it is used, maintained, and serviced in accordance with the manufacturer's instructions. The user should understand how to set the correct parameters and interpret the obtained results.

CAUTION!

To reduce the risk of electric shock, turn the power off before removing the instrument cover. Disconnect the battery before removing sensor module for service. Never operate the instrument when the cover is removed. Remove instrument cover and sensor module only in an area known to be non-hazardous.

MiniRAE 3000/ppbRAE 3000 Pocket Reference

WARNINGS

STATIC HAZARD: Clean only with damp cloth.
For safety reasons, this equipment must be operated and serviced by qualified personnel only. Read and understand the User’s Guide completely before operating or servicing.

Use only RAE Systems battery packs, part numbers 059-3051-000, 059-3052-000, and 059-3054-000. This instrument has not been tested in an explosive gas/air atmosphere having an oxygen concentration greater than 21%. Substitution of components may impair intrinsic safety. Recharge batteries only in non-hazardous locations.

Do not mix old and new batteries or batteries from different manufacturers.

The calibration of all newly purchased RAE Systems instruments should be tested by exposing the sensor(s) to known concentration calibration gas before the instrument is put into service.

For maximum safety, the accuracy of the instrument should be checked by exposing it to a known concentration calibration gas before each day’s use.

Do not use USB/PC communication in hazardous locations.

Intrinsic Safety: US and Canada: Class I, Division 1,
Groups A,B, C, D
Europe: ATEX (0575 Ex II 2G Ex ia
IIC/IIB T4 Gb)
KEMA 07 ATEX 0127
Complies with EN60079-0:2009,
EN60079-11:2007
IECEx CSA 10.0005 Ex ia IIC/IIB T4 Gb
Complies with IEC 60079-0:2007,
IEC 60079-11:2006
(IIC: 059-3051-000 Li-ion bat pack or
059-3054-000 NiMH bat pack;
IIB: 059-3052-000 alkaline bat pack)

Special Notes

⚠ When the instrument is taken out of the transport case and turned on for the first time, there may be some residual organic or inorganic vapor trapped inside the detector chamber. The initial PID sensor reading may indicate a few ppm. Enter an area known to be free of any organic vapor and turn on the instrument. After running for several minutes, the residual vapor in the detector chamber will be cleared and the reading should return to zero.

⚠ The battery of the instrument discharges slowly even if it is turned off. If the instrument has not been charged for 5 to 7 days, the battery voltage will be low. Therefore, it is a good practice to always charge the instrument before using it. It is also recommended to fully charge the instrument for *at least 10 hours* before first use. Refer to the User Guide’s section on battery charging for more information on battery charging and replacement.

MiniRAE 3000/ppbRAE 3000 Pocket Reference

Contents

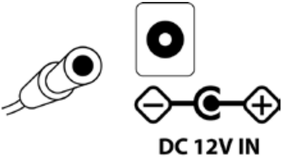
Charging The Battery

Always fully charge the battery before using the instrument. The instrument’s Li-ion battery is charged by placing the instrument in its cradle. Contacts on the bottom of the instrument meet the cradle’s contacts, transferring power without other connections.

Note: Before setting the instrument into its charging cradle, visually inspect the contacts to make sure they are clean. If they are not, wipe them with a soft cloth. Do not use solvents or cleaners.

Follow this procedure to charge the instrument:

1. Plug the AC/DC adapter’s barrel connector into the instrument’s cradle.



2. Plug the AC/DC adapter into the wall outlet.
3. Place the instrument into the cradle, press down, and lean it back. It locks in place and the LED in the cradle glow

The instrument begins charging automatically. The “Primary” LED in the cradle blinks green to indicate charging. During charging, the diagonal lines in the battery icon on the instrument’s display are animated and you see the message “Charging...”

When the instrument’s battery is fully charged, the battery icon is no longer animated and shows a full battery. The message “Fully charged!” is shown. The cradle’s LED glows continuously green.

Note: If you see the “Battery Charging Error” icon (a battery outline with an exclamation mark inside), check that the instrument or rechargeable battery has been set into the cradle properly. If you still receive the message, check the Troubleshooting section of this guide.

Charging A Spare Rechargeable Battery

A rechargeable Li-ion battery can be charged when it is not inside the monitor. The charging cradle is designed to accommodate both types of charging. Contacts on the bottom of the battery meet the contacts on the cradle, transferring power without other connections, and a spring-loaded capture holds the battery in place during charging.

1. Plug the AC/DC adapter into the monitor’s cradle.
2. Place the battery into the cradle, with the gold-plated contacts on top of the six matching charging pins.
3. Plug the AC/DC adapter into the wall outlet.

The battery begins charging automatically. During charging, the Secondary LED in the cradle blinks green. When charging is complete, it glows steady green.

Release the battery from the cradle by pulling it back toward the rear of the cradle and tilting it out of its slot.

Note: If you need to replace the Li-ion battery pack, replacements are available from RAE Systems. The part number is 059-3051-000.

Note: An Alkaline Battery Adapter (part number 059-3052-000), which uses four AA alkaline batteries (Duracell MN1500), may be substituted for the Li-Ion battery.

WARNING!

To reduce the risk of ignition of hazardous atmospheres, recharge and replace batteries only in areas known to be non-hazardous. Remove and replace batteries only in areas known to be non-hazardous.

Low Voltage Warning

When the battery's charge falls below a preset voltage, the instrument warns you by beeping once and flashing once every minute, and the "empty battery" icon blinks on and off once per second. Turn off the instrument within 10 minutes and either recharge the battery by placing the instrument in its cradle, or replace the battery with a fresh one with a full charge.

Pump Status

During operation, make sure the probe inlet and the gas outlet are free of obstructions. Obstructions can cause premature wear on the pump, false readings, or pump stalling. During normal operation, the pump icon alternately shows inflow and outflow as shown here:

During duty cycling (PID lamp cleaning), the display shows these icons in alternation:

If there is a pump failure or obstruction that disrupts the pump, you will see this icon blinking on and off:

If you see this blinking icon, consult the Trouble-shooting section in the User's Guide.

Calibration Status

The instrument displays this icon if it requires calibration:

Calibration is required (and indicated by this icon) if:

- The lamp type has been changed (for example, from 10.6 eV to 9.8 eV).
- The sensor has been replaced.
- It has been 30 days or more since the instrument was last calibrated.
- If you have changed the calibration gas type without recalibrating the instrument.

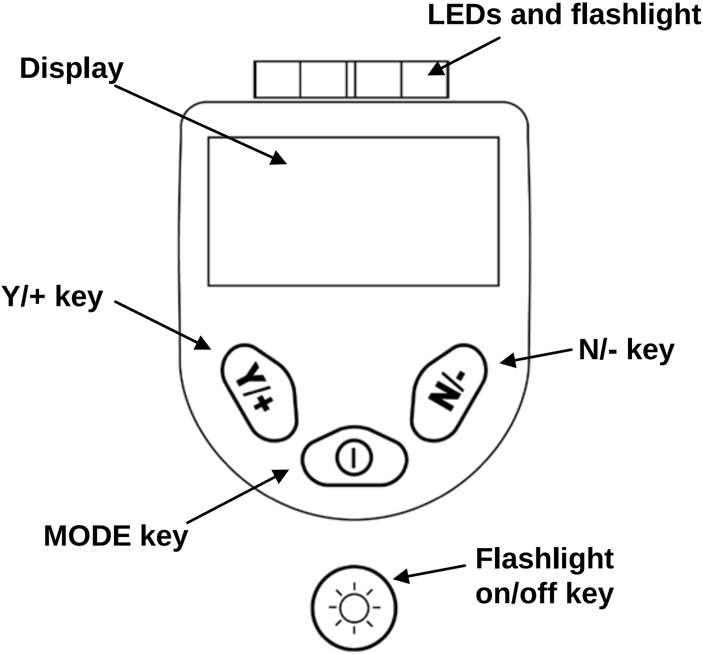
User Interface

The instrument’s user interface consists of the display, LEDs, an alarm transducer, and four keys. The keys are:

Y/+
MODE
N/-
Flashlight on/off

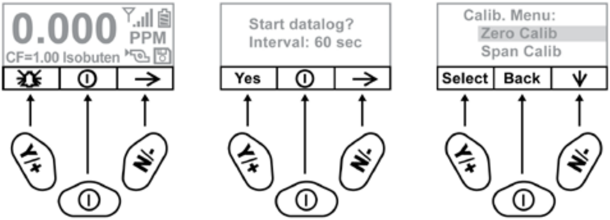
The LCD display provides visual feedback that includes time, battery condition, and other functions.

In addition to their labeled functions, the keys labeled Y/+, MODE, and N/- act as “soft keys” that control different parameters and make different selections within the instrument’s menus. From menu to menu, each key controls a different parameter or makes a different selection.


LEDs and flashlight
Display
Y/+ key
N/- key
Y/+
N/-
MODE key
Flashlight on/off key

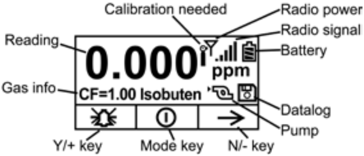
Three panes along the bottom of the display are "mapped" to the keys. These change as menus change, but at all times the left pane corresponds to the [Y/+] key, the center pane corresponds to the [MODE] key, and the right pane corresponds to the [N/-] key. Here are three examples of different menus with the relationships of the keys clearly shown:

RELATIONSHIP OF BUTTONS TO CONTROL FUNCTIONS



Display

The display shows the following information:



Graph	Graphic representation of concentration plotted over time
Gas info*	Tells the Correction Factor and type of calibration gas
Reading	Concentration of gas as measured
Calibration needed	Indicates that calibration should be performed
Radio power	Indicates whether radio connection is on or off
Radio signal	Indicates signal strength in 5-bar bargraph
Battery	Indicates battery level in 3 bars
Pump	Indicates that pump is working
Datalog	Indicates whether datalog is on or off
Y/+	Y/+ key's function for this screen
MODE	MODE key's function for this screen
N/-	N/- key's function for this screen

Operating The Instrument

The instrument is designed as a broadband VOC gas monitor and datalogger for work in hazardous environments. It gives real-time measurements and activates alarm signals whenever the exposure exceeds preset limits. Prior to factory shipment, the instrument is preset with default alarm limits and the sensor is pre-calibrated with standard calibration gas. However, you should test the instrument and verify the calibration before the first use. After the instrument is fully charged and calibrated, it is ready for immediate operation.

Turning The Instrument On

1. With the instrument turned off, press and hold [MODE].
2. When the display turns on, release the [MODE] key.

The instrument is now operating and performs self tests. If any tests (including sensor and memory tests fail), refer to the Troubleshooting section of the User's Guide.

Note: In Basic User/Hygiene Mode (the default setting), the instrument stops after self-testing, and asks whether to perform a zero air (fresh air) calibration. You can start this calibration, quit, or abort the calibration while the instrument is undergoing calibration. When the zero calibration is done, you see screen telling you that the zero calibration is complete, along with its value. After calibration (or after you abort the calibration), the instrument then shows a numerical reading screen with icons. This indicates that the instrument is fully functional and ready to use.

Turning The Instrument Off

1. Press and hold the Mode key for 3 seconds. A 5-second countdown to shutoff begins.
2. Once the countdown stops, the instrument is off. Release the Mode key.
3. When you see “Unit off...” release your finger from the [MODE] key. The instrument is now off.

Note: You must hold your finger on the key for the entire shutoff process. If you remove your finger from the key during the countdown, the shutoff operation is canceled and the instrument continues normal operation.

Operating The Built-In Flashlight

The instrument has a built-in flashlight that helps you point the probe in dark places. Press the flashlight key to turn it on. Press it again to turn it off.

Note: Using the flashlight for extended periods shortens the battery’s operating time before it needs recharging.

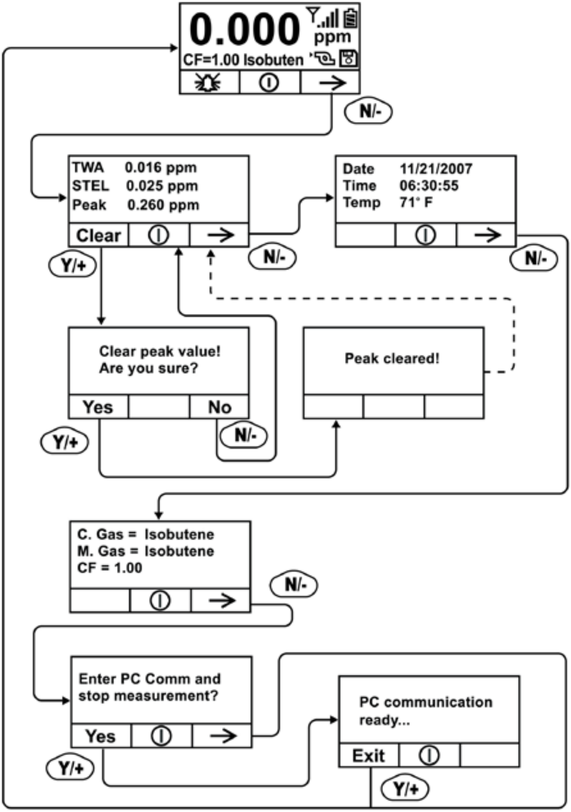
Basic User Mode/Hygiene Mode (Default Settings)

The instrument is programmed to operate in Basic User Mode/Hygiene Mode as its default. This gives you the most commonly needed features while requiring the fewest parameter adjustments.

Pressing [N/-] steps you from one screen to the next, and eventually return to the main display. If you do not press a key within 60 seconds after entering a display, the instrument reverts to its main display.

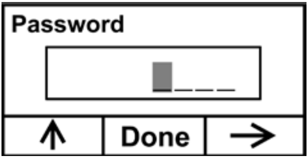
Note: While viewing any of these screens, you can shut off your instrument by pressing [MODE].

Note: Whenever you see the alarm icon in the lower left pane, you can press [Y/+] to test the alarms.


0.000
ppm
CF=1.00 Isobuten
N/-
TWA 0.016 ppm
STEL 0.025 ppm
Peak 0.260 ppm
Clear
N/-
Y/+
Date 11/21/2007
Time 06:30:55
Temp 71° F
N/-
Clear peak value!
Are you sure?
Yes
No
N/-
Y/+
Peak cleared!
C. Gas = Isobutene
M. Gas = Isobutene
CF = 1.00
N/-
Enter PC Comm and
stop measurement?
Yes
Y/+
PC communication
ready...
Exit
Y/+

Entering Calibration

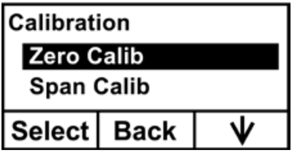
1. Press and hold [MODE] and [N/-] until you see the Password screen.



2. In Basic User Mode, you do not need a password to perform calibrations. Instead of inputting a password, enter calibration by pressing [MODE].

   Note: If you inadvertently press [Y/+] and change any of the numbers, simply press [MODE] and you will be directed to the calibration menu.

The Calibration screen is now visible with Zero Calibration highlighted.



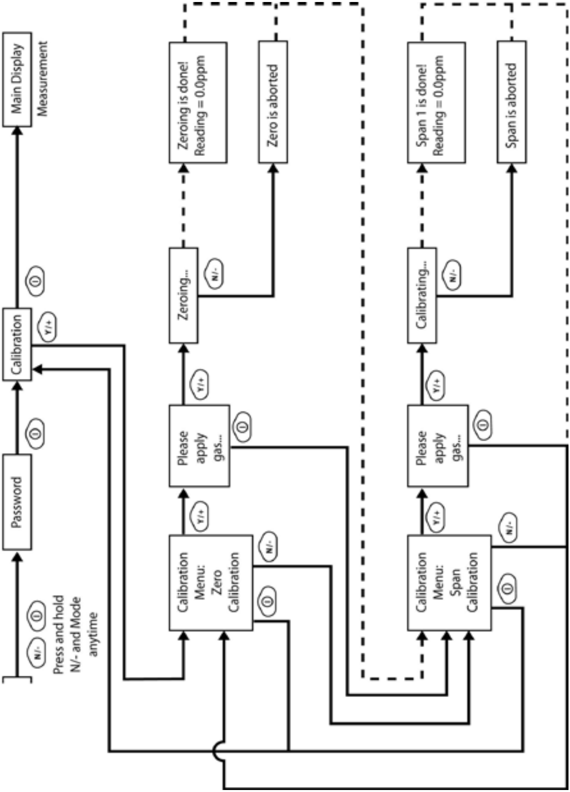
These are your options:

- Press [Y/+] to select the highlighted calibration (Zero Calib or Span Calib).
- Press [MODE] to exit calibration and return to the main display and resume measurement.
- Press [N/-] to toggle the highlighted calibration type.

Standard Two-Point Calibration (Zero & Span)

The following diagram shows the instrument's calibrations in Basic/Hygiene mode.

Note: In the diagram, a dashed line indicates automatic change to another screen.


Press and hold
N/- and Mode
anytime
N/-
Password
Calibration
Y/+
Main Display
Measurement
Calibration
Menu:
Zero
Calibration
Y/+
N/-
Please
apply
gas...
Y/+
Zeroing...
N/-
Zeroing is done!
Reading = 0.0ppm
Zero is aborted
Calibration
Menu:
Span
Calibration
Y/+
N/-
Please
apply
gas...
Y/+
Calibrating...
N/-
Span 1 is done!
Reading = 0.0ppm
Span is aborted

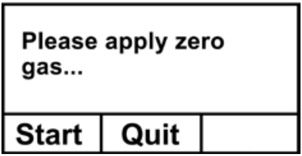
Zero (Fresh Air) Calibration

This procedure determines the zero point of the sensor calibration curve. To perform a fresh air calibration, use the calibration adapter to connect the instrument to a "fresh" air source such as from a cylinder or Tedlar bag (optional accessory). The "fresh" air is clean, dry air without organic impurities and an oxygen value of 20.9%. If such an air cylinder is not available, any clean ambient air without detectable contaminants or a charcoal filter can be used.

At the Zero Calibration menu, you can proceed to perform a Zero calibration or bypass Zero calibration and perform a Span calibration. You may also go back to the initial Calibration menu if you want to exit calibration.

- Press [Y/+] to start calibration.
- Press [MODE] to quit and return to the main calibration display.

If you have pressed [Y/+] to enter Zero calibration, then you will see this message:



Please apply zero gas...

1. Turn on your Zero calibration gas.
2. Press [Y/+] to start calibration.

   Note: At this point, you may press [MODE] if you decide that you do not want to initiate calibration. This will take you directly to the Calibration menu, highlighted for Span calibration.

3. Zero calibration starts and displays this message:

   Zeroing...

During the zeroing process, the instrument performs the Zero calibration automatically and does not require any actions on your part.

Note: To abort the zeroing process at any time and proceed to Span calibration, press [N/-] at any time while zeroing is being performed. You will see a confirmation message that says "Zero is aborted!" and then the Span calibration menu appears.

When Zero calibration is complete, you see this message:

Zeroing is done!
Reading = 0.000 ppm

The instrument will then show the Calibration menu on its display, with Span Calib hightlighted.

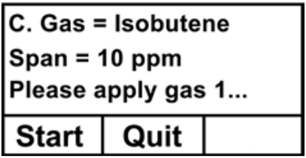
Span Calibration

This procedure determines the second point of the sensor calibration curve for the sensor. A cylinder of standard reference gas (span gas) fitted with a 500 cc/min. flow-limiting regulator or a flow-matching regulator is the simplest way to perform this procedure. Choose the 500 cc/min. regulator only if the flow rate matches or slightly exceeds the flow rate of the instrument pump. Alternatively, the span gas can first be filled into a Tedlar bag or delivered through a demand-flow regulator. Connect the calibration adapter to the inlet port of the instrument, and connect the tubing to the regulator or Tedlar bag.

Another alternative is to use a regulator with >500 cc/min flow but allow the excess flow to escape through a T or an open tube. In the latter method, the span gas flows out through an open tube slightly wider than the probe, and the probe is inserted into the calibration tube. At the Span Calibration menu, you perform a Span calibration. You may also go back to the Zero calibration menu or to the initial Calibration menu if you want to exit calibration.

- Press [Y/+] to enter Span calibration.
- Press [N/-] to skip Span calibration and return to Zero calibration.
- Press [MODE] to exit Span calibration and return to the top calibration menu.

If you have pressed [Y/+] to enter Span calibration, then you will see the name of your Span gas (the default is isobutylene) and the span value in parts per million (ppm). You will also see this message that prompts you:



C. Gas = Isobutene
Span = 10 ppm
Please apply gas 1...

1. Turn on your span calibration gas.
2. Press [Y/+] to initiate calibration.

   Note: You may press [MODE] if you decide that you do not want to initiate calibration. This will abort the span calibration and take you directly to the Calibration menu for Zero calibration.

3. Span calibration starts and displays this message:

Calibrating...

During the Span calibration process, there is a 30-second countdown and the instrument performs the Span calibration automatically. It requires no actions on your part.

Note: If you want to abort the Span calibration process, press [N/-] at any time during the process. You will see a confirmation message that says “Span is aborted!” and then the Zero calibration menu appears. You can then proceed to perform a Zero calibration, perform a Span calibration, or exit to the topmost Calibration menu.

When Span calibration is complete, you see this message:

Span 1 is done!
Reading = 100.0 ppm

The instrument then exits Span calibration and shows the Zero calibration menu on its display.

Note: The reading should be very close to the span gas value.

Exiting Two-Point Calibration

When you are done performing calibrations, press [MODE], which corresponds with “Back” on the display. You will see the following message:

Updating settings…

The instrument updates its settings and then returns to the main display. It begins or resumes monitoring.

Alarm Signal Summary

If the measured gas concentration exceeds any of the preset limits, the buzzer and red flashing LED are activated immediately to warn you of the alarm condition. The instrument also alarms if one of the following conditions occurs: battery voltage falls below a preset voltage level, failure of the UV lamp, or pump stall.

Message	**Condition**	**Alarm Signal**
HIGH	Gas exceeds "High Alarm" limit	3 beeps/flashes per second*
OVR	Gas exceeds measurement range	3 beeps/flashes per second
MAX	Gas exceeds electronics' maximum range	3 beeps/flashes per second
LOW	Gas exceeds "Low Alarm" limit	2 beeps/flashes per second*
TWA	Gas exceeds "TWA" limit	1 Beep/flash per second*

STEL	Gas exceeds "STEL" limit	1 Beep/flash per second*
Pump icon flashes	Pump failure	3 beeps/flashes per second
Lamp	PID lamp failure	3 beeps/flashes per second plus "Lamp" message on display
Battery icon flashes	Low battery	1 flash per minute, 1 beep per minute plus battery icon flashes on display
CAL	Calibration failed, or needs calibration	1 beep/flash per second
NEG	Gas reading measures less than number stored in calibration	1 beep/flash per second

* Hygiene mode only. In Search mode, the number of beeps per second (1 to 7) depends upon the concentration of the sampled gas.

Preset Alarm Limits & Calibration

The instrument is factory calibrated with standard calibration gas, and is programmed with default alarm limits.

Cal Gas (Isobutylene)	**Cal Span**	**unit**	**Low**	**High**	**TWA**	**STEL**
ppbRAE 3000	10	ppm	10	25	10	25
MiniRAE 3000	100	ppm	50	100	10	25

Sampling Pump

When approaching the end of the specified lifetime of the pump, it will consume higher amount of energy and reduce its sample draw capability significantly. When this occurs, it is necessary to replace or rebuild the pump. When checking the pump flow, make sure that the inlet connector is tight and the inlet tubing is in good condition. Connect a flow meter to the gas inlet probe. The flow rate should be above 450 cc/min when there is no air leakage.

If the pump is not working properly, refer the instrument to qualified service personnel for further testing and, if necessary, pump repair or replacement.

Ordering Replacement Parts

If you need replacement parts, contact your local RAE Systems distributor. A list is available online:

http://www.raesystems.com

In the U.S., you can order sensors, replacement batteries, and other accessories online at:

http://istore.raesystems.com/

Special Servicing Note

If the instrument needs to be serviced, contact either:

1. The RAE Systems distributor from whom the instrument was purchased; they will return the instrument on your behalf.
2. The RAE Systems Technical Service Department. Before returning the instrument for service or repair, obtain a Returned Material Authorization (RMA) number for proper tracking of your equipment. This number needs to be on all documentation and posted on the outside of the box in which the instrument is returned for service or upgrade. Packages without RMA Numbers will be refused at the factory.

Troubleshooting

Refer to the User's Guide for troubleshooting details.

RAE Systems by Honeywell

3775 N. First St.
San Jose, CA 95134-1708 USA

Web: www.raesystems.com

Technical Support

To contact RAE Systems Technical Support Team:

Monday through Friday, 7:00AM to 5:00PM Pacific (US) Time

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Email: tech@raesystems.com

PN: 059-4030-000-D
Rev. B August 2010

RAE
SYSTEMS
by Honeywell

THE PID HANDBOOK

Theory and Applications of Direct-Reading Photoionization Detectors

Third Edition

RAE SYSTEMS
by Honeywell

THE PID HANDBOOK

Theory and Applications of Direct-Reading Photoionization Detectors (PIDs)

Third Edition

Acknowledgments

We thank the many people who contributed to this book, including RAE Systems' chief technology officer, Dr. Peter Hsi; vice president of marketing and products, Thomas Nègre; and director of product management, Bobby Sheikhan. Additionally, we extend thanks and gratitude to the many contributors without whom this project would have been impossible: Tom Mulhern and James Strohecker.

Document No: 000-4000-000

ISBN: 0-9768162-1-0

Patent Summary

2/95 US 5,393,979 "Photo-ionization Detector for Detecting Volatile Organic Gases" — Hsi

10/96 US 5,561,344 "Photo-ionization Detector for Detecting Volatile Organic Gases" (continue) — Hsi

6/98 US 5,773,833 "Photo-ionization Detector for Volatile Gases Measurement" — Hsi

3/99 US 6,313,638 "A Dual Channel Photo-ionization Detector and a Method for Eliminating Influence of Ultraviolet Intensity" — Sun & Hsi

6/99 US 6,320,388 Europe pending "Multiple Channel Photo-ionization Detector for Simultaneous and Selective Measurement of Volatile Organic Compound" — Sun & Hsi

9/99 US 6,333,632 Europe pending "Alternating Current Discharge Ionization Detector" —Yang & Hsi

3/00 US 6,469,303 "Non-dispersive Infrared Gas Sensor" — Sun & Hsi

5/01 US 6,225,633 B1 10/98 Europe 1243921 5/01 Japan 4053817 "Photo-Ionization Detector and Method for Continuous Operation and Real Time Self-cleaning" — Sun & Hsi

1/02 US 6,509,562 9/08 EP1 229 995 B1Europe "Selective Photo-ionization Detector Using Ion Mobility Spectrometry" — Yang & Hsi

6/03 US 6,967,485 "Automatic Drive Adjustment of Ultraviolet Lamps in Photo-Ionization Detectors" — Hsueh, Yeh, Sun & Hsi

8/03 US 7,258,773, Europe pending "Solid Polymer Electrolyte Oxygen Sensor" — Zhou, Sun & Hsi

12/03 US 6,661,233 B2 "Gas Analyzer with Real-time Broadband Monitoring and Snapshot Selective Detection" — Yang & Hsi

5/04 US 6,734,435B2 "Photo-ionization Detector and Method for Continuous Operation and RealTime self-cleaning" — Hsi & Sun (continuation of US 6,225,633)

8/05 US 7,592,603, Europe pending "Combined Radiation Dosimeter and Rate Meter" — Yuzhong June Wang, Peter Hsi

China Patents Granted:

ZL 02280230.4 Photo-ionization detector

ZL 200720067821.2 Concentrator and gas sampling system

ZL 200720066496.8 Heater for the GC column

ZL 200720066495.3 Oxygen sensor

ZL 200630195809.0 Miniature gas sensor

ZL 02256504.3 Combustible gas detector

ZL 02340070.6 External appearance design for combustible gas pipeline valve

ZL 02340069.2 External appearance design for combustible gas detector

ZL200930127413.6 Radioactive Detector Gate

ZL200920246147.3 Radiation safety gate design

ZL200680032878.7 Combined radiation dosimeter and rate meter

China Patents Pending:

PCT/CN2004/00090 5 200480043755.4 Integrated photo-ionization detector

PCT/CN2006/002609 200680055975.8 VOC detection using photo-ionization detector and method

200710040807.8 Photo-ionization detector used in gas chromatograph and method

200710038443.X PCT/CN2008/070573 Integrated electrolyte gas sensor

200810036757 Formaldehyde sensor

200910045439.5 Hydrogen generator

200810207495.X Material and method to resist organic silicon poisoning in catalytic gas sensor

200810207494.5 Material and method to resist organic silicon and sulfur poisoning in catalytic gas sensor

200910055547 Electrode material, sensor and manufacturing method for sulfur dioxide gas measurement

200910247216.7 Extremely low concentration gas detector

201010131805.1 Components of carbon dioxide detectors

200480029898.X Solid polymer electrolyte oxygen sensor

Disclaimer

The use of trade names or data from a particular manufacturer's instrument is for illustrative purposes only and is not intended to indicate either an endorsement or denegration of that manufacturer's product. When tests were performed with other manufacturer's instruments, all effort was made to operate the units correctly and accurately according to the manufacturer's instructions. However, due to the limited number of experiments, no claim is made that reported results are typical for that model instrument under optimal conditions. Any negative connotations that may have been imparted to any manufacturer's products are unintended and are counter to the spirit in which this book was written.

PREFACE: FROM HUMAN NOSE TO PID

The instrumentation developed to detect chemical contamination is an extension of our human senses. One of these senses, the sense of smell, occurs primarily because chemicals volatilize. This volatilization occurs most readily at room temperature for generally light molecules. These molecules float through the air, and, upon entering nasal passages behind the nose, activate olfactory sensor neurons. The neuron activation occurs as the odorant molecule binds to the neuron's cilia. In order for the odorant to bind and ultimately be recognized, the receiving neuron must have been encoded by a specific gene to recognize a particular chemical structure.

Signals from neurons with the same receptors converge on glomeruli in the olfactory bulb located in the brain. The glomeruli's response then creates a code that is transmitted by nerve fibers to various brain regions. This transmission means that smell is interpreted both from a sensory perspective and as an initiator of memory, emotions, and behavior in the limbic system. These signals also affect the brain's cortex where conscious thought occurs.

Now to the really interesting stuff: Genes also appear to control other types of chemical sensing, such as the ability of sperm to locate an egg. Similar receptors may function in a special structure in the nose called the vomeronasal organ. The vomeronasal organ detects pheromones. These signals may then regulate hormone release, mating, and social functions in animals, including humans. The chemicals responsible for these biological processes are not the typical volatiles!

Over the course of time, these systems have protected us from rotten food, poisons, enemies, animal attack, and other "stinky" humans. Unfortunately, in our modern environment many chemicals never experienced by even our recent ancestors are used. To make matters even more complicated, these chemicals may change over time with exposure to our very dynamic ecosystem, including other contaminants; making their detection more difficult. Thus, instrumentation to detect environmental signals was and is needed, given the limitations of the human sensory system.

In response to the need to detect volatile organics, one of the first instrument components to be developed was an ionization detector. The early instrumentation relied on flame as an energy source to split molecules. The molecular structure was passed through a flame-bearing component and as energy went into the molecule, the molecule separated. The resultant molecules were then attracted to detectors based on their ionization.

Although the flame ionization detector (FID) was very effective, the flame generation via burning hydrogen gas was and is somewhat problematic. The essential problem was the need to acquire and transport compressed hydrogen gas cylinders. For obvious reasons, commercial airline pilots did not give eager environmental scientists permission to bring these cylinders onto their passenger aircraft. Consequently, unless local sources for the compressed hydrogen gas were available, the gas had to be shipped via commercial carrier to the remote sites. This process only worked well when the environmental site was near an airport, and the environmental scientist was adept at logistics.

The photoionization detector (PID) was developed in part to ameliorate the problems with on-site acquisition of flame ionization gases. These PIDs are the most frequently used on-site detection instruments for volatiles at the parts-per-million (ppm) level. Since many environmental sites are of concern due to volatiles – from petroleum products or chemical usage, including spills – the PID is a necessity.

While FIDs and PIDs had parallels in the static laboratory detection devices used, the key was to provide instrumentation that would work effectively on-site in somewhat uncontrolled locations. The reasons for this need were twofold: (1) to determine contaminant levels and (2) to provide a warning system for the workforce and other potentially exposed individuals.

Levels of personal protective equipment (PPE), including respiratory protection, for site workers or any affected humans are determined based on contaminant levels. From this information, appropriate engineering controls, PPE, and site or facility siting are chosen. Chemical information is needed for future documentation purposes on-site and in-area or surrounding environ. The PID continues to be invaluable for this environmental site work both in our exterior site realm and in indoor workplace locations.

However, as our scientific understanding has increased, nagging questions have arisen. Was the ppm detection level sufficient? What about exposure levels for sensitive populations? What about exposures that extended beyond a defined 8-hour workday? These concepts were particularly important since the permissible exposure limits (PELs) defined by OSHA were not chosen to protect workers from any chemical effect. Rather, the PELs are chemical exposure limits that, given an 8-hour workday, would not have a lasting biological effect – as long as a 16-hour recovery period occurred before the next exposure interval.

So, instrumentation that provided lower levels of detection and longer time ranges has been developed. Developments include instruments that can detect volatiles at ppb levels, and instruments the can datalog volatile trends over a 24-hour time interval (or longer). These instruments and their ppb sensors can now be used not just to detect chemical usage and spillage, but also for chemical detection related to biological risks.

Biological activity and the resultant risk associated with microbial activity can be very difficult to quantify. Of course the familiar rotting food, mildew, or sweaty feet types of smells are part of our sensory “database.” However, even these can be invisible to us after olfactory fatigue has occurred. (Olfactory fatigue is a condition in which a person’s nose, after exposure to certain odors, is no longer able to detect the odor.) So, to quantify biological activity, a persistent need has developed for real time sensing instrumentation. By using the microbial volatile organics as markers for biological activity and ultimately biological risk, the hope is that quantification of the risk associated with actively growing bacteria and fungi will be possible for some of these life forms.

Another use for the new PID technology is to predict chemical presence vis-à-vis absorption or adsorption to particulates. Think back to the last time you walked outdoors after a rainstorm. Remember that smell? The moistened air was carrying small particles, including Actinomycetes spores from formerly dry soil, on small invisible water bubbles. When inhaled, these aerosols made their way to your olfactory receptors and your brain interpreted their chemical signature as the earthy, “after-the-rain” smell. Other “after-the-rain smells” you noticed may be from the environmental degradation action of acid rain (an unfortunate side-effect of burning fossil fuels) on chemical substrates, and the volatile oils newly emitted from plants. All of these chemicals are transferred to you on aerosolized raindrops.

Consequently, the key to many inhalation chemical exposures is the generation of both liquid and particulate aerosols. Thus, the off-gassing of the volatile component present in these aerosols can be predictive of contaminant levels both from the volatile itself and the liquid or particulate substrate. By this definition, the substrate may also include other contaminants including semi-volatile liquids, and gases. As an example, hog farm odor intensity is directly proportional to the amount of dust in the feed lot, So, the detection of airstream volatiles is an indicator not just of the volatile adsorbed to the dust, but that dust in the air is not being adequately controlled.

Fortunately, hog waste odor is one we do sense – at least until olfactory fatigue occurs. The danger is in the volatiles and semi-volatiles carried on these aerosols that we do not smell. Remembering that the "dose makes the poison," the presence of volatiles adsorbed to particulates is often a more effective dosing vector than just inhaling the volatiles themselves. The particulates "stick" in the body and subsequent off-gassing and dissolution provide a more persistent chemical source than volatile gases that are inhaled and exhaled more readily. These same substrates may also carry semi-volatiles that off-gas at body temperature, radon gas, and biological risk components (spores, bacteria, viruses).

If exposure is occurring in our homes, hospitals, schools, and other facilities where ventilation may not be adequate and our resident time is excessive, given the potential chemical dosing effect, then all of these concerns are compounded. Thus, the PIDs which were the staple instrumentation for outdoor environmental work, have become a first line of alert for indoor environmental contaminant detection.

This book provides information as to how these PIDs function as our much-needed "extra sense." Given that PID durability and functionality have improved as described herein, this technological transition has made PID usage easier. Calibration stability, internal diagnostic programs, and increased detector efficacy are important advances in PID instrumentation. Just to be able to use higher ionization potentials to cleave the more "difficult" molecular structures without worrying that a lamp will burn out every 30 minutes is a great step forward.

In my practice as a certified industrial hygienist, I rely on quality instrumentation to achieve my goals – to provide information that can be used to protect human life and the environment. The PID technology provided in RAE Systems instrumentation provides one of the reliable means used to determine both chemical and biological risk potential associated with volatiles. This handbook provides an excellent description of how PIDs work. Both PID potential uses and limitations are discussed. My congratulations to RAE Systems for being both scientists and teachers! I believe as an applied scientist, Certified Industrial Hygienist, and former teacher, that knowledge is power. In this case, power to make our environment better and our habitat safer.

Martha J. Boss, CIH, CSP
Principal Toxicologist, URS Corporation

Martha Boss is a practicing industrial hygienist and safety engineer living in Omaha, Nebraska. Martha won the Army Science award at the Des Moines Science Fair, and later earned a B.A. in Biological Education from the University of Northern Iowa and a B.S. in Biology from the University of Nebraska. These endeavors led to a career in industrial hygiene through work for the U.S. Army and through the auspices of EPA grants.

During the Gulf War Desert Storm operations, Martha was tasked under the War Powers Act to assist in the preparation of a western Army base to house and train special forces. Martha worked with fellow Army industrial hygienists and engineers to assess biological, radiological, and chemical warfare sites and find solutions. The Army continued her training at such institutions as Johns Hopkins, Harvard, and other top centers throughout the United States.

Martha is currently principal Toxicologist for URS Corporation and practices as a certified industrial hygienist and certified safety professional. She is a member of the Hazardous Substances Research Center T3 Board for EPA Region 7, a diplomate of the American Academy of Industrial Hygiene, serves on the editorial advisory board for Stevens Publishing, and is a member of the American Industrial Hygiene Association and the American Society of Safety Engineers.

TABLE OF CONTENTS

1. INTRODUCTION

This book describes the theory, performance and applications of direct-reading photoionization detectors (PIDs). Photoionization is a well-established detection method developed originally for use with high-performance, laboratory-size gas chromatographs (GCs). Smaller GC/PIDs described as transportable, allow measurements to be performed in the field, but generally still require a fixed power supply and have limited mobility. This book focuses on handheld, direct-reading PIDs that are battery-powered and thus provide complete freedom of movement. Some PIDs that are fixed-mounted or pre-filtered are described. However, systems with high-resolution separation prior to the PID are purposefully excluded. The book is intended to assist the user in the operation and in the interpretation of field measurements for such applications as industrial hygiene, chemical process control, emergency chemical release response, and environmental clean-up. Ultimately, we hope the book will help the industrial, government and public community to provide a safer workplace and a cleaner environment.

PIDs are broad-band sensors that respond to a large variety of organic and some inorganic compounds. The general class of compounds suitable for detection is volatile organic compounds (VOCs). For simplicity, this handbook uses the abbreviation VOC to refer to all the PID-detectable compounds, even though some volatile inorganic compounds and many semi-volatile organic compounds are also detectable, and selected VOCs are not detectable. The measurable concentrations are typically in the range 0.01 to 10,000 ppm (parts per million), while being most accurate in the lower end of that range up to about 2,000 ppm. Competing non-selective organic vapor detectors include portable flame ionization detectors (FIDs), with a range of approximately 0.5 to 50,000 ppm, infrared (IR) analyzers with a range of about 0.02 to 20,000 ppm, metal oxide semiconductors (MOS) with a range of about 1 to 10,000 ppm, and catalytic oxidation bead combustible gas (LEL) sensors, with a range of approximately 200 to 50,000 ppm. PIDs are suitable for use at lower concentrations than are accessible to catalytic bead sensors, and where small size and ease of use make them preferable to FIDs.

Portable PIDs first came to market in 1974 with the development of the HNU Model 101, designed primarily for testing of soil vapors during environmental clean-up activities. The units were relatively bulky and heavy (e.g., 9 lbs.), and had a separate hand-held probe and a controller carried by a shoulder strap. The readout was by needle deflection, and no datalogging was available. With the advent of microelectronics and batteries with high power densities, modern PIDs are made smaller, lighter, and with sophisticated data processing and storage capabilities. The aid of intelligent power management circuitry reduces power consumption and prolongs battery life or further reduces battery size. Presently, the smallest PIDs containing an internal pump and designed for process control or environmental clean-up include the Photovac 2020, the MiniRAE 2000, the ppbRAE and the PhoCheck. These units weigh under two pounds, are about the size of a telephone handset, and in some cases can store 15,000 data points (or more). Other PIDs on the market have comparable features.

The year 1996 saw the introduction of the ToxiRAE PID, which weighs 7 ounces and is small enough to fit into a shirt pocket. This development accelerated the entry of PID use in the industrial hygiene market, where the multitude of chemicals used in and manufactured by industry are far greater than typically encountered in site remediation. As a result, correction factors for over 250 chemicals have been determined, which allow their measurement using only a single calibration gas, isobutylene. The availability of such a large list of factors has expanded the use of other, larger PIDs as well.

About 6 years ago came the introduction of PIDs capable of detecting low ppb levels of organic compounds with resolutions of 1 to 10 ppb (parts per billion). These instruments have become powerful tools in measuring ambient levels of organic vapors in general indoor air environments, such as offices, not associated with chemical processing. The need for such measurements increases as regulatory agencies begin to include total VOC limits in their indoor air quality guidelines. These measurements present new challenges in zeroing the meter because the typical ppb levels of ambient VOCs can no longer be taken as a zero point. Interpreting results is also more difficult because the identity of the organic vapors is generally unknown and may be variable.

The continuing process of miniaturization and improved PID sensitivity promises the development of a variety of new applications. In 1997 a traditional 4-gas confined space monitor was combined with a miniature PID for the first time, resulting in a VOC/LEL/O_2/CO/H_2S five-gas monitor. Such instruments protect the worker not only from gases immediately dangerous to life, but also from toxic vapors that have long-term health effects. In recent years, several new variants of the multi-gas meter with PID have appeared, some using exchangeable (i.e., disposable) PID sensors.

Another recent advance is the introduction of dual-wavelength PIDs such as 9.9/10.9 eV and 10.6/9.5 eV lamps. Although these have not found wide market favor, they offer the possibility of using multiple wavelengths and being programmed with pattern recognition for compound classification.

With further development one can envision examples of new variations such as lower-cost disposable PID sensors, PIDs embedded into articles of clothing and furniture for personal air-quality monitoring, and PID arrays for highly localized monitoring. Recently emerging applications for ppb level detection beyond Indoor Air Quality testing include: facility perimeter monitoring, detection of drugs and chemical warfare agents, and locating the source of microbially generated VOCs such as from molds in buildings. Many other currently unforeseen applications will certainly become feasible as PID technology continues to advance to smaller sizes, greater reliability, and better sensitivity and selectivity.

RAE Systems PID Related Development History

1993: MicroRAE introduced, the world's first personal PID monitor.

1994: MiniRAE professional PID introduced and US patent granted. ModuRAE continuous fixed-system PID introduced.

1995: ToxiRAE pocket PID introduced, the world's smallest PID.

1996: MultiRAE introduced, the world's first multi-sensor gas monitors to include PID.

1997: UltraRAE introduced, a substance-specific PID for benzene and other VOCs.

1998: RAE Systems awarded ISO 9001 certification. RAE Systems introduces the MiniRAE 2000 handheld PID.

1999: ppbRAE introduced, the world's first portable PID with parts-per-billion resolution.

2000: AreaRAE introduced, a multi-sensor gas detector with PID and wireless communication systems.

2001: MultiRAE IR and MultiRAE IAQ introduced, the world's first multi-sensor instruments to include both PID and CO_2 sensors.

2007: MiniRAE 3000, ppbRAE 3000, UltraRAE 3000 introduced, 3rd generation of PID with built-in wireless

2011: MultiRAE Family, the world's first wireless portable mulit-threat monitors for visibility of chemical and radiation threat data.

2011: Complete closed-loop wireless solution for portable gas monitors that includes the EchoView Host Mini-Controller and the ToxiRAE Pro family of single-gas wireless monitors.

2012: ProRAE Guardian Real-Time Wireless Safety System that combines gas, radiation, GPS and biomentric data in a rapidly deployable, secure wireless threat detection system.

2014: QRAE 3 introduced, the world's first 4-gas wireless detector.

2. PID THEORY AND TECHNOLOGY

2.1 Overview

The PID consists of a short-wavelength ultraviolet (UV) lamp shining onto a small cell containing the gas sample. Within the cell is a set of electrodes that have an electrical potential applied. The UV light photoionizes trace organic compounds, but not the air, resulting in electrons being ejected and forming positively charged molecules. The electrons and positive ions are propelled to the electrodes and the resulting current is proportional to the gas or vapor concentration. In general, any compound with ionization energy (IE) lower than that of the lamp photons can be measured.

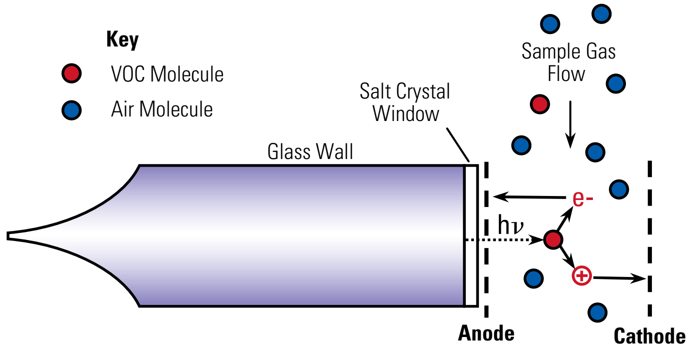

FIGURE 2.1.1. General schematic of a PID sensor

The timescale of these processes are femtoseconds to milliseconds, and therefore they are essentially instantaneous for the purposes of practical industrial hygiene and safety measurements. The response time of PID instruments (typically a few to several seconds) is usually determined by the rate at which the sample is pumped through the detection chamber and flushed completely. Adsorption processes in the instrument inlet system can slow the response time for low-volatility compounds.

CAUTION: Never look directly through the crystal at the discharge of an operating PID lamp without wearing safety glasses, as the UV light can be damaging to the eyes.

2.2 PID Lamp Design

The heart of the PID is a lamp that emits photons in the vacuum-ultraviolet region. The photon energy depends on the type of gas used to fill the lamp, and the crystal used as a transmission window.

Lamp Gases and Crystals

Table 2.2.1 lists the relevant characteristics of common gases and crystals used for PID lamps. Salt crystals are used as windows because common silica glasses do not transmit the low wavelength light required to ionize target VOCs. Inert fill gases tend to give the longest-life lamps and have emission lines at desirable wavelengths. Gas mixtures are sometimes used to ease initial turn-on and optimize output intensity. The fill gas pressure is typically below ambient. The output of the lamp increases as the fill gas pressure increases; however, an optimum value is reached, above which the output decreases. This decrease can be due to (1) the generated photons are self-absorbed by the fill gas before they exit the lamp and (2) the ions collide with other atoms before they are accelerated enough to cause excitation to a photon-emitting state. The latter effect makes the lamp more difficult both to start and to run. Practical constraints on lighting the lamp often limit the internal lamp pressure to levels below those where self-absorption becomes significant.

TABLE 2.2.1. Typical PID lamp gas and crystal characteristics

Nominal Lamp Photon Energies (eV)	Fill gas	Major Emission Lines		Relative Intens.*	Window Crystal	Crystal Transmittance λ Range (nm)**
		(eV)	(nm)			
11.7-11.8	Ar	11.83	104.8	1000	LiF	105 - 5000
		11.62	106.7	500		
10.6	Kr	10.64	116.5	200	MgF_2	115 - 7000
		10.03	123.6	650		
10.2	H_2	10.2	121.6	1000	MgF_2	
		10.2	121.6	500		
9.8-10.0	Kr	10.03	123.6	650	CaF_2	125 - 8000
9.5-9.6	Xe	9.92	125	250	BaF_2	135 - 9900
		9.57	129.6	1000		
		8.44	147	600		
9.5	O_2	9.52	130.2	900	CaF_2	
		9.5	130.5	600		
		9.49	130.6	300		
8.4	Xe	8.44	147	600	Al_2O_3	145 - 4500
					SiO_2	145 - 2300

* Relative emission intensity, from CRC Handbook of Chemistry and Physics.
** Wavelength limits for 80% transmittance through a 1 mm-thick crystal.
Wavelength λ calculated as λ(nm) = 1239.84 / E(eV).

In Table 2.2.1, the most common fill gas-crystal combinations are listed opposite each other. However, other combinations are sometimes used, such as the Xe/MgF_2 lamp designated as a 9.6 eV lamp.

The lamp is usually identified by the highest-energy photons it emits. However, this nomenclature is not applied uniformly. Some manufacturers label the Ar/LiF lamp as 11.8 eV, while others call it 11.7 eV. The HNU "10.2 eV" lamp responds to compounds with IE up to 10.5 eV and has quantitatively similar response as other manufacturers' 10.6 eV Kr/MgF_2 lamps. Another supplier identifies the Kr/MgF_2 lamp as a 10.0/10.6 lamp to emphasize that the major emission line is at 10.0 eV but that there is response up to 10.6 eV. The Xe/MgF_2 lamp, designated as a 9.6 eV, would be expected to emit significant amounts of the 9.9 eV line, as can be seen in Table 2.2.1.

PID lamps also emit many other wavelengths at lower energy or lower intensity than the major lines listed. Some of this light is visible as the blue/violet color seen when a lamp is on (which does not have enough energy to ionize most VOCs). In addition, the transmission of the crystal depends on its thickness, initial quality and age. Therefore, it is sometimes possible to obtain a small response from a gas that has an ionization energy higher than the nominal value for the lamp. Conversely, as lamps age, the crystal can gradually become solarized (UV-blocking crystal defects formed by light-induced crystal reorganization), corroded by moisture, or contaminated with deposits. The lamp may no longer be able to ionize some compounds near the upper limit of the nominal lamp output. These processes tend to affect the shorter wavelength limit of the crystal transmission the most, and therefore output near the edge of the transmission are more affected than at longer wavelengths.

Common Lamps

The most common, strongest, and longest-lived lamp is the 10.6 eV lamp, comprising a krypton fill gas and a magnesium fluoride window. These lamps typically have operating lives of at least 10,000 hours, for at least one year of continuous use or a few to several years of intermittent use.

Of the lamps listed in Table 2.2.1, the 11.7/11.8 eV lamp responds to the broadest range of compounds, including many chlorinated aliphatic compounds. The lower-energy lamps, such as 8.4 and 9.8 eV, offer the best selectivity. Thus, for example, a 9.8 eV lamp could be used to measure benzene selectively in the presence of pentane, or CS_2 in the presence of H_2S (see Section 4.5). An 11.7 eV lamp will measure all compounds that a 10.6 or 9.8 eV lamp measures, but not vice versa. The 11.7/11.8 eV lamps tend to have the weakest outputs and shortest lives because (1) the LiF crystal absorbs some of the main emission line, (2) the crystal is more difficult to seal onto the glass lamp housing because of a difference in thermal expansion coefficient, (3) the crystal is more prone to solarization if not highly pure, and (4) the crystal is more susceptible to etching by liquid water due to its higher solubility than other crystals.

Dual-Wavelength Lamps

Recently described are lamps that use a combination of crystals to obtain two photon energies within a single housing. In some cases the lamp is formed using a single discharge zone and attaching two additional crystals as filters on top of the main MgF_2 crystal. In another case, the lamp has two small discharge zones, each filtered by a different crystal, contained inside the main lamp housing and MgF_2 crystal. Examples of the latter include 9.9/10.9 eV and 9.5/10.6 eV dual-wavelength lamps. Such lamps allow the selective measurement of compounds in a mixture, and detection of variations of compound mixture ratios.

UV Lamp Failure Modes

Electrodeless PID lamps do not burn out the same way as incandescent bulb does, because they have no filament inside. Incandescent bulbs fail when the filament suddenly breaks, whereas PID lamps tend to lose power gradually due to gas leaks, crystal solarization, or surface degradation from organic deposits or water etching. Therefore, the strength of a lamp can usually be determined by instrument diagnostics, giving advance notice before a lamp needs replacement.

Electrode discharge lamps can also fail by corrosion of the electrodes and clouding of the lamp window by deposition of electrode metals.

Ionization of Air Components

A fundamental requirement of practical PID lamps used for environmental measurements is that they do not suffer from interference by the ambient atmosphere. Table 2.3.1 lists the ionization energy of the major components of air. Most PID lamps do not have enough photon energy to ionize any of the air components. However, with the 11.7/11.8 eV lamps there is a very slight baseline signal formed by the ionization of oxygen, the lowest IE component of air. Therefore, changes in the matrix gas oxygen levels can have some effect on the response of 11.7 eV lamps, and to a lesser extent for other lamps (see Section 3.2.1).

TABLE 2.3.1. Ionization energies of the major components of air

Gas	Mole Fraction (% by Volume)	Mole Fraction (ppmv)	I.E. (eV)
N_2	78.084	780,840	15.58
O_2	20.946	209,460	12.07
Ar	0.934	9,340	15.76
CO_2	0.033	330	13.78
Ne	0.0018	18.18	21.56
He	0.000524	5.24	24.59
CH4	0.0002	2	12.61
Kr	0.000114	1.14	14
H_2	0.00005	0.5	15.43
N_2O	0.00005	0.5	12.89
Xe	0.0000087	0.087	12.13
H_2O	0 - 4	0 - 40,000	12.62

2.3 Excitation Methods

Various methods of exciting the gases inside PID lamps are available. The method chosen may affect lamp design and size, mainly reflecting differences in configuration of the excitation electrodes. The UV light source usually is the single most power-hungry element in a portable PID instrument. Therefore, the excitation method strongly impacts the overall size and weight of the instrument.

DC Discharge Excitation

This type of UV lamp is typically made of a sealed glass envelope with two metal electrodes inside or embedded in the envelope, as shown schematically in Figure 2.3.1. Because the excited gas directly contacts the electrodes, a potential for corrosion exists, and therefore the choice of fill gases is more limited.

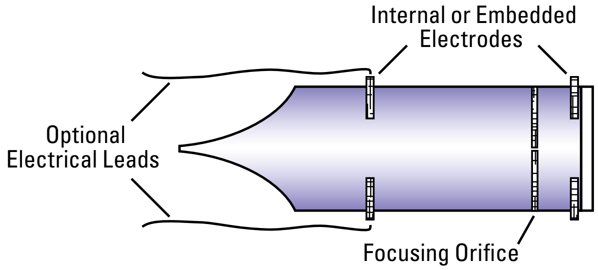

FIGURE 2.3.1. Cross-section view of DC discharge lamp

A high voltage of typically 600 to 1500 V DC is applied between the anode and cathode to initiate a glow discharge inside the lamp. A precision orifice inside the lamp is used to confine the discharge and excite the natural resonance frequencies of the gases. After the initial excitation, the voltage is reduced to about 300 V to sustain the glow discharge. A typical size of this type of UV lamp is about 2" long and 3/4" to 1" in diameter. The power consumption of DC discharge lamps is relatively high, in the range of several watts.

The heat generated by such lamps can result in a significant warm-up time for the instrument to come to thermal equilibrium. Conversely, it can be of benefit to prevent moisture condensation in the sensor cavity and lamp crystal surface.

RF Excitation

This type of UV lamp uses a radio frequency (RF) coil wrapped around the glass envelope to excite the gas (Figure 2.3.2). No metal parts contact the fill gas. The electric or magnetic field RF frequency can be in the range of hundreds of kHz to tens of MHz (14 MHz is typical). The RF coil acts as an antenna, which couples the electromagnetic energy into the gas in the lamp. A typical size for this type of lamp is about 2" long and 0.5" in diameter. The power consumption of RF Excited Lamps is usually in the range of a fraction of a watt to a few watts.

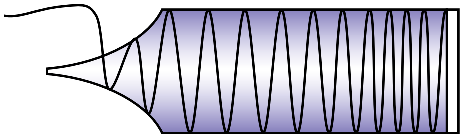

FIGURE 2.3.2. RF excited lamp

A disadvantage of RF excitation is that the antenna radiates radio waves outwardly as well as inwardly, thus potentially causing interference with other instruments or radio communication equipment. In addition, the energy coupling form the RF coil to the lamp is not very efficient unless the driving circuit is perfectly tuned. Therefore, an RF excited UV lamp requires more complex circuitry and constant tuning of the center frequency in order to maintain the coupling efficiency.

AC Electric Field Excitation

AC electric field excitation uses a pair of parallel electrodes placed outside the glass envelope, as shown in Figure 2.3.3. A high-voltage, low-frequency RF signal (<100 kHz) is applied to the electrodes to excite the lamp. Residual ions travel alternately toward each electrode and excite and further ionize the fill gas by cascading collisions. The glow discharge can be operated in a non-continuous fashion (Figure 2.3.4), but with an on-off frequency that is rapid compared to the time constant of gas flow through the ionization chamber. In this fashion, the power consumption of the PID can be reduced without affecting its measurement capability.

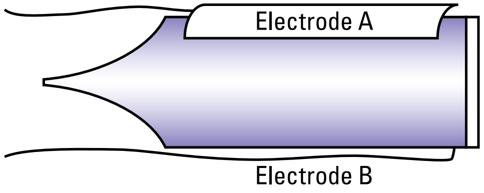

FIGURE 2.3.3. Electric field excited lamp

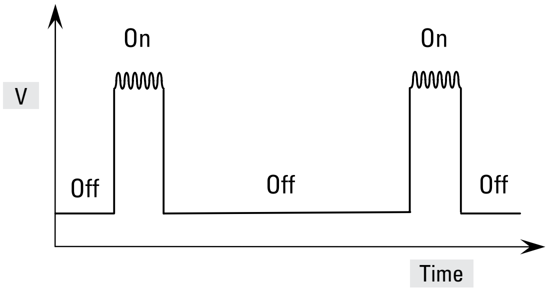

FIGURE 2.3.4. Pulsed RF excitation

Such excitation methods occasionally result in an initial difficulty in turning on the lamp. Therefore, a somewhat higher initial power is used to turn on the lamp, followed by a power reduction during the normal use. Once turned on, lamps appear to retain the ability to turn on easily for several months, presumably by retaining a trace amount of ions, by an unknown mechanism.

Another advantage of this driving method is that the low frequency of <100 kHz is well below that of most of radio communication equipment, thus reducing the possibility of RF interference.

2.4 Ionization Chamber Design

A typical ionization chamber consists of a pair of electrodes inside a small cavity in front of the UV lamp. The ionization chamber is sometimes termed the “sensor,” in order to distinguish it from the UV lamp, even though the lamp often forms one wall of the chamber and is an integral part of the PID sensor. A bias voltage of up to a few hundred volts is applied between the two electrodes to collect the ions and electrons. The sensor chamber design can have a significant effect on the sensitivity, linearity, response time, and influence of matrix gas variations. In general, a longer light pathlength in the chamber increases sensitivity, but increases response time and suffers more from non-linearity (Figure 2.4.1) and matrix gas light blockage.

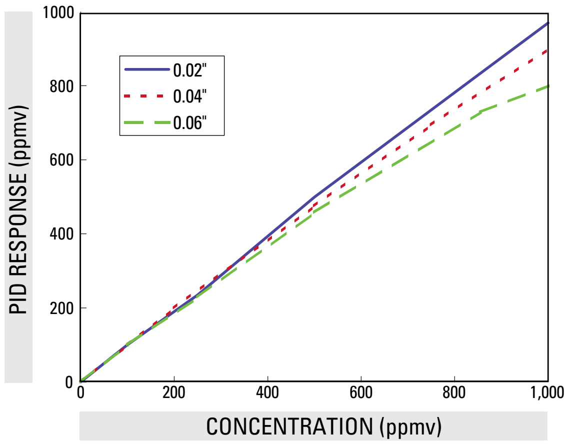

FIGURE 2.4.1. Effect of sensor light pathlength on response linearity

There are basically two different geometries used in the construction of the ionization chamber and the arrangement of the electrodes, using either long or short light path lengths.

Long Path Sensor (e.g., Cylindrical Chamber)

In one example of this design (Figure 2.4.2), the two electrodes are arranged as two concentric cylinders with the lamp shining through their axis. The sample gas flows directly towards the lamp and then exits the sides. This arrangement gives the greatest sensitivity because it provides enough pathlength to absorb and utilize most of the UV light. The larger separation also makes small sensor manufacturing variations more tolerable, and has less susceptibility to current leakages caused by dust and humidity. However, the relatively large chamber size requires a high bias voltage because the distance between anode and cathode is relatively large. It also causes deviations from linearity at lower analyte concentrations, and suffers more from competitive light absorption by matrix gases.

With the advent of modern microelectronics capable of accurately measuring very low currents, the need to optimize light utilization efficiency has been greatly reduced. Therefore, long path sensors have been largely replaced by smaller, more linear short-path sensors.

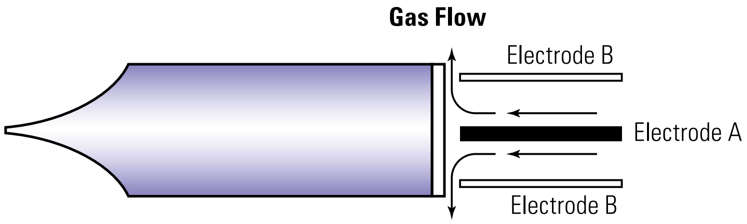

FIGURE 2.4.2. Long path PID sensor scheme

Short Path Sensor (e.g., Parallel Plate Chamber)

In this design (Figure 2.4.3), the chamber is formed by parallel plates (one of which is usually the lamp surface), separated by about 1 mm or less. In order to allow the UV light through, the electrodes are arranged as a set of wire meshes, parallel wires, or interdigital fingers. In the latter two cases the electrodes can be an alternating set of anodes and cathodes, to shorten the ion path and maximize sensitivity. This sensor design allows lower bias voltage and has better linearity and less matrix gas effects than long-path sensors.

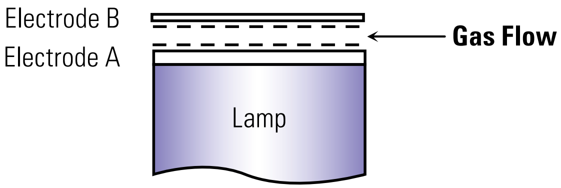

FIGURE 2.4.3. Short path PID sensor scheme

2.5 Overall Instrument Design

Figure 2.5.1 gives a typical overall design for a modern PID instrument. The monitor is powered by either disposable (alkaline) batteries or by rechargeable batteries, such as NiCd, NiMH, or Li-ion. Lead-acid rechargeable batteries are falling out of use because of their lower power densities. The user interacts with the monitor through a keypad, or it can be programmed directly from a computer. A pump draws the gas sample into the sensor and then pumps it out through the side, in some cases allowing sample collection. A liquid crystal display (LCD) or other digital display shows instantaneous readings and other parameters.

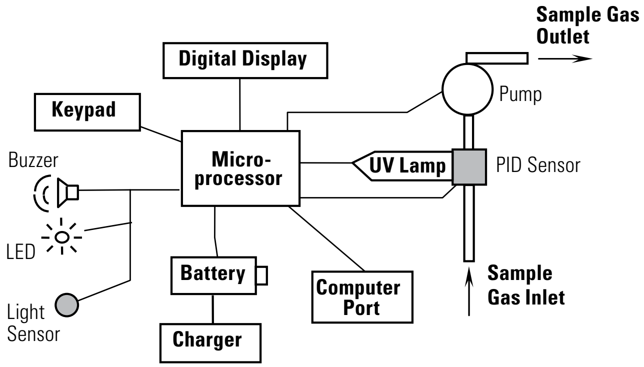

FIGURE 2.5.1. Overall PID instrument schematic

A chip microcomputer measures the PID sensor readings and calculates the gas concentrations based on calibration to known standard gases. The microprocessor is also used to control the operation of the lamp, pump, alarm buzzer, LED, light sensor and data storage. The light sensor controls a backlight, which is turned on in low light conditions for ease of reading. Alarms can often be programmed for both instantaneous concentrations and for cumulative values such as TWA and STEL. Error alarms and messages alert the user to fault conditions and assist in troubleshooting instrument problems.

The data are commonly stored in non-volatile memory with up to 20,000 data point capacity, or up to 2 weeks of continuous monitoring at a 1-minute sample interval. Newer units using memory cards can have much greater storage capacity. Infrared or RS-232 transceivers provide an interface between the monitor and a PC, so that data can be downloaded for record keeping. Figure 2.5.2 gives an example of a modern PID.

FIGURE 2.5.2. MiniRAE 3000 portable PID

2.6 Photoionization Process and Inherent Measurement Efficiency

Photoionization Process

PIDs use light in the vacuum-ultraviolet range to ionize target compounds. Table 2.5.1 illustrates the relation of vacuum-ultraviolet light to the rest of the electromagnetic spectrum.

TABLE 2.6.1. Electromagnetic spectrum*

Descriptive Name	Photon Wavelength	Possible Effects
Gamma Rays	0.0001 – 0.1 nm	Indiscriminant ionization
X-Rays	0.01 – 10 nm	Ionization from inner shell electrons
Vacuum Ultraviolet	10 – 200 nm	Ionization from outer shell electrons
Ultraviolet	200 – 380 nm	High-energy photochemical reactions
Visible	380 – 800 nm	Low-energy photochemical reactions
Infrared	0.8 – 1000 μm	Heating; increasing rotational, vibrational and translational energies
Microwaves	1 mm – 100 cm	Sound generation; heating

* (Adapted from Smith, 1977)

The photoionization process involves the absorption of a photon by a molecule. At relatively low photon energies, the electrons in the molecule can be raised to an excited state, in which they travel in a new orbit around the nucleus at a greater average distance from it. The excited state quickly relaxes upon collision with another molecule, resulting simply in heating of the gas. However, if the photon energy is high enough, the excited electron can leave the orbit, resulting in a free electron and a positive radical ion:

$$\mathrm{VOC} + h\nu \mapsto \mathrm{VOC}^{*} \mapsto \mathrm{VOC}^{+\cdot} + e^{-}$$

The energy required to eject an electron is termed the ionization energy (often less correctly referred to as the ionization potential) and it depends strongly on the gas or VOC type. In many cases there is a rather sharp threshold of energy that needs to be exceeded before ionization will take place. However, the reported ionization energy does not always represent a sharp cut-off for the practical onset of ionization for a few reasons.

The ionization energy listed in common databases is the adiabatic ionization energy (Linstrom & Mallard, 2001). The adiabatic IE is defined as the minimum difference between the lowest energy state of the neutral molecule and the lowest energy state of the resulting ion (see Figure 2.6.1). In some cases, the ion initially formed upon absorption of a photon can relax its bond geometry to a lower energy state after forming. Therefore, the ion that is initially formed has higher energy than the lowest ionic energy state. The practical energy required to ionize a molecule is the vertical ionization energy, which is always higher than the adiabatic ionization energy.

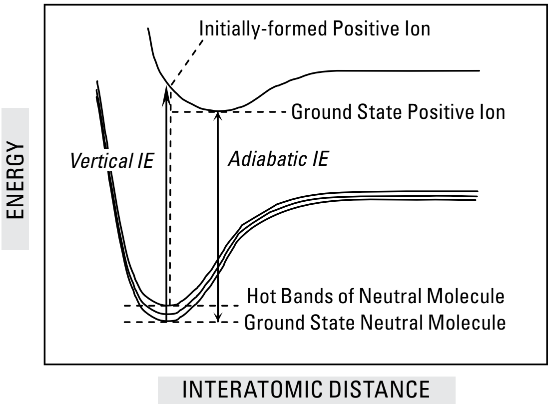

FIGURE 2.6.1. Potential energy between atoms in a molecule as a function of internuclear distance

However, the vertical IE is reduced due to the presence of hot bands. These are a series of energy levels, slightly higher than the ground state, resulting from various rotational and vibrational energy states the molecule can have. The practical energy required for ionization (indicated by the dashed line in Figure 2.6.1) is less than the vertical IE, because the starting point is one of the hotband levels. Because there are several hot band levels, the practical ionization energy is actually a range of energies, rather than a distinct value.

Photoionization in the Adsorbed Phase

Some evidence suggests that the actual photoionization process occurs predominantly when the VOC is adsorbed onto the electrode and that the gas-phase ionization component is minor (Mergemeier et al., 1998). This evidence is based partly on the observation that PID response is proportional to the surface area of the electrodes. However, some of the evidence is also consistent with purely gas-phase photochemistry, and the relative importance of adsorbed versus gas phase processes may well depend on the concentration of the compound and its affinity for the electrode surface. In any case, simple equations derived for purely gas-phase photochemistry are useful in understanding some practical aspects of photoionization detection, such as the effects of concentration and flow rate.

Lambert-Beer Law of Light Absorption

In both gas and condensed homogeneous phases, the light absorbance is proportional to the concentration of the VOC, in accordance with the Lambert-Beer law:

$$A = \varepsilon \ell c$$

$$I = I_o 10^{-A} = I_o 10^{-\varepsilon \ell c}$$

Where I_o is the initial light intensity emitted from the lamp, I is the intensity of light reaching the end the sensor cavity, A is the absorbance in units of length^{-1}, ε is the molar extinction coefficient in concentration^{-1} $\cdot$length^{-1}, ℓ is the pathlength (sensor cavity depth) in length, and c is the concentration. The *transmittance* T is defined as the fraction of light passing through the solution, and the *fraction absorbed*, f_A, is the complementary fraction of light absorbed by the solution:

$$\text{Transmittance } T = \frac{I}{I_o} = 10^{-\varepsilon \ell c}$$

$$\text{Fraction Absorbed } f_A = 1 - T = 1 - 10^{-\varepsilon \ell c}$$

This equation is plotted in Figure 2.6.2. It provides useful insights when examined at the two extremes of very low ($f_A \longrightarrow 0$) and very high ($f_A \longrightarrow \infty$) fractions of absorbed light.

Low Absorbance Approximation

At low total absorbance ($\varepsilon \ell c < 0.1$), one may make the mathematical approximation

$$1 - 10^{-\varepsilon \ell c} \approx 2.303 \varepsilon \ell c$$

Therefore, at low total absorbance, as is usually the case for PID measurements (low concentration and short pathlength), we have:

$$\text{Fraction of Light Absorbed, } f_A = 2.303 \varepsilon \ell c$$

Furthermore, at low concentrations, the rate of ion generation and collection is directly proportional to f_A because the chance of interaction with another ion is extremely low. Therefore, the above equation means that the electrical signal intensity is directly proportional to the concentration of the chemical being measured. This low absorbance approximation corresponds to the initial, linear portion of the curve in Figure 2.6.2.

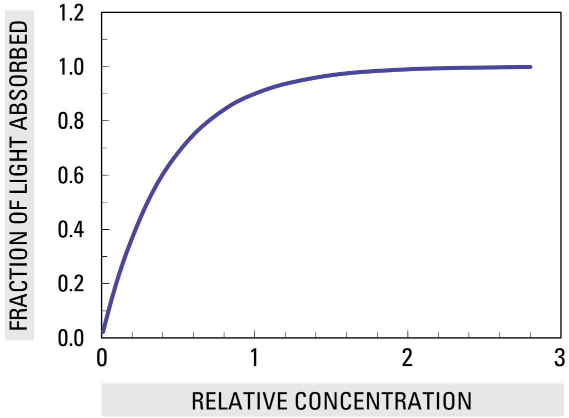

FIGURE 2.6.2. Fraction of light absorbed vs. concentration showing linear response at low concentrations and saturation by total absorbance at very high concentrations

High Concentration Limit

At high concentrations, the signal must reach an upper limit when all of the light is absorbed (Figure 2.6.2):

$$\text{Fraction Absorbed } f_A = 1 - 10^{-\varepsilon \ell c} \approx 1$$

In this case, the electrical signal is limited by the light intensity and is independent of both concentration and mass flow rate.

Observed PID Response vs. Concentration

The observed PID response mimics the light absorption equations at low and intermediate concentrations. Figures 2.6.3 and 2.6.4 show that commercial PIDs have linear raw response in the ppb and ppm range, and begin to deviate slightly at approximately 500 to 1000 ppm isobutylene (this raw response is usually linearized electronically – see below). However, at very high concentrations above about 10,000 ppm, the response actually drops with higher concentrations. This effect is not explained by a limit in ion generation due to complete light absorbance. It must be due to a decrease in the collection efficiency of ions in reaching the detection electrodes after being generated. The next section describes the chemical reactions that can account for such decreased efficiency.

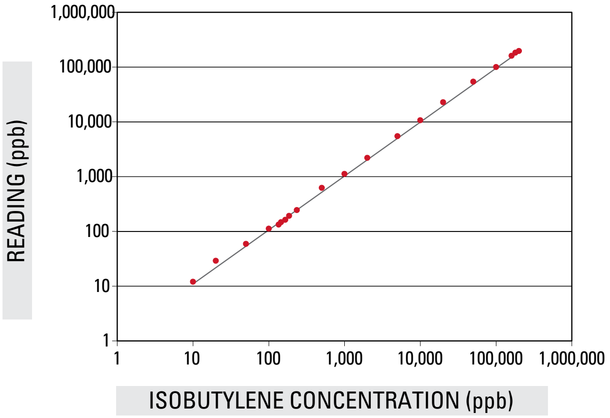

FIGURE 2.6.3. Response of a ppbRAE PID with 10.6 eV lamp as a function of isobutylene concentration in the ppb to middle ppm range

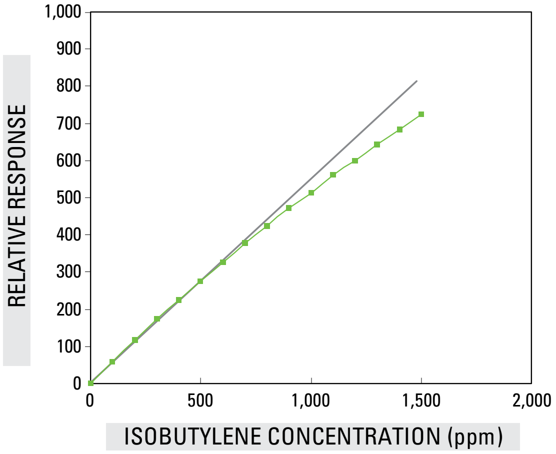

FIGURE 2.6.4. Raw response of a MiniRAE 2000 PID with 10.6 eV lamp as a function of isobutylene concentration in the high ppm range

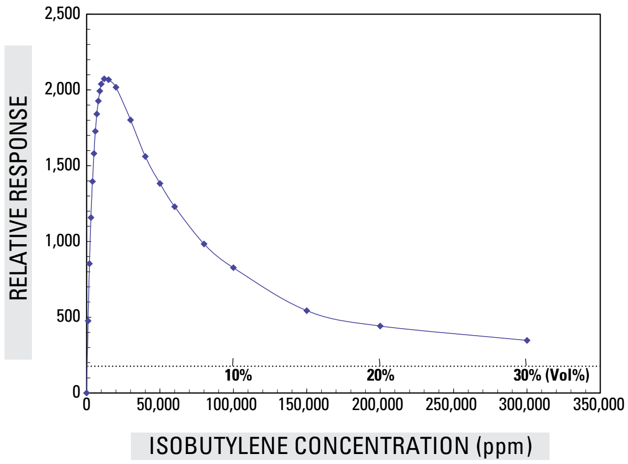

FIGURE 2.6.5. Raw response of a MiniRAE 2000 PID with 10.6 eV lamp as a function of isobutylene concentration in the volume % range

Photo-initiated Radical Reactions in the Sensor Cavity

Following their initial photo-generation, the fate of the resulting electrons and ions depends on various conditions in the sensor cavity. In the presence of oxygen and water vapor, a variety of secondary chemical reactions can occur with the initial ions before reaching the electrodes, such as:

Secondary Ion Formation:

Fragmentation: $VOC^{+\cdot} \longrightarrow VOC_1\cdot + VOC_2^{+\cdot}$ (secondary ion)

Hydration: $VOC^{+\cdot} + H_2O \longrightarrow VOC(OH_2)^{+\cdot}$ (secondary ion)

Oxidation: $VOC^{+\cdot} + O_2 \longrightarrow VOC^{+}OO\cdot$ (secondary ion)

$e- + O_2 \longrightarrow O_2^{-\cdot}$ (secondary ion)

Neutralization:

$VOC^{+\cdot} + e^- \longrightarrow VOC$

$VOC^{+\cdot} + O_2^{-\cdot} \longrightarrow VOC\text{-}O_2$

$VOC(OH_2)^{+\cdot} + O_2^{-\cdot} \longrightarrow HO\text{-}VOC\text{-}OOH$

$VOC^{+}OO\cdot + O_2^{-\cdot} \longrightarrow VOC\text{-}O_2 + O_2$

Many more photochemical processes can take place; the above are examples of some of the most common ones. To summarize, the key processes are:

$$VOC + h\nu \longrightarrow VOC^* \longrightarrow VOC^{+\cdot} + e^-$$

$$VOC^{+\cdot} \text{ or } e^- \longrightarrow \text{secondary ions}$$

$$VOC^{+\cdot} \text{ or } e^- \text{ (or secondary ions)} \longrightarrow \text{measured at electrodes}$$

$$VOC^{+\cdot} \text{ or } e^- \text{ (or secondary ions)} \longrightarrow \text{neutral products not measured}$$

The time scale of the photon absorption and photoionization processes are on the order of femtoseconds (10^{-15} s) to picoseconds (10^{-12} s), and that of the subsequent ion collection and secondary chemical reactions is on the order of microseconds (10^{-6} s) to milliseconds (10^{-3} s).

At low concentrations of VOC below a few thousand ppm, ion measurement dominates over neutralization, and a significant and constant fraction of the electrons and ions reaches the electrodes and is measured. The formation of secondary ions does not reduce the response significantly because they are measured as well as the initial ions. In this case, response is quite linear, as indicated in Figures 2.6.3 and 2.6.4.

At intermediate concentrations, typically above about 500 to 1000 ppm, response begins to deviate from linearity (see Figure 2.6.4). This occurs partly because of light limitations (Figure 2.6.2) and partly because neutralization reactions begin to compete with ion collection at the electrodes. As shown before, the rate of ion formation is first-order in (directly proportional to) VOC concentration. By contrast, the rate of neutralization reactions increases with the square of the ion concentration because two ions are needed for this process. Therefore, neutralization competes more effectively at high concentrations than at low concentrations because at high concentrations there are more counter-ions present in a local region to neutralize the initial ions before they reach the sensor. In addition, the secondary ions are often heavier and have reduced mobility compared to the initial VOC ions. Therefore they have a greater chance of encountering a neutralizing ion before being detected.

At *very* high concentrations, the net result of light limitations and neutralizations is that the response drops, as shown in Figure 2.6.5. In this situation the photo-ions are generated at such a high local concentration that neutralization reactions occur before most of the ions can reach the electrodes to be measured. Such a drop in response at high concentrations is inherent, and is also observed in other photochemical systems wherein the products can recombine to form undetected compounds (see for example, Lichtenthaler et al, 1989).

To summarize, the curvature and drop-off in response of PIDs at high concentrations is a superposition of two factors: a limit in ion generation (light intensity) due to high absorbance, and a reduction in ion collection efficiency due to recombination reactions.

Linearization

Most modern PIDs have built-in curve-fitting algorithms that compensate for the curvature in raw response and give a linear reading in concentration. Such corrections are successful in extending the linear range to at least a few thousand ppm, as shown in Figure 2.6.6. At higher concentrations, compensated readings are subject to increasing error. When the inherent response levels off and then drops, as shown in Figure 2.6.5 at about 10,000 ppm, corrections are difficult or impossible. Measurements at high levels are preferably performed using a dilution system to reduce the VOC concentrations closer to the linear range of the instrument.

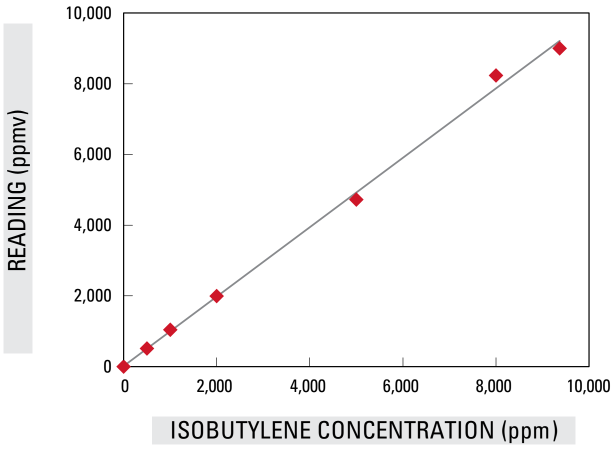

FIGURE 2.6.6. Example of linearized PID response

Photocurrent Efficiency

Certain fractions of the photons and VOC molecules entering the sensor result in ions collected by the electrometer. Photochemical efficiency can be measured from two points of view:

a) the efficiency of VOC transformation to electrical signal (i.e., what fraction of the VOCs are consumed)

b) the efficiency of light utilization from the lamp (i.e., what fraction of battery power results in signal) which is further broken down to:

    i) efficiency of light generation from the power supply

    ii) efficiency of light conversion to electrical signal from VOCs

Both of these efficiencies depend on the measurement conditions and concentrations and tend to be rather low. In case a, a low efficiency is preferable to avoid deposits and sample loss, as long as enough signal is obtained to achieve the desired sensitivity. In case b, a low efficiency is undesirable but not a great limitation because other power requirements such as the sample pump begin to dominate. The instrument designer is primarily concerned with light generation efficiency (b-i). It affects the detection limit achievable with a given lamp, sensor design and power source. This efficiency is generally below a few percent* and may be limited by the lamp crystal used to transmit the light. The light utilization efficiency (b-ii) depends strongly on the measurement conditions (i.e., analyte concentration and inherent quantum efficiency) and is largely out of the designer's control. It is often exceedingly low, and follows a pattern similar to that in Figure 2.6.5. However, these low efficiencies need not concern the user, as modern electronics allow accurate measurement of ever smaller electrical signals.

On the other hand, the operator may be concerned about the efficiency of VOC destruction (a) if it is desirable to collect a sample of the vapors for further analysis after the PID measurement. Empirical measurements show that the PID detection process is essentially non-destructive. The concentration of organic vapors exiting a PID sensor is essentially the same as that entering. We can estimate a lower limit to the ionization efficiency as follows:

At a flow rate of 0.5 L/min, a typical PID results in a photocurrent on the order of 40 pA/ppm of VOC at low VOC concentrations. From these data one can calculate that at 1 ppm the VOC amount passing through the sensor is 3×10^{-10} mol VOC/s and the photocurrent is 4×10^{-16} mol electrons/s, or 1.2×10^{-6} mol electrons/mol VOC. Thus, on the order of 0.0001% of the total VOC passing through the sensor results in a measureable photocurrent. It is possible that many more photoions are generated, but that they are simply not collected efficiently at the electrodes. Uncollected photoions could re-neutralize or react before reaching the sensor. However, the empirical observation that the VOC concentration is essentially unchanged is in agreement with the calculation that an extremely small fraction of the VOC molecules are actually ionized. $VOC^{+\cdot}$ ions collected at the electrode may be reduced to regenerate the starting VOC. However, such regeneration is not the main reason PIDs are considered non-destructive; the reason is that only a very small fraction of VOC molecules are ionized and reach the sensor to begin with.

Sample Collection

Because of the low transformation extent in the sensor, it is often possible to collect a sample at the outlet of the instrument, such as on an activated carbon tube or in a Tedlar gas bag, for use in subsequent laboratory analysis. The ability to do this depends more on possible losses through adsorption in the sampling pump and connecting tubing than on losses due to the photoionization measurement process. For example, multi-gas instruments are more likely to have losses occurring on other sensors or in the more complex flow path. The ability to collect a sample without loss is particularly useful for making empirical correlations between PID readings and laboratory measurements, because the same sample measured by the PID can be submitted for analysis.

Photoproducts

From the inherent nature of the PID measurement process it is clear that photoreactions must occur in the sensor chamber in order for the desired response to be obtained. For the vast majority of cases under typical operating parameters for portable PIDs, these transformations are very minor compared to the total VOC concentration. However, in certain instances the photoproducts of these minor transformations are significant for various reasons.

First, some photoproducts can accumulate on the lamp and sensor. This can occur because photo-oxidation reactions tend to convert non-polar, volatile compounds to more-polar, less volatile photoproducts. A notable example of this is in the PID measurement of phosphine, where even tens of ppm of PH3 can cause a reduced response in a matter of minutes. This effect is believed to be due to the photooxidation of PH3 to phosphoric acid or polyphosphates, resulting in a film build-up on the lamp. Further evidence with other photoionization sources lacking a lamp crystal indicates that build-up of photoproducts on the sensor electrodes also can be responsible for a loss of sensitivity. Similar effects have been observed with H_2S and methyl bromide, although to a far lesser extent and only at concentrations above a few thousand ppm.

Second, PID lamps produce some ozone from the air at ppb levels by the reactions:

$$O_2 + h\nu \longrightarrow 2\,O\cdot$$

$$O_2 + O\cdot \longrightarrow O_3$$

As long as the pump is flowing air at typical flow rates of a few hundred cc/min, the ozone concentration remains low and generally has no significant effects. But if the lamp is on while the flow is off, ozone can accumulate and have secondary effects such as gradual damage to internal rubber or plastic components. At very low flows, several ppm of ozone may be present, which could react with some organics collected in a sample bag. However, gas-phase ozone reactions tend to be slow, and ozone decomposes catalytically on many surfaces. Therefore, the effect of such ozone can be important only when the organic vapor concentrations collected are in the low ppm range or less.

Effect of Flow Rate

PID measurements are observed to be essentially independent of flow rate, as reported by Freedman (1980) and confirmed in our laboratory and others. This result is in accord with adherence to the Lambert-Beer law of light absorption, which states that at low light intensities, the fraction of light absorbed by a fluid mixture is proportional to the concentration of the absorbing substances (not on mass flow). The concentration of substances does not change in the sensor chamber because (a) only a negligible fraction is converted to other substances and (b) the light intensities are far too low to keep a significant fraction of the substances in an excited state. The latter occurs because the speed of light and the rates of photophysical excitation and deactivation are so much more rapid than the rate of photon generation from the lamp. Therefore, a greater fraction of light cannot be absorbed by flowing more material through the cell, because the concentration is essentially the same whether the gas is flowing or standing still. By contrast, response on an FID can be flow-dependent under typical conditions where all the analyte is consumed in the sensor.

Higher flow rate can give stronger or faster response for compounds that have low vapor pressure and thus are prone to adsorption losses in the inlet probe, filters, or sensor components. This is because the adsorption sites are more quickly saturated at higher mass flows. Some filters cause significant flow reductions, and therefore for adsorbing compounds removing filters increases response rate because of both higher flow rate and less available surface for adsorption.

2.7 Linear Additivity of PID Response

At the low concentrations typical for PID measurements (ppm range), it is expected that analyte substances in a mixture will chemically behave independently. In this case, the response for all the components of a mixture should be linearly additive. Figure 2.7.1 shows the response of several mixtures of benzene, isobutylene, and H2S, compared to the total reading predicted from the sum of the components when measured individually. In each case, the calculated and measured responses agreed within <10%, even when the benzene varied from 0 to >50% of the total response. Such tests indicate that the total response of a defined mixture can be predicted from each compound's contribution, without the need to measure responses to each type of mixture. These results are in agreement with the findings of Lee, et al. 1987. Conversely, if the total response and the ratio of components are known, this result allows back-calculation of the concentration of each component.

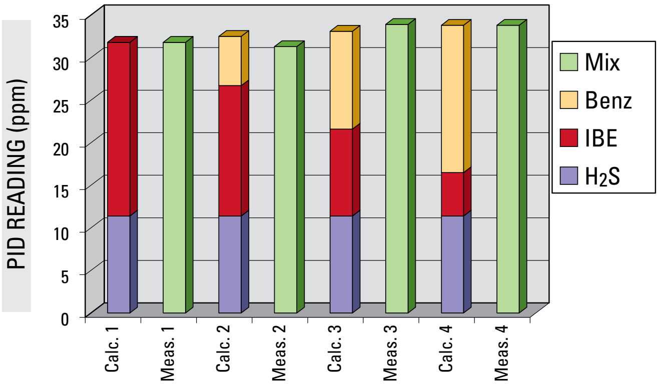

FIGURE 2.7.1. Additivity of PID response in mixtures

3. PID MEASUREMENT PARAMETERS

This chapter describes the many factors that affect the measurement and interpretation of continuous PID readings. In general, any compound with ionization energy (IE) lower than that of the lamp photons can be measured. As shown in Figure 3.0.1, the compound correction factor (CF, see definition in Section 3.1.2), which is inverse to response, increases to infinity as the upper limit of the lamp output is reached.

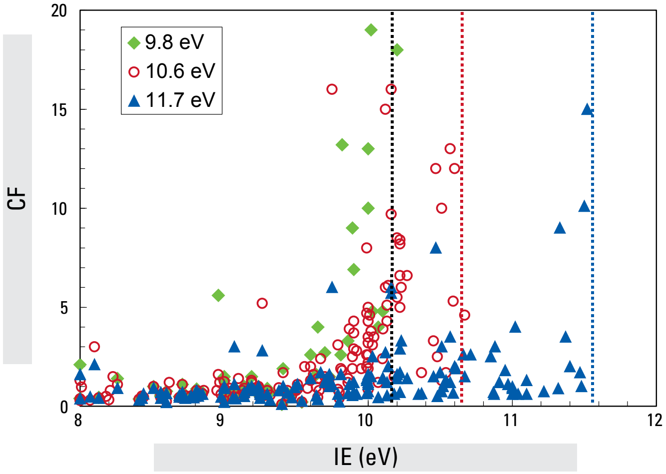

FIGURE 3.0.1. PID correction factor vs. compound ionization energy for various lamps

Compounds with IE <11.7 eV are measurable by PID, and those with lower IE are generally more sensitive (have low CFs). The response depends predominantly on the gas and crystal type; form factors such as size and shape play only a very minor role, if at all. Different manufacturers of the same type of lamp tend to have very similar correction factors, although this should not be assumed, and factors should be obtained directly from the instrument supplier.

Table 3.0.1 below lists the most-sensitive compound classes, and Appendix 3 is an extensive list of CFs for over 300 individual compounds.

TABLE 3.0.1. Approximate response of compound classes by PID

Compound Class	Relative Sensitivity
Aromatics including Heterocycles	++++
Olefins	+++
Sulfides & Mercaptans	+++
Organic Amines	+++
Ketones	+++
Ethers	+++
Silicate Esters	+++
Organic Esters	++
Alcohols	++
Aldehydes	++
Alkanes	++
Alkyl halides	
Iodides	++++
Bromides	+++
Chlorides	+
Fluorides	–
Borate & Phosphate Esters	++
H_2S, NH_3 & PH_3	+ to ++
Organic Acids	+
Noble Gases, H_2, CO, CO_2, O_2, N_2, HCN, SO_2 & O_3	–
Mineral Acids	–

++++ = most sensitive, **+** = least sensitive, **–** = non-detectable

Aromatics, olefins, ketones, ethers, amines, and organic sulfides are among the most sensitive commonly encountered compounds. Substituents on the aromatic ring affect the sensitivity only marginally, and many aromatics have a CF in the range 0.5±0.2. Also notable are poly-olefins such as terpenes (turpentine), multifunctional compounds such as hexamethyldisilazane, and iodine compounds. The most sensitive compound known to the author is elemental iodine (I2), having a CF of 0.1 with 9.8, 10.6 and 11.7 eV lamps. It is a common misconception that halogenated compounds are not detected or poorly detected by PID. Fluorine substitution does reduce response, but chlorine, bromine and iodide substitution increase response. For example, chloroethane is about 14 times more sensitive than ethane itself using an 11.7 eV lamp. In other cases, a strong response is imparted to chlorinated compounds by the other functional groups, such as the double bond in perchloroethylene (CF = 0.57 @ 10.6 eV) and the aromatic nucleus in chlorobenzene (CF = 0.40 @ 10.6 eV).

Alkanes give a response that increases with chain length. Methane is not detectable with any lamp; ethane, propane and butane require an 11.7/11.8 eV lamp; and higher alkanes respond with lower CFs and lower-energy lamps as the number of carbons increases. Thus, for example, long-chain aldehydes and acids gain their sensitivity from the alkyl group rather than the functional group.

So far it has not been possible to predict correction factors from the ionization energies. For example, trans-1,2-dichloroethene (CF = 0.45 @ 10.6 eV) and decane (CF = 1.4 @ 10.6 eV) have an identical IE of 9.65 eV, yet trans-1,2-dichloroethene is 3 times more sensitive. Within a series of similar compounds with the same functional groups, such as linear alkanes (i.e., pentane, hexane, heptane, octane, and decane), it is possible to obtain a rough correlation with chain length. Simple ketones such as acetone (CF = 1.1 @ 10.6 eV), methyl ethyl ketone (CF = 0.9 @ 10.6 eV), and methyl isobutyl ketone (CF = 0.8 @ 10.6 eV) have very similar CFs. Nearly all simple benzene derivatives have a CF of 0.5±0.2. However, for many types of compounds not enough accurate data are available, either on ionization energies or on CFs for similar compounds, to make useful correlations. Therefore, when CFs are needed for new compounds they must be measured.

3.1 Calibration and Correction Factors

Most PID manufacturers recommend that instruments used for industrial hygiene measurements be calibrated each day of use. This recommendation is similar to that of the International Safety Equipment Association (ISEA) recommendation for combustible gas/ O_2/CO/H_2S monitors used for confined space entry (see Section 3.1.1). While ISEA makes no such recommendation for PIDs, the document for confined space monitors is a useful guide. The frequency of calibration can be extended based on experience in the field, but typically the interval should not be longer than 30 days.

In general, PIDs hold their calibrations for days to weeks. Various factors can cause changes in response, including lamp degradation, coating of the lamp with dust and chemicals, temperature, pressure, and matrix gases, including humidity (see details in subsequent chapters). Different lamps have different inherent lifetimes, as noted in Chapter 2.2. For example, an 11.7 eV lamp may require daily calibration even under clean use conditions, whereas a 10.6 eV lamp may run for weeks without needing recalibration.

Lamp Self-Cleaning

Some newer PIDs offer a built-in self cleaning algorithm that turns the lamp on with the pump off during charging, or alternately turns the pump off and on during the measurements while the lamp remains on. During the pump-off periods, the lamp and sensor are cleaned by the accumulated ozone and associated photooxidation processes. Such lamp cleaning maintains the calibration and can reduce the required frequency to months (see Chapter 4 for more details).

3.1.1 ISEA Statement on Calibration for Direct Reading Portable Gas Monitors Used in Confined Spaces

1. A position statement on verification of calibration is needed to:
   - Reemphasize to OSHA and other standards writing bodies the importance of verifying the calibration of instruments used to monitor the atmosphere in potentially hazardous locations.
   - Clarify the differences between a full calibration and a functional (bump) test.
   - Clarify when daily tests are needed and when less frequent tests may be appropriate.
2. Definition of two methods of verifying calibration:
   - Functional (bump) test - A means of verifying calibration by using a known concentration of test gas to demonstrate that an instrument's response to the test gas is within acceptable limits.
   - Full calibration - The adjustment of an instrument's response to match a desired value compared to a known concentration of test gas.
3. Recommended frequency of verification of calibration:
   - A functional (bump) test or full calibration of direct reading portable gas monitors should be made before each day's use in accordance with the manufacturer's instructions using an appropriate test gas.

   - Any instrument which fails a functional (bump) test must be adjusted by means of a full calibration procedure before further use.

Note: If environmental conditions which could affect instrument performance are suspected to be present, such as sensor poisons, then verification of calibration should be made on a more frequent basis.

4. If conditions do not permit daily testing to verify calibration, less frequent verification may be appropriate if the following criteria are met:
   - During a period of initial use of at least 10 days in the intended atmosphere, calibration is verified daily to be sure there is nothing in the atmosphere which is poisoning the sensor(s). The period of initial use must be of sufficient duration to ensure that the sensors are exposed to all conditions which might have an adverse effect on the sensors.
   - If the tests demonstrate that it is not necessary to make adjustments, then the time interval between checks may be lengthened but should not exceed 30 days.
   - The history of the instrument since last verification can be determined by assigning one instrument to one worker, or by establishing a user tracking system such as an equipment use log.

3.1.2 Calibration Gas Selection

The most accurate way to calibrate a PID is to use a standard gas prepared with the compound of interest, at a concentration near the expected measurement range. Isobutylene (IBE) is by far the most common calibration gas because it is inexpensive, readily available, has intermediate sensitivity, and has very low toxicity. Some manufacturers recommend benzene as a reference calibration gas, but use of benzene is decreasing because its relatively high toxicity has become recognized in recent years. Use of correction factors to adjust the scale to the compound of interest is possible. However, direct calibration with the measurement gas is always more accurate because the correction factors can vary slightly from instrument to instrument and with different use conditions such as temperature, humidity and concentration.

The calibration concentration is preferably close to the expected measurement concentration. In principle, if the instrument is perfectly zeroed and the response is perfectly linear, then any calibration concentration could be used. For practical purposes this is true for isobutylene calibration typically in the range 100 - 2000 ppm for many PIDs. For measurements in the low ppm range, calibration at 100 ppm usually gives good precision because the response is quite linear at low concentrations. For sub-ppm measurements (10-1000 ppb), it is preferable to use a span value in the low ppm range, which is somewhat higher than the measurement range. This is because contaminants in the matrix gas begin to cause larger errors in both the zero and span gas concentrations. It is often difficult to obtain a calibration gas standard at 1 ppm certified to better than 20% accuracy.

For measurements in the 2000 - 10,000 ppm range, it is increasingly important to match the span concentration to the measurement concentration, because of the inherent non-linearity of the measurement, and thus greater variability even after firmware linearizations. Linearity may be good for isobutylene, but different for other gases, and thus the linearization scheme may under- or over- compensate the response curvature. In such cases, it may be helpful to dilute the sample gas into a more linear range. Most PID manufacturers offer a dilution probe or fitting for this purpose. Sample dilution has the additional benefit that it can modify (e.g., dry) the matrix gas, resulting in fewer matrix effect corrections and lower maintenance (e.g., lamp and sensor cleanings).

3.1.3 Calibrations with Isobutylene (IBE)

CAUTION: It is important to understand that calibrating a PID to a specific gas does not make the instrument selective to that gas. A PID always responds to all the gases that the lamp can ionize, and gives the readout in equivalent units of the calibration gas.

Correction factors have been determined that enable the user to quantify a large number of chemicals using only a single calibration gas, typically isobutylene (IBE). When the instrument is calibrated with IBE, there is no need to recalibrate it when other compounds are to be measured. Rather, a correction factor (CF) can be applied to have the PID read out in units of the new compound.

The CF is the ratio of the response to isobutylene over the response to a particular compound. Practically, it is defined as:

$$\mathrm{CF} = \mathrm{CF}^{\mathrm{IBE}}_{\mathrm{VOC}} = \frac{\text{True VOC Concentration}}{\text{PID Reading}}$$

Once the CF has been established, the true concentration can be obtained by multiplying the reading by the CF:

$$\text{True VOC Concentration} = \mathrm{CF}^{\mathrm{IBE}}_{\mathrm{VOC}} \times \text{PID Reading}$$

Correction factors are inverse to sensitivity. Compounds with CF greater than 1.0 are less sensitive than isobutylene, and those with CF less than 1.0 are more sensitive than isobutylene.

CF Measurement

To measure the CF, take separate, equal concentrations of the calibration gas and the measurement gas, and measure the responses (R). Then:

$$\mathrm{CF}^{\text{cal gas}}_{\text{meas gas}} = \frac{R_{(\text{cal gas})}}{R_{(\text{meas gas})}}$$

For example, on a PID 100 ppm isobutylene reads 98, and 100 ppm benzene reads 185. The CF = 98/185 = 0.53.

If the isobutylene concentration is different than the test gas concentration during CF determination:

$$\text{Isobutylene based CF for benzene} = \mathrm{CF}^{\mathrm{IBE}}_{\mathrm{benz}} = \frac{R_{\mathrm{IBE}}}{C_{\mathrm{IBE}}} \times \frac{C_{\mathrm{benz}}}{R_{\mathrm{benz}}}$$

For example, on a PID 100 ppm isobutylene reads 96 and 50 ppm benzene reads 91, the CF = (96 x 50)/(100 x 91) = 0.53.

CF Application

Further measurements no longer require the isobutylene check. For example, a reading of 23 in benzene-laden air would correspond to:

$$23\ \text{ppm}_{\text{(isobutylene equivalents)}} \times 0.53_{\text{(CF)}} = 12\ \text{ppm}_{\text{(benzene)}}$$

Many instruments now allow the user to call up and apply the CF from an on-board library. Thus, the instrument would be calibrated with isobutylene but read directly in units of benzene or other desired compounds. Note that this factor does not make the monitor selective for a particular compound; it still responds to all detectable compounds, but quantitates them on a different scale.

3.1.4 Converting CFs to Other Calibration Compounds

CFs are always relative to the calibration gas. To estimate CFs for other calibration gases, simply divide the isobutylene CF for the measurement compound by the CF for the new calibration compound. Thus, a new scale of calibration factors can be determined for any compound with known isobutylene CF.

$$\text{Isobutylene based CF for hexane} = CF_{hex}^{IBE} = \frac{R_{IBE}}{C_{IBE}} \times \frac{C_{hex}}{R_{hex}}$$

Where R_{IBE} = Response to isobutylene at a concentration C_{IBE}

R_{hex} = Response to n-hexane at a concentration C_{hex}

CF_{hex}^{IBE} = CF for hexane calibrated to Isobutylene

At equal concentrations of hexane and isobutylene (tested separately), this equation reduces to:

$$\text{Isobutylene based CF for hexane} = CF_{hex}^{IBE} = \frac{R_{IBE}}{R_{hex}} \ (= 4.3)$$

$$\text{Likewise, the isobutylene based CF for toulene} = CF_{tol}^{IBE} = \frac{R_{IBE}}{R_{tol}} \ (= 0.5)$$

By analogy, the toluene-based CF for hexane is:

$$CF_{hex}^{tol} = \frac{R_{tol}}{R_{hex}} = \frac{R_{IBE}}{R_{hex}} \times \frac{R_{tol}}{R_{IBE}} \quad \frac{CF_{hex}^{IBE}}{CF_{tol}^{IBE}} = \frac{4.3}{0.5} = 8.6$$

Where R_{tol} = Response to toluene at a concentration C_{tol}

CF_{tol}^{IBE} = CF for toulene calibrated to isobutylene

CF_{hex}^{tol} = CF for hexane calibrated to toulene

Thus, all the CF values from Appendix 3 can be converted to a toluene scale (toluene calibration) by dividing the 10.6 eV lamp values by 0.5 (multiplying by 2). Or, they could all be converted to a hexane scale by dividing the 10.6 eV lamp values by 4.3.

In some instruments where CFs are built into the firmware, all the user needs to do is call up the calibration gas and the measurement gas. Then the instrument will calculate the modified factors for the non-isobutylene calibration gas and apply them to the readings.

3.1.5 Conversion of ppmv Readings to Other Units (mg/m³)

PIDs typically give a response in units of ppmv, or parts per million by volume, as opposed to ppmw or parts per million by weight. In this manual the term ppm is taken to be synonymous with ppmv. Because dilute gas samples follow the ideal gas law closely, ppmv is equivalent to ppm by mole.

More precisely, portable PIDs typically give a response in the same units as the calibration gas supplied. The most common calibration gas is 100 ppm isobutylene, which is manufactured as 100 ppmv. However, the monitor is usually insensitive to the concentration units; therefore if the gas standard concentration is defined in other units, such as mg/m³, then the response will be in mg/m³ equivalents of the calibration gas. Likewise if the standard gas is supplied in %LEL or lbs./MMCF (lbs./million cubic feet), then the PID response will be in %LEL or lbs./MMCF equivalents, respectively, of the calibration gas.

Appendix 9 gives a table of conversion factors between different gas phase concentration units. Additional tables are provided in Appendix 9 to correct the conversion factors for various temperatures and pressures. The conversion between ppmv and mg/m³ requires the compound molecular weight (m.w.) and, at room temperature 25°C (77°F) and sea-level atmospheric pressure, reduces to:

$$\text{Conc. (ppmv)} = \frac{24.46 \text{ x Conc. (mg/m}^3\text{)}}{\text{m.w. (g/mol)}}$$

$$\text{Conc. (mg/m}^3\text{)} = 0.041 \text{ x Conc. (ppmv) x m.w. (g/mol)}$$

Example 1: Conversion from Compound ppmv to mg/m^3

Convert 46 ppmv of ethyl acetate (m.w. = 88.1) and 100 ppm IBE (m.w. = 56.1) to mg/m^3 at room temperature and atmospheric pressure:

Conc. (mg/m^3) = 0.041 x 46 ppmv x 88.1 g/mol = 166 mg/m^3
Conc. (mg/m^3) = 0.041 x 100 ppmv x 56.1 g/mol = 230 mg/m^3

Example 2: Calibration with a Standard Directly in mg/m^3

A PID is calibrated using a cylinder of 100 ppmv IBE, but the span value is set to 230 (mg/m^3). The unit then reads directly in mg/m^3 of isobutylene.

CAUTION: When calibrating a PID in mg/m^3 units, one cannot use the CFs in Appendix 3 for converting to mg/m^3 units of another gas, because Appendix 3 applies only to ppmv to ppmv conversions. It is necessary to convert the readings from mg/m^3 IBE back to ppmv before the CFs from Appendix 3 can be applied, and then reconvert the ppmv value of the new compound to mg/m^3.

To make the unit display in mg/m^3 of another compound, either calibrate directly with that compound, setting the span value to its mg/m^3 concentration, or calibrate with isobutylene and use the procedure in Example 3.

Example 3: Conversion from Isobutylene Equivalents to mg/m^3

A PID with 10.6 eV lamp is calibrated to isobutylene (IBE) in ppmv and reads 10 ppmv on a sample of ethyl acetate. According to Appendix 3, the correction factor for ethyl acetate is 4.6. Therefore, the true concentration is 10 x 4.6 = 46 ppmv of ethyl acetate. From the Example 1 above, 46 ppmv equals 166 mg/m^3.

An overall correction factor can be calculated to convert directly from IBE equivalent ppmv to compound mg/m^3:

Conc. (mg/m^3) = 0.041 x IBE equiv. (ppmv) x CF x m.w. (g/mol)
Conc. (mg/m^3) = {0.041 x CF x m.w. (g/mol)} x IBE equiv. (ppmv)
= CF* x IBE equiv. (ppmv)
CF* = 0.041 x CF x m.w. (g/mol)

In this example, the new CF* value is 0.041 x 4.6 x 88.1 = 16.6. Therefore, the 10 ppm reading equals 10 x 16.6 = 166 mg/m^3. This new CF* can often be programmed into the PID to allow direct reading of ethyl acetate mg/m^3 after calibration to a ppmv standard isobutylene.

Example 4: Conversion from Isobutylene Equivalents to mgC/m^3

First convert the IBE equivalent ppmv readings to true ppmv of the compound. Then convert ppmv to mg/m^3 as in Examples 1 and 3. Finally, multiply by the weight fraction of carbon in the compound. For ethyl acetate the four carbons make up a molecular weight fraction of 48/88.1 = 54%. Thus, the 166 mg/m^3 in Example 3 correspond to 0.54 x 166 = 90.4 mgC/m^3.

Example 5: Conversion from Isobutylene Equivalents to mg/m^3 and mgC/m^3 for Compound Mixtures

In the case of compound mixtures, first convert the mixture response to ppmv of each individual component, as described in the Section 3.1.6. Then convert each individual component to mg/m^3 by multiplying by the molecular weight and dividing by the gas molar volume as in Example 1. Then add all the mg/m^3 values to obtain total concentration in mg/m^3.

Given a PID reading of 100 ppmv isobutylene equivalents on a mixture comprised of 5% benzene and 95% n-hexane, calculate the total concentration in mg/m^3 as follows. The CF for this mixture is 3.2, as described in Example 1 of Section 3.1.6. The total VOC concentration is thus 100 x 3.2 = 320 ppmv, consisting of 16 ppmv benzene and 304 ppm hexane.

Benzene m.w. = 78.1 g/mol or 72.1 gC/mol
0.041 x 16 ppmv x 78.1 g/mol = 51 mg/m^3

Hexane m.w. = 86.2 g/mol or 72.1 gC/mol
0.041 x 304 ppmv x 86.2 g/mol = 1074 mg/m^3

TABLE 3.1.1. Conversion from ppmv to mg/m^3 for mixtures

Compound	ppmv	mg/m^3	mgC/m^3
Benzene	16	51	47
Hexane	304	1074	899
Total	320	1125	946

Thus, after calibration to isobutylene, a response of 100 ppmv on the PID corresponds to 320 ppmv, 1125 mg/m^3, and 946 mgC/m^3 of the mixture.

Unknown Compound Mixtures

For unknown compound mixtures, it is not possible to convert rigorously to ppmv, mg/m^3 or mgC/m^3. In such cases, average or estimated molecular weights and carbon mole fractions may prove useful. However, it is incorrect to use the molecular weight and carbon mole fraction of the calibration gas (e.g., isobutylene) for these conversions.

3.1.6 Measurement of Vapor Mixtures

Because the PID is a non-specific measurement technique, mixtures of compounds give a weighted total response of all detectable compounds. Usually it is desirable to know the concentration of each individual compound, or at least the most toxic one. Numerous examples exist, such as benzene in gasoline, butadiene in the presence of solvents used in rubber and plastics manufacture, formaldehyde in paint solvents, and CS_2 in the presence of H_2S during plastics manufacturing.

1. GENERAL CONSIDERATIONS FOR MIXTURES

Human Exposure Limits for Mixtures

According to the ACGIH (1997), exposure effects are, to a first approximation, taken to be the sum of the effects of the individual components. Exceptions occur where individual components act in separate organs and effects are less than additive, or when they act synergistically, and effects are more than additive. Making the assumption of additivity allows the calculation of TWAs for mixtures, and thus the recommended alarm limit setpoints for a PID.

Calculated CFs for Mixtures

Tests have shown that the response of PIDs to mixtures of compounds are linearly additive (see Section 2.7 and Lee, et al. 1987). Therefore, it is possible to calculate an overall correction factor based on the exact mixture composition from the CFs of the individual components. Part 3 of this section describes the equations used, and further examples of CF calculations for mixtures are given in Chapter 4 and in Appendix 4. The concentration of the individual components can then be extracted from a simple measurement of the total VOC concentration, even if some of the components are not detectable.

Empirically Measured CFs for Mixtures

Alternatively, if the mixture is very complex or not precisely known (but reproducible, e.g., gasoline), the CF can be measured empirically using the equations in Section 3.1.3. A common method is to evaporate a known weight of a liquid mixture into a known volume of air. In such cases it is necessary to determine the CF in non-standard units (e.g., (mg/m^3)/ppmv), or to use an estimated average molecular weight to calculate the CF in the standard dimensionless units (ppmv/ppmv). Another method of establishing a known vapor concentration is to collect a typical gas sample on a charcoal tube or in a gas bag and submit it for laboratory analysis. One method that has been successful is to attach a charcoal sorbent tube to the effluent of the PID and thus measure the PID response at the same time as the sample collection (Drummond, 1997).

Surrogate Compound Measurement

In some cases, the most toxic compound is a detectable but minor component of the mixture, such as 1% benzene or tetraethyllead in gasoline. In other cases, the target compound does not respond on the PID at all, such as when using an 11.7 eV lamp to measure undetectable methane in natural gas from the response of the minor components ethane and propane. In these cases, it is impossible to distinguish the minor or undetectable component from the much higher response of other detectable compounds. However, if the percentage of the minor or undetectable component is constant, the other detectable compounds provide a marker for the target compounds and a surrogate measurement can be made. Given that the fraction of the target component is constant and known, mixture CFs can be used to determine both the total vapor concentration and the concentration of a trace or undetectable component.

2. VARIABLE MIXTURES

Both calculated and measured CFs are suitable only if the mixture composition is constant. If the mixture ratio varies, it is not possible to determine either the individual or total concentrations using a single sensor (whether it be PID, FID, IR, or any other technique). In such cases it is necessary to either employ multiple sensors with different detection abilities, or to apply a separation technique before detection. Examples of the latter include portable GCs or simpler scrubbers, such as RAE-Sep tubes or cellulose filters, to select for the component of interest.

Controlling Compound Approach

Alternatively, one can set the alarm limit to that for a controlling compound. This is a conservative approach, which sets the alarm to a low enough level to ensure that the user is protected in a worst-case scenario. The controlling compound is often, but not necessarily, the most toxic compound. In this method, the unit is calibrated to isobutylene and equivalent alarm concentrations for each compound in the mixture are calculated as:

$$\text{Alarm Limit} = \text{Exposure Limit} / \text{CF}$$

The calculated isobutylene equivalent alarm limits are then compared and the alarm set to the lowest value. For example, in the mixture in Table 3.1.2, ethyl acrylate is the most toxic compound and controls the alarm, which would be set at 10 ppm. Overprotection is provided for toluene and hexane and the possibility for false positive alarms exists, but the operator is assured protection for all compounds at any mixture ratio.

TABLE 3.1.2. Controlling compound evaluation #1

Chemical Name	10.6 eV CF	OSHA PEL (ppm)	IBE Equivalent Alarm Limit (ppm)
Ethyl acrylate	2.4	25	10
Toluene	0.50	200	400
n-Hexane	4.3	500	116

TABLE 3.1.3. Controlling compound evaluation #2

Chemical Name	10.6 eV CF	OSHA PEL (ppm)	IBE Equivalent Alarm Limit (ppm)
Ethanol	12	1000	83
Toluene	0.50	200	400
Acetone	1.1	1000	910

In the example in Table 3.1.3, toluene is the most toxic compound, but ethanol is the controlling compound because of its low sensitivity (high CF). Therefore, if the PID is set to an alarm of 83 ppm, it will protect workers from all three chemicals no matter what the relative concentrations are.

Appendix 5 Lists isobutylene equivalent alarm limits for a range of compounds, including many from the OSHA Z-List. If the alarm is set to that for any one compound, the user will be warned against overexposure to any other chemicals above it on the list. All exposure limits are listed as the OSHA PEL, except that the nerve agents at the end of the table also include the LC50, or the 50% lethal concentration after one minute exposure. Using a PID for these chemicals cannot protect at 8-hour exposure levels, but can be useful in warning against potentially lethal concentrations.

3. CF & ALARM LIMIT CALCULATIONS FOR SIMPLE GAS MIXTURES

The PID response of a mixture is weighted to the relative sensitivity and relative concentration of each compound:

$$\text{CF}_{\text{mix}} = 1 / (X_1/\text{CF}_1 + X_2/\text{CF}_2 + X_3/\text{CF}_3 + \ldots X_i/\text{CF}_i)$$
$$\text{TLV}_{\text{mix}} = 1 / (X_1/\text{TLV}_1 + X_2/\text{TLV}_2 + X_3/\text{TLV}_3 + \ldots X_i/\text{TLV}_i)$$
$$\text{Alarm Setting} = \text{TLV}_{\text{mix}} / \text{CF}_{\text{mix}}$$

where X_i, TLV_i, and CF_i are the mole fraction of total VOCs, TLVs, and CFs of the individual components, respectively.

Example 1: All Compounds Detected

Air contaminated with ppm level VOCs distributed as 5% benzene (CF = 0.53, TLV = 0.5 ppm) and 95% n-hexane (CF = 4.3, TLV = 50 ppm) has a correction factor of

$$\text{CF}_{\text{mix}} = 1 / (0.05/0.53 + 0.95/4.3) = 3.2$$

A reading of 100 would then correspond to 320 ppm of the total mixture, comprised of 16 ppm benzene and 304 ppm hexane. The TLV for this mixture is

$$\text{TLV}_{\text{mix}} = 1 / (0.05/0.5 + 0.95/50) = 8.4 \text{ ppm}$$

corresponding to 8.0 ppm hexane and 0.4 ppm benzene. The alarm setting for an instrument calibrated with isobutylene is

$$\text{TLV reading} = 8.4 / 3.2 = 2.6 \text{ ppm}$$

A common practice is to set the lower alarm limit to half the TLV reading, and the higher limit to the TLV. In this case, one would set the lower and higher alarms to 1.3 and 2.6 ppm, respectively.

Example 2: Not All Compounds Detected (Surrogate Method)

Air-VOC mixture containing 30% phenol (CF = 1.0, TLV = 5 ppm) and 70% methylene chloride (CF = No Response, TLV = 25 ppm) has a correction factor, TLV, and alarm setting of

$$CF_{mix} = 1 / (0.3/1.0 + 0.7/\infty) = 3.3$$

$$TLV_{mix} = 1 / (0.3/5 + 0.7/25) = 11.4 \text{ ppm}$$

$$\text{TLV reading} = 11.4 / 3.3 = 3.4 \text{ ppm}$$

The suggested low and high alarm settings are 1.7 and 3.4 ppm. The TLV mixture corresponds to 30% of 11.4 = 3.4 ppm phenol and 70% of 11.4 = 8.0 ppm methylene chloride. In this case, the PID with a 10.6 eV lamp does not respond to the methylene chloride and all the response is due to the phenol. The alarm setting of 3.4 ppm is lower than the TLV of the phenol alone (5 ppm), because the methylene chloride contributes to the toxicity of the mixture even though it is not measured.

CAUTION: If the percentage of the toxic component is variable, the surrogate measurement method can lead to serious inaccuracies, and a more specific detection method is required.

Selective measurement methods include using a separation tube in front of the PID (e.g., UltraRAE), portable GCs, laboratory GCs, and gas detection tubes with prelayers that remove interferences.

4. CF & ALARM LIMITS FOR MIXTURES FROM AN EVAPORATING LIQUID

Determination of CFs for an evaporating liquid mixture present some special challenges that can be addressed using some limiting assumptions for headspace vapors and evaporated spills.

Usually liquid mixtures are identified in terms of weight percent. Calculation of CFs and exposure limits in ppmv then requires that the concentrations first be converted to mole percent (i.e., mole fraction). This is done as follows:

$$\frac{(\text{Wt\% A})/(\text{m.w. A})}{(\text{Wt\% A})/(\text{m.w. A}) + (\text{Wt\% B})/(\text{m.w. B}) + (\text{Wt\% C})/(\text{m.w. C}) + \ldots\text{etc.}}$$

where wt% is the weight percentage of component A and m.w. is its molecular weight in g/mol.

Example 3: Conversion of Weight % to Mole %.

For example, a liquid mixture has the following weight percentages:

60% Ethyl acetate (EA)	m.w. = 88.1 g/mol
25% Methyl ethyl ketone (MEK)	m.w. = 72.1 g/mol
15% Toluene (Tol)	m.w. = 92.1 g/mol

TABLE 3.1.2. Conversion of Wt.% to Mol% for liquid for mixtures

Compound	Wt. % (g/kg liq)	m.w. (g/mol)	(Wt%)/(m.w.) (mol/kg liq)	mol %
Ethyl acetate (EA)	600	88.1	6.81	57.2
Methyl ethyl ketone (MEK)	250	72.1	3.47	29.1
Toluene (Tol)	150	92.1	1.63	13.7
Total	1000	-	11.91	100.0

In this example, the weight percentages and mole percentages are similar. When the molecular weights and CFs of the components are similar, the conversion of weight percent to mole percent typically has little effect on the CF calculation for the mixture. The conversion is necessary for mixtures of components of substantially differing molecular weights.

a. Vapors From a Large Liquid Reservoir

CAUTION: The concentration of vapors directly above a tank of organic liquid is often too concentrated to measure directly. As shown in Figure 2.6.5, some PIDs may give a false low response when exposed to percent levels of VOCs. Therefore, the PID is more suitable for measuring such vapor mixtures after they are some distance from the tank headspace and are diluted.

General Equations. Vapors above a large liquid reservoir have a different equilibrium composition than that of the liquid mixture, as can be calculated by Raoult's Law:

$$P_T = P_1X_1^{\ell} + P_2X_2^{\ell} + P_3X_3^{\ell} \ldots + P_nX_n^{\ell}$$

where P_T is the total vapor pressure of organic compounds above the liquid, P_1 is the vapor pressure of Component 1 if it were a pure liquid, and X_1^{ℓ}

is the mole fraction of Component 1 in the liquid mixture, P_2 is the vapor pressure of Component 2, and so on.

The mole fraction in the gas phase is $X_n^g = \dfrac{P_n X_n^\ell}{P_T}$

The mole fractions thus calculated refer only to the fraction of total vaporized compounds without regard to the air or other matrix gas. Raoult's Law is most applicable for mixtures of similar compounds and is most exact at high mole fractions.

Dilute Solutions. For dilute solutions, the solute behavior often deviates from Raoult's Law and it is more accurate to apply Henry's Law to the solute and Raoult's Law to the solvent. This approach requires knowledge of the Henry constant (H_{Solute}) for the solute:

$$P_{Solute} = H_{Solute} X_{Solute}^\ell$$

$$P_T = H_{Solute} X_{Solute}^\ell + P_{Solvent} X_{Solvent}^\ell$$

But since $X_{Solvent}^\ell$ is nearly 1.0, the second term approaches the vapor pressure of the pure solvent:

$$P_T = H_{Solute} X_{Solute}^\ell + P_{Solvent}$$

The mole fractions are then:

$$X_{Solute}^g = \frac{H_{Solute} X_{Solute}^\ell}{P_T} \quad \text{and} \quad X_{Solvent}^g = \frac{P_{Solvent}^\ell}{P_T}$$

Example 4: Conversion of Liquid to Vapor Mole Fractions

Using the mixture in Example 3 above, the liquid mole fractions are 0.572 for ethyl acetate, 0.291 for MEK, and 0.137 for toluene. The vapor-phase mole fractions are calculated as in Table 3.1.3.

TABLE 3.1.3. Calculation of vapor mole fraction from liquid mole fraction

Compound	X_n	P_n @20°C (mm Hg)	$P_n X_n^\ell$ (mm Hg)	X_n^g
Ethyl acetate (EA)	0.572	73	41.7	0.619
Methyl ethyl ketone (MEK)	0.291	78	22.7	0.337
Toluene (Tol)	0.137	22	3	0.044
Total	1	-	67.4	1

The average CF and alarm limits are then calculated using the equations in subsection 1 of this chapter (see Example 1). The average CF is 1.6 calculated from the gas-phase mole fractions, compared to 1.4 calculated from the liquid-phase mole fractions.

TABLE 3.1.4. CFs and alarm limits vs calculation method

Factor	Calc. By Vapor mol% (large reservoir)	Calc. By Liq. mol% (small spill)	Calc. By Liq. Wt.% (small spill)
Correction Factor	1.6	1.4	1.4
TLV (8-hr TWA)	244 ppm	178 ppm	174 ppm
Alarm Setpoint (cal to IBE)	150 ppm	131 ppm	126 ppm

Note that in this example there is little difference between the CF and alarm setpoints for calculations using liquid mole % or liquid weight %. This is generally true for mixtures of compounds with similar molecular weights. However, as the component molecular weights and vapor pressures diverge, it becomes increasingly more important to perform the conversions to vapor-phase mole percentages before calculating the CFs and exposure limits.

b. Vapors From a Small Spill or Liquid Leak

If the liquid release is small, compared to the gas-phase volume, all the liquid will evaporate and there will no longer be an equilibrium with a liquid phase. If evaporation occurs quickly, then the vapor will have the same composition as the original liquid. In Example 4, a CF of 1.4 would be more appropriate to use for a small spill or leak that evaporates quickly.

If evaporation occurs slowly, the composition of the vapor mixture varies with time. Then the vapor composition and CF will initially be closer to those of the most volatile components and later resemble more the least volatile components.

3.1.7 PID Correlations with FID Measurements

Introduction

Many regulatory agencies request inventories of chemicals released to the air to be provided in units of methane or hexane equivalents. This is done as a way of normalizing the overall environmental impact of a broad variety of different chemical types to a common unit, i.e., the total number of carbon atoms released. Traditionally, methane equivalents of a mixture of organic compounds have been measured using a laboratory gas chromatograph (GC) calibrated with methane using a flame ionization detector (FID). Portable FIDs and PIDs provide a convenient, cost-saving method of making measurements in the field. Portable FIDs function on the same principle as the laboratory FIDs; however the sample inlet designs of many portable FIDs often result in responses that are not proportional to the number of carbons in the organic compound. Therefore, methane equivalents measured on a portable FID do not necessarily correspond to the desired laboratory FID equivalents, which are proportional to carbons.

Portable PIDs offer advantages over portable FIDs in their ease of use, smaller size and weight, lower cost, and lack of need for hydrogen cylinders. In addition, a PID does not have interference from methane, which is exempt from most regulatory emissions limits. Methane is prevalent from both biogenic sources and from natural gas distribution leaks, and thus use of a PID will reduce the number of false positive responses due to methane. This chapter describes methods for converting PID measurements to laboratory GC-FID methane equivalents. Conversion of PID readings to hexane equivalents is performed by analogous equations.

Empirical Correlations

The conceptually simplest conversion approach is to simultaneously make PID measurements while taking gas samples that are sent to a laboratory for GC-FID analysis. When the results are compared, a PID-FID correlation factor or curve can be developed. For example, Coy, et al. (2000) found the following correlation when calibrating the PID to isobutylene and sampling with charcoal for GC:

$$\log(\text{GC total ppm}) = -0.042 + 1.05*\log(\text{PID ppm})$$

This calibration applied to vapors from painting operations, including such compounds as petroleum distillates, mineral spirits, isobutyl acetate, isobutyl alcohol, isopropanol, toluene, xylenes, ethylbenzene, and MEK.

Drummond (1997) studied gasoline vapors measured by a PID worn by a tanker truck driver during loading. The average benzene concentration determined by charcoal tubes and lab GC correlated with the isobutylene-calibrated PID as follows:

$$\text{Benzene ppm} = 0.20*(\text{PID ppm})$$

In these cases, the GC results gave actual concentrations of the individual components in ppm, but could have easily given methane equivalents by calibrating the GC-FIDs to methane.

The advantage of this approach is its simplicity and accuracy once the correlation has been obtained. It also can be used on highly complex and unknown mixtures. The disadvantage is that it applies to only one mixture, and more laboratory tests are needed to establish a new correlation for each new mixture encountered. The methods described below allow estimation of PID-FID conversion factors for many mixtures without the need for sampling and laboratory measurements.

PID Lamp Selection

A variety of lamps are available for general hydrocarbon monitoring (see Chapter 2.2). The 10.6 eV lamp responds to pentane and higher hydrocarbons, and the 11.7 eV lamp responds to ethane (weakly), propane and higher hydrocarbons. As mentioned above, methane and ethane are exempt from most regulations. Unless propane or butane are specifically known to be present, the 10.6 eV lamp is preferred because it responds broadly to many solvents and fuels and has a considerably longer working life than the 11.7 eV lamp. Even if propane or butane are present, their proportion of the total hydrocarbons can be measured in a few laboratory tests and then the ratio used to correct the 10.6 eV PID readings. Therefore, the 10.6 eV lamp is recommended unless compounds that require an 11.7 eV lamp dominate the emissions scenario. Appendix 3 is an extended list of compounds and their responses on these two lamps.

Procedure

To convert PID readings to methane equivalent FID readings, proceed as follows:

1) Calibrate the PID to isobutylene using the standard procedures
2) Measure the gas or gas mixture.
3) Multiply the observed readings by the PID-FID Correction Factor listed in one of the last two columns in the Tables in Appendix 6.

Ideally, the value selected is the measured factor in the second-to-last column. In the absence of a measured value, an upper limit to the methane-equivalent response can be estimated from the number of carbons in the molecule (last column).

PID-FID Correction Factor Derivation for Methane Equivalents

The rationale behind the PID-FID correction factors (CFs) is as follows:

The PID CF is defined as the value by which the readings are multiplied in order to obtain the true ppmv concentrations, when the unit has been calibrated to isobutylene:

$$\text{True ppmv} = \text{PID reading} \times \text{PID CF} \qquad (1)$$

The Lab FID Response Factor (RF) is defined as the relative response of the compound compared to methane. The methane equivalent FID response is

$$CH_4 \text{ Equivalents} = \text{True ppmv} \times \text{FID RF} \qquad (2a)$$

An estimate of the FID RF is the number of carbon atoms in the molecule, in which case Eq (2a) becomes:

$$CH_4 \text{ Equivalents} = \text{True ppmv} \times \#\text{C Atoms} \qquad (2b)$$

Combining Eqs (2a) or (2b) with Eq (1) yields:

$$CH_4 \text{ Equivs} = \text{PID read} \times \text{PID CF} \times \text{FID RF} \qquad (3a)$$
$$CH_4 \text{ Equivs} = \text{PID read} \times \text{PID CF} \times \#\text{Cs} \qquad (3b)$$

The PID-FID CFs are thus:

$$\text{PID-FID CF (Meas.)} = \text{PID CF} \times \text{FID RF} \qquad (4a)$$
$$\text{PID-FID CF (Calc.)} = \text{PID CF} \times \#\text{Cs} \qquad (4b)$$

If the PID is calibrated using the gas of interest, then it reads directly in true ppmv and therefore it is not necessary to multiply by the PID CF, only by the FID RF or the number of carbon atoms. In other words, the PID gives the true ppmv used in Eq. 2a or 2b.

Example 1: Single Compound

1. Toluene is the only compound being measured. The Lab FID RF is available in Table 5.6.1 and therefore the PID-FID CF is known (col. 5).
    a) The reading is 10 ppm with the PID calibrated to isobutylene. The lab FID equivalent is 10 x 2.6 = 26 ppm methane units.
    b) With the PID calibrated directly to toluene (or calibrated to isobutylene but using the built-in correction factor to read in toluene units) the display reading is 5 ppm. The lab FID equivalent is 5 x 5.1 = 26 ppm methane units.
2. Methyl cellosolve (2-methoxyethanol) is the only compound. The Lab FID RF is not available, and therefore the PID-FID CF is estimated from the number of carbon atoms (Table 5.6.1, column 6). The PID reading of 10 ppm corresponds to 10 x 7.2 = 72 ppm FID equivalents. This value can be considered a safe upper limit because the true factor is almost certainly less than the 7.2 estimated from the number of carbons.

Example 2: Compound Mixture (Methane Equivalents)

The vapors consist of the following mixture:

60% Ethyl acetate (EA)
25% Methyl ethyl ketone (MEK)
15% Toluene (Tol)

The unit is calibrated to isobutylene and the reading is 50 ppm. As described in Chapter 3.1.6, the average CF for this mixture is calculated as:

$$\text{CFmix} = 1/(X_{EA}/CF_{EA} + X_{MEK}/CF_{MEK} + X_{Tol}/CF_{Tol}) \qquad (5)$$
$$\text{CFmix} = 1/(0.60/4.6 + 0.25/0.86 + 0.15/0.50) = 1.4$$

The true total concentration is 50 x 1.4 = 70 ppm, which consists of 42 ppm ethyl acetate, 17.5 ppm MEK, and 10.5 ppm toluene. Multiplying each compound by its respective FID RF factor from Table 5.6.1:

$$CH_4 \text{ Equivalents} = 42 \times 2.0 + 17.5 \times 2.2 + 10.5 \times 5.1 = 176 \text{ ppm}$$

To simplify, an average FID RF can be calculated for the mixture as:

$$\text{RFmix} = X_{EA} \times RF_{EA} + X_{MEK} \times RF_{MEK} + X_{Tol} \times RF_{Tol} \qquad (6)$$
$$\text{RFmix} = 0.60 \times 2.0 + 0.25 \times 2.2 + 0.15 \times 5.1 = 2.5$$

Then, according to Eq. 3a:

$$CH_4 \text{ Equivs} = \text{PID read} \times \text{PID CF} \times \text{FID RF} \qquad (3a)$$
$$CH_4 \text{ Equivs} = 50 \times 1.4 \times 2.5 = 175 \text{ ppm}$$
$$CH_4 \text{ Equivs} = \text{PID reading} \times 3.5 = 175 \text{ ppm}$$

Example 3: Mixture with Non-Responding Compounds

The vapors consist of the following mixture:

60% Ethyl acetate (EA)
25% Methylene chloride (MC)
15% Toluene (Tol)

The unit is calibrated to isobutylene and the reading is 50 ppm. There is no response to methylene chloride with the 10.6 eV lamp; therefore, its correction factor is infinite. The average CF for this mixture is calculated as:

$$\text{CFmix} = 1/(X_{EA}/CF_{EA} + X_{MC}/CF_{MC} + X_{Tol}/CF_{Tol})$$
$$\text{CFmix} = 1/(0.60/4.6 + 0.25/\infty + 0.15/0.50) = 2.3$$

The average FID RF is calculated as (Eq. 6):

$$\text{RFmix} = 0.60 \times 2.0 + 0.25 \times 0.94 + 0.15 \times 5.1 = 2.2$$

According to Eq. 3a:

$$CH_4 \text{ Equivs} = 50 \text{ ppm} \times 2.3 \times 2.2 = 253 \text{ ppm}$$

Note that the 50 ppm PID response is equivalent to a higher methane equivalent response in this example than in Example 2 because the PID is blind to 25% of the total VOC.

Example 4: Mixture with Unknown FID RF

If the lab FID RFs were unknown in Examples 2 and 3 above, one would estimate the RFs as the number of carbons, which usually leads to a safe overestimation:

For Example 2:

$$\text{RFmix} = 0.60 \times 4 + 0.25 \times 4 + 0.15 \times 7 = 4.5$$
$$CH_4 \text{ Equivs} = 50 \text{ ppm} \times 1.4 \times 4.5 = 315 \text{ ppm}$$

compared to a value of 175 ppm from actual RFs.

For Example 3:

$$\text{RFmix} = 0.60 \times 4 + 0.25 \times 1 + 0.15 \times 7 = 3.7$$
$$CH_4 \text{ Equivs} = 50 \text{ ppm} \times 2.3 \times 3.7 = 426 \text{ ppm}$$

compared to a value of 253 ppm from actual RFs.

It is clear that the availability of accurate response factors will help avoid false-positive alarms.

PID-FID Correction Factor Derivation for Hexane Equivalents

Although a PID with 10.6 eV lamp can be calibrated with hexane, the resulting PID hexane equivalents are different than FID hexane equivalents. Therefore, the same procedures should be used for hexane as described above for methane, by substituting the factors in Table 5.6.2 in place of those in Table 5.6.1.

Example 5: Compound Mixture (Hexane Equivalents)

For the same compound mixture as in Example 2, the unit is calibrated to isobutylene and reads 50 ppm:

60% Ethyl acetate (EA)
25% Methyl ethyl ketone (MEK)
15% Toluene (Tol)

$$\text{CFmix} = 1/(0.60/4.6 + 0.25/0.86 + 0.15/0.50) = 1.4$$

The true total concentration is 50 x 1.4 = 70 ppm, which consists of 42 ppm ethyl acetate, 17.5 ppm MEK, and 10.5 ppm toluene. Multiplying each compound by its respective FID RF factor from Table 5.6.2:

$$\text{Hexane Equivalents} = 42 \times 0.42 + 17.5 \times 0.48 + 10.5 \times 1.1 = 38 \text{ ppm}$$

To simplify, an average FID RF can be calculated for the mixture as:

$$\text{RFmix} = X_{EA} \times RF_{EA} + X_{MEK} \times RF_{MEK} + X_{Tol} \times RF_{Tol} \qquad (6)$$
$$\text{RFmix} = 0.60 \times 0.42 + 0.25 \times 0.48 + 0.15 \times 1.1 = 0.54$$

Then, analogous to Eq. 3a:

$$\text{Hexane Equivs} = \text{PID read} \times \text{PID CF} \times \text{FID RF}$$
$$\text{Hexane Equivs} = 50 \times 1.4 \times 0.54 = 38 \text{ ppm}$$
$$\text{Hexane Equivs} = \text{PID reading} \times 0.76 = 38 \text{ ppm}$$

3.2 Effect of Humidity and Other Matrix Gases

Aside from the basic components of air, matrix gases including water vapor (Chelton et al.,1983; Maslansky, 1993), methane (Nyquist et al.,1990; Maslansky, 1993) and oxygen variations (Mouradian & Flannery, 1994) can affect the response of a PID. PIDs are commonly calibrated using a dry calibrations gas and then used to measure in ambient air with various degrees of relative humidity. Biogenic methane and carbon dioxide are sometimes present in landfill gases at the percent level, enough to affect PID response. PIDs are often used to measure organic compounds in industrial process streams, where matrix gas concentrations can be quite high, e.g., at the volume percent level. The most common matrix gases include hydrogen, helium, argon, carbon dioxide, butane, chlorofluorocarbons, nitrogen, and methane. These gases do not respond on the PID themselves, but may affect (usually reduce) the response to detectable vapors.

3.2.1 Oxygen Effects

Figure 3.2.1 shows the effect of varying oxygen concentration on the response of several commercial PIDs using 10.6 eV lamps. Most PIDs show a moderate quenching by oxygen, such that the response in pure oxygen (100% O_2) is about 60-80% of that in air. In pure nitrogen (0% O_2) the response may rise or fall compared to that in air with 20.9% O_2, but typically the difference is less than 25%. Possible mechanisms for these quenching effects include absorption of UV light by O_2 and the trapping of free electrons generated from the photoionization process, to produce $O_2^{-\cdot}$ radical ions, as described in Chapter 2.6. O_2 can also react with the positive VOC ions to produce peroxyradical ions ($VOC^{+\cdot} + O_2 \longrightarrow VOC^{+}OO\cdot$). These secondary ions move more slowly toward the electrodes and thus can be neutralized more easily before being measured.

The Thermo Environmental 580 series PIDs are an exception and exhibit much larger oxygen effects, as reported by Mouradian and Flannery (1994). These authors noted a PID response to isobutylene that was 325% as high in pure nitrogen than in air. They pointed out correctly that calibration gas standards in “air” are often prepared commercially by mixing pure nitrogen with pure oxygen, rather than from purified air. Oxygen contents can thus vary, in their case ranging from 14% to 23%, which would have caused PID calibration errors of up to 17%. However, these oxygen effects are not reproducible in other PIDs, and in our experience, O_2 concentrations in synthetic air calibration gases are rarely outside the range of 19.5% to 22.5%. This oxygen variation would cause at most a 2% to 3% error in most PID responses, and therefore the user usually need not be concerned about O_2 variations in the calibration gas.

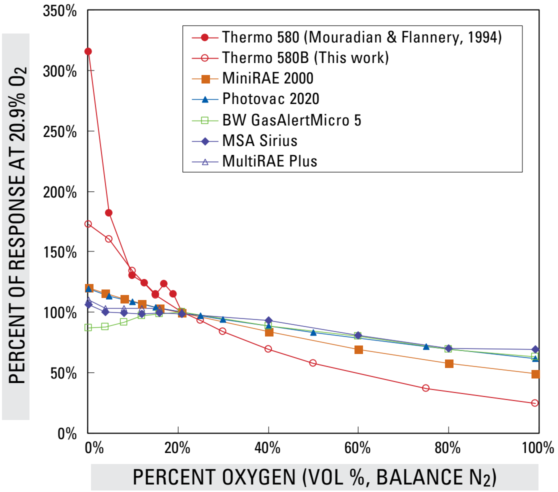

FIGURE 3.2.1. Effect of oxygen on various PID responses to 100 ppm isobutylene

Several results point to differences in sensor design as the cause of differences in oxygen dependence. Note that some of the instruments used for Figure 3.2.1 show a small drop in response in pure nitrogen, while others show a rise. These instruments have different sensor styles but nearly all had nominal 10.6 eV lamps. Moreover, Figure 3.2.2 shows that the MiniRAE Plus exhibits no oxygen dependence whatsoever between 0% and 20.9% oxygen, for the three different compounds tested. By contrast, the MiniRAE 2000 shows a rise of about 20% in pure nitrogen, compared to air (Figure 3.2.1). These two instruments use exactly the same lamp, and therefore the response differences must be due to the somewhat different sensor designs rather than lamp type.

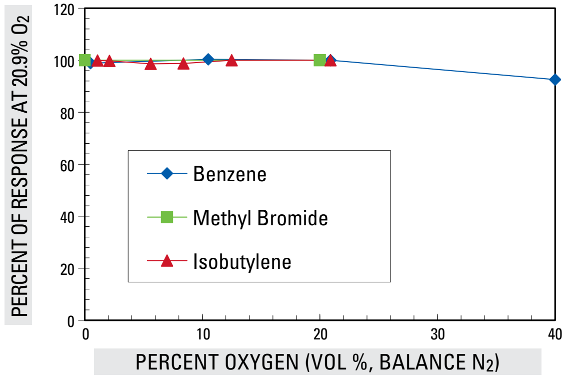

FIGURE 3.2.2. Effect of oxygen on MiniRAE Plus PID response to various compounds with a 10.6 eV lamp

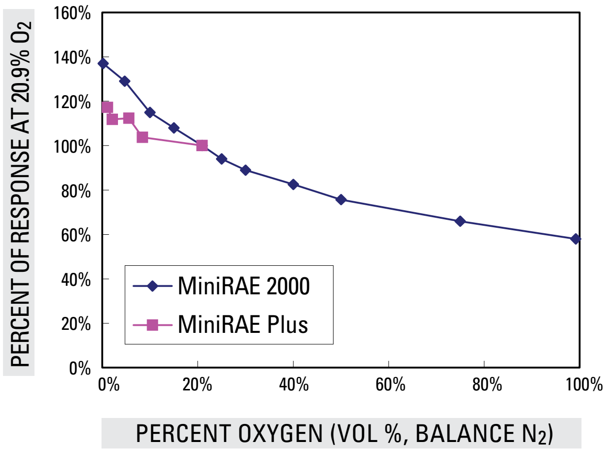

FIGURE 3.2.3. Effect of oxygen on MiniRAE PID response to 100 ppm isobutylene with an 11.7 eV lamp

Figure 3.2.3 shows that with an 11.7 eV lamp, the effect of O_2 on a MiniRAE instrument is about the same as with a 10.6 eV lamp above 21% O_2, but somewhat greater below 21% O_2. The reason for these differences in oxygen effect are unknown.

In conclusion, it is clear that oxygen effects vary from manufacturer to manufacturer and therefore the supplier should be consulted before making any corrections for changes in oxygen level.

3.2.2 Effects of Methane and Other Gases

Landfill and other excavation sites may evolve methane and CO_2, generated from anaerobic biological activity. The question is sometimes raised whether a PID can be used to measure VOCs such as mercaptan odorants in natural gas. In still other cases PIDs are used in industrial process streams containing a number of possible matrix gases. Clearly, water vapor is present ubiquitously, and its effects need to be considered.

Figure 3.2.4a shows that methane reduces the response on various PIDs by about the same amount. The negative readings for the HNU instrument in Figure 3.2.4b indicate a baseline shift with elevated methane. Figure 3.2.5 shows the effect of various gases in the lower volume % range. There is no effect of CO_2, Ar, He, or H_2 up to 5 volume %. In contrast, methane, water vapor, methanol, butane, and R-123 (2,2-dichloro-1,1,1-trifluoroethane) show a reduction in response to either isobutylene or toluene. Figure 3.2.6 shows the matrix gas effect up to higher concentrations approaching 100%. All PIDs show a reduced response when methane is present above about 1% or 10,000 ppm. Measurements in natural gas, which is >85% methane, will give extremely low response and thus are impractical. The lack of major effect of CO_2, Ar, He, or H_2 suggests that these gases do not absorb the UV light very strongly. The fact that all organic matrix gases tested, including methane, showed a reduction in response, suggests that these all absorb the 9.8 eV and 10.6 eV light. It further suggests that any other organic matrix vapors will exhibit similar reductions in response (e.g., Figure 2.6.5 for isobutylene).

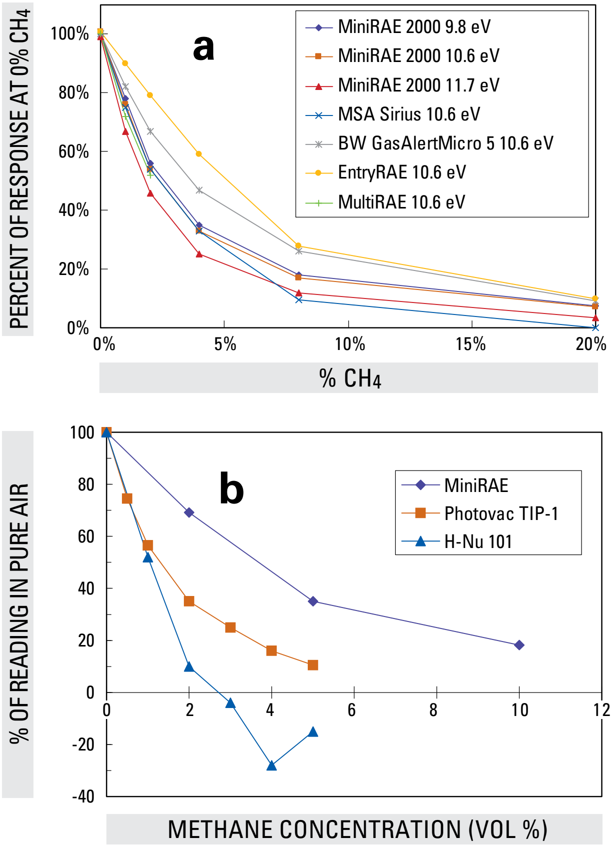

FIGURE 3.2.4. Effect of methane on the response of various PIDs with 10.6 eV lamps. Data for the Photovac TIP-1 and HNU-101 are adapted from Nyquist et al. (1990)

The curves in Figures 3.2.5 and 3.2.6 for Ar, He and H_2 used nitrogen as a balance gas instead of air in order to avoid complications with the oxygen effects described before. Figure 3.2.7 shows the response to increasing argon in a practical situation where air is likely to be the balance gas. The apparent increase in response at higher argon concentrations in air is due to the depletion of oxygen rather than an enhancement due to argon. The same result should occur with hydrogen and helium.

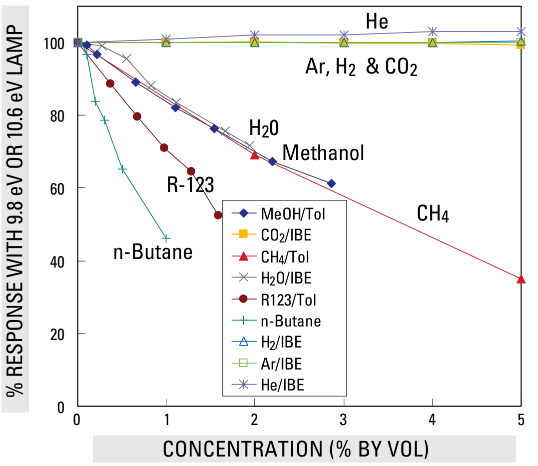

FIGURE 3.2.5. Effect of matrix vapors on MiniRAE PID Response to 50 ppm toluene, 100 ppm IBE, or butane self-quenching. All experiments except those of H_2, He, Ar, and butane had pure air as the balance gas. The others had N_2 as the balance

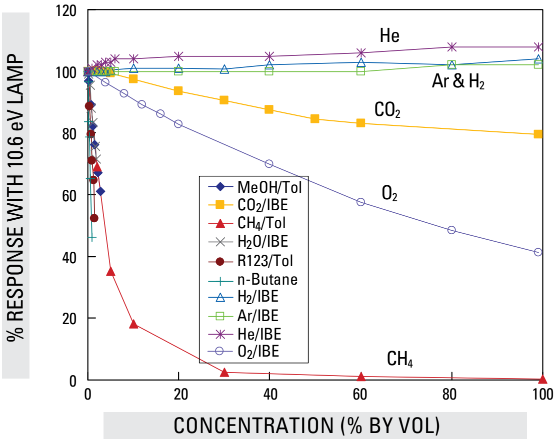

FIGURE 3.2.6. Effect of various gases on MiniRAE PID response with a 10.6 eV lamp. The 9.8 eV lamp has similar effects with CH_4 and O_2

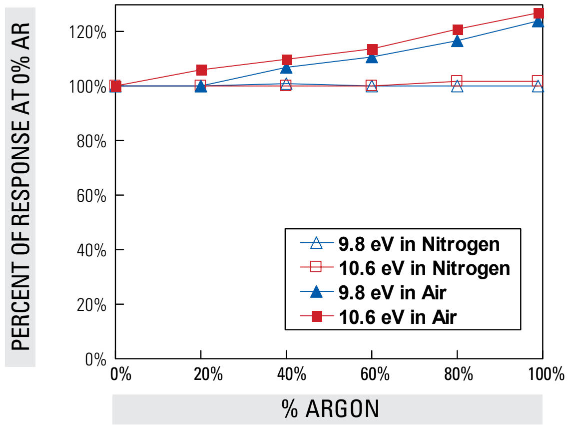

FIGURE 3.2.7. Comparison of argon effect on PID response to IBE in air vs. N_2

Thus, in the common situation where the PID is calibrated using a standard gas in dry air, and argon is used to purge air from a vessel, an apparent increase in response would be observed as the air (i.e., oxygen) is displaced. If the PID had been calibrated using humid air instead of dry air, the apparent rise in Figure 3.2.7 would have been even greater as both the oxygen and water vapor are displaced.

The butane effect in Figure 3.2.5 is an example of self-quenching. That is, butane is both the measured gas and the matrix quenching gas. The values plotted are the ratio of the observed response to the response expected assuming a linear rise with concentration. A similar plot for self-quenching could be obtained from the data for isobutylene shown in Figure 2.6.5. Thus, non-linearities at high concentrations of detectable gases are essentially the same phenomenon as the quenching effects of non-detectable matrix gases. As described above, these phenomena are high absorbance of the active light (Figure 2.6.2) and increased neutralization reactions due to high local ion concentrations (Chapter 2.6).

3.2.3 Humidity Effects

Water vapor is ubiquitous in ambient air and can reduce PID response, as shown in Figures 3.2.5 and 3.2.7(a). A secondary effect that is a common occurrence is the condensation of water vapor on the PID sensor, causing a false-positive “leak” current. These two phenomena have opposite effects on the response and must be distinguished carefully.

Water Vapor Quenching

Figure 3.2.7(a) shows that various PIDs have similar reduced response at high relative humidity. The quenching effect is independent of lamp type for 10.6 and 11.7 eV lamps. Compensation using a humidity sensor is possible, but complicated by the fact that the response times of most RH sensors are much slower than those of modern PIDs with built-in electronic pumps. Therefore, compensation is not commonly employed.

PIDs are commonly calibrated with dry calibration gas and then used to measure in ambient air with various degrees of relative humidty. In this case, corrections are necessary if the absolute concentration of the measured vapor is desired. Alternatives to performing corrections are to either humidify the calibration gas, or to dry the sample gas during measurements. Drying the sample gas using dessicant filter tubes is possible for non-polar compounds like gasoline and trichloroethylene, and is described in more detail in Chapter 4.13. These tubes are of great advantage in removing both quenching and "leak current" effects during continuous PID readings, and reduce the need for sensor cleanings. However, heavy and polar compounds tend to adsorb to the reagent, causing slower response, particularly at low temperatures and low concentrations. Some compounds such as amines absorb completely and cannot be measured using the dessicant tubes.

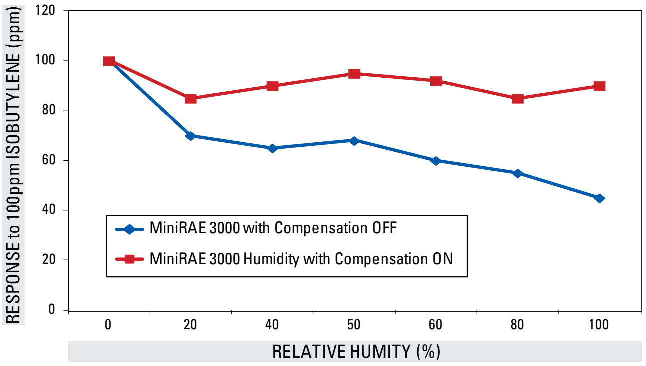

FIGURE 3.2.7(a). Effect of humidity PID response

Correcting the response by humidifying the calibration gas is possible using moisture exchange tubes consisting of a Nafion membrane. Such tubes allow humidification of the calibration gas close to the ambient level. Use of moisture exchange tubes is described in more detail in Chapter 4.14.

The moisture exchange tube has limitations: the humidity equilibration is not exact, and it only compensates correctly at one humidity, but not when humidity changes. Such changes are commonly encountered when a PID is calibrated indoors and then used outdoors for measurements. Nevertheless, the readings will be closer than if no compensation were performed at all, and may be adequate for many purposes.

Procedures for correcting VOC readings to ambient RH are described in the following section. Because the quenching depends on the absolute concentration of water vapor, rather than the relative humidity, the data in Figure 3.2.8 can be used to calculate curves for other temperatures at the same total water content.

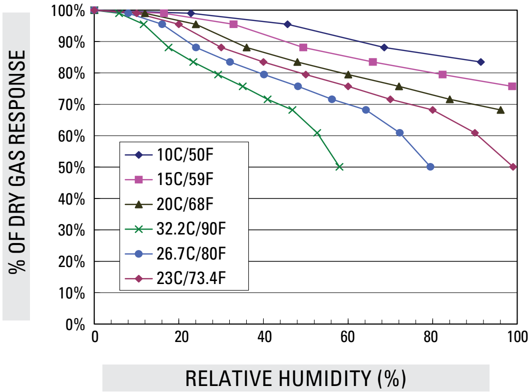

FIGURE 3.2.8. Calculated PID humidity effect curves vs. temperature for MiniRAE 2000

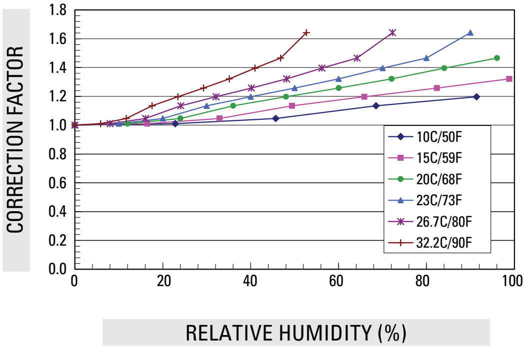

FIGURE 3.2.9. Correction factors for humidity vs. temperature for MiniRAE 2000

Figure 3.2.9 and Table 3.2.1 give correction factors derived from Figure 3.2.8. When the unit is calibrated in dry gas, multiply the CF by the observed reading at ambient RH to obtain the true concentration. For other PIDs, the manufacturer should be consulted to obtain humidity correction tables.

Humidity-Induced Current Leakage

When making measurements at high relative humidity, PIDs may exhibit an apparent response that appears as a rising drift. This signal is due to a current leakage between the electrodes in the sensor, caused by condensation on the sensor. A similar phenomenon, although usually less severe, can occur when some high-boiling compounds deposit onto the sensor. When water vapor deposits, it causes a slight short-circuit that results in current leakage and an apparent VOC response. Condensation occurs most obviously when a PID is brought from a cool, dry indoor environment to a warm, humid outdoor environment. This condition can be avoided by warming the PID to the measurement temperature before entering the humid environment.

Water vapor can only condense on a clean sensor when the relative humidity is very close to 100%. However, water can be absorbed by dust particles when the RH is somewhat lower. Therefore, the current leakage is exacerbated when minute, invisible dust or dirt particles collect on the sensor. Most humidity-induced drift problems can be solved by a thorough cleaning of the sensor, preferably using an ultrasonic cleaner. Thus, maintaining a clean sensor is usually very important when working in high-humidity environments. Additional aids include ensuring the sensor is not bent or corroded, and use of drying filters to condition the sample gas. Chapter 4 gives more information for working in humid environments.

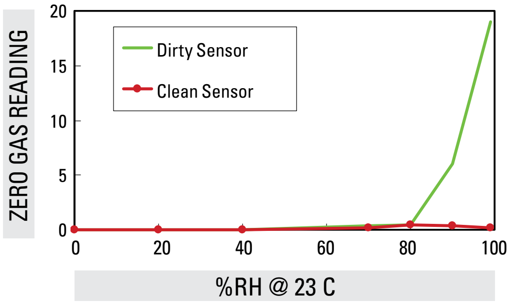

FIGURE 4.13.2. Response to zero gas vs. humidity on "dirty" vs "clean" sensor

TABLE 3.2.1. Humidity correction factors for MiniRAE 2000

%RH	10°C 50°F	15°C 59°F	20°C 68°F	23°C 73°F	26.7°C 80°F	32.2°C 90°F
0.0	1.00					
22.8	1.01					
45.7	1.05					
68.5	1.14					
91.4	1.20					
0.0		1.00				
16.5		1.01				
32.9		1.05				
49.4		1.14				
65.9		1.20				
82.4		1.26				
98.8		1.32				
0.0			1.00			
12.0			1.01			
24.0			1.05			
36.0			1.14			
48.0			1.20			
60.0			1.26			
72.1			1.32			
84.1			1.40			
96.1			1.47			
0				1.00		
10				1.01		
20				1.05		
30				1.14		
40				1.20		
50				1.26		
60				1.32		
70				1.40		
80				1.47		
90				1.64		
0.0					1.00	
8.0					1.01	
16.1					1.05	
24.1					1.14	
32.1					1.20	
40.1					1.26	
48.2					1.32	
56.2					1.40	
64.2					1.47	
72.3					1.64	
0.0						1.00
5.9						1.01
11.7						1.05
17.6						1.14
23.4						1.20
29.3						1.26
35.1						1.32
41.0						1.40
46.8						1.47
52.7						1.64

3.3 Temperature and Pressure Effects

Corrections for temperature and pressure tend to be minor and are often ignored in PID measurements. However, for accurate quantitation, they must be taken into consideration. No correction is necessary if the instrument is calibrated at the same temperature and pressure as the subsequent measurements. Therefore, the discussion below applies only when the unit is calibrated at a different temperature or pressure as those present during subsequent measurements.

PIDs respond proportionally to absolute concentration, whereas the conventional desired reading is in ppmv, a relative concentration, i.e., a mole or volume fraction (% of molecules of compound per molecules of total gas [air]), rather than an absolute concentration. As the gas density decreases, the apparent response is reduced because there are fewer molecules per unit volume sampled. Thus, a correction is needed when gas density changes after calibration.

Temperature Effects

Photochemical reactions generally have low temperature coefficients. Therefore, the effect of temperature is expected to be primarily due to a change in gas density, and thus concentration. Figure 3.3.1 shows that the response decreases as the temperature increases, but by somewhat more than would be expected from gas density changes alone. The cause for the temperature effect is unknown.

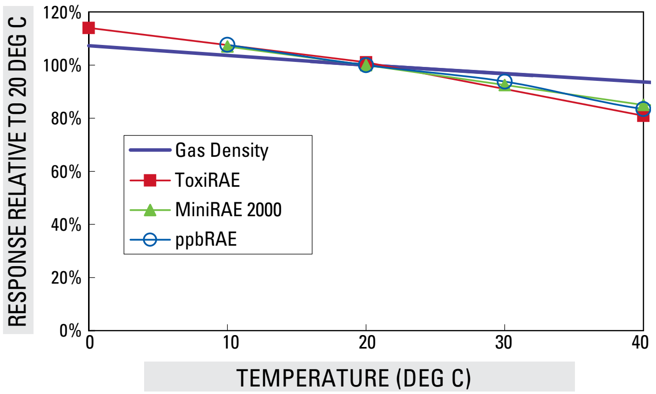

FIGURE 3.3.1. Effect of temperature on three PIDs

Pressure Effects

Rapid pressure changes are encountered in such instances as when descending a mine shaft or in a submarine, or when rising in an elevator or aircraft. In some cases, a PID is calibrated at a central location and then transported for use at a high elevation without recalibration. The following equations can be used to correct for gas density effects due to pressure changes.

$$\text{Corrected reading} = \frac{\text{Observed Reading x 760 mm Hg}}{\text{Pressure (mm Hg)}}$$

$$\text{Corrected reading} = \frac{\text{Observed Reading x 101.3 kPa}}{\text{Pressure (kPa)}}$$

$$\text{Corrected reading} = \frac{\text{Observed Reading x 14.7 psia}}{\text{Pressure (psia)}}$$

If the calibration is performed at a pressure different from one atmosphere, the values 760 mm Hg, 101.3 kPa, and 14.7 psi should be substituted by the calibration pressure. The pressure in mm Hg can be estimated as a function of altitude using the equation:

$$P\text{ (mm Hg)} = 760\exp(-0.1286[\text{alt(km)}])\text{ below 2 km}$$

Example correction factors are listed in the table below as a function of altitude, assuming calibration at sea level. Weather changes may also affect the atmospheric pressure, but the necessary corrections are usually <10%.

TABLE 3.3.1. Pressure corrections

Example Location	Altitude (km)	Altitude (feet)	Pressure, (mm Hg)	CF
San Francisco, CA	0	0	760	1.00
Atlanta, GA	0.3	1000	731	1.04
Spokane, WA	0.6	2000	703	1.08
Rapid City, SD	0.9	3000	676	1.12
Salt Lake City, UT	1.2	4000	650	1.17
Denver, CO	1.5	5000	625	1.22
Colo. Springs, CO	1.8	6000	601	1.27
Santa Fe, NM	2.1	7000	578	1.32
Alta, UT	2.4	8000	555	1.37
Winter Park, CO	2.7	9000	534	1.42
Keystone, CO	3.0	10000	514	1.48

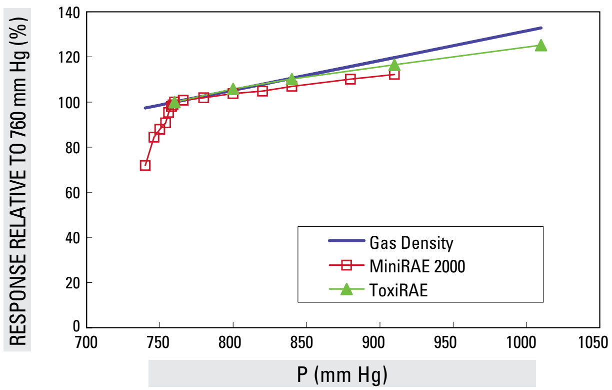

FIGURE 3.3.2. Pressure dependence for two PIDs

Figure 3.3.2 shows that the pressure dependence observed for two commercial PIDs is similar to the dependence expected from gas density above ambient pressure. The dependence deviates at pressures below ambient for unknown reasons. In these experiments, the entire instrument and calibration gas bag are placed at subambient pressures. Therefore, the deviation is not caused by leaks. These results emphasize the importance of calibrating at the same pressure as the measurements, thus compensating for such deviations as shown in Figure 3.3.2.

3.4 Effects of Sampling Equipment and Procedures

The measurement ability of any instrument can only be as good as the sampling process involved in moving the sample to the PID sensor. This chapter considers the effect of sampling procedures, sample pressure, adsorption losses, and other pressure effects.

Spatial and Temporal Variations of the Sample

The samples themselves may vary in location and in time. Therefore, it is difficult to correlate readings from instruments that have different pump flow rates and in some cases, even slightly different locations. For example, measurements taken in ambient air with a gas detection tube, which may require a few minutes, may not agree with those from a PID whose response time is a few seconds, due to variations in ambient air mixing. It is usually only possible to obtain comparable readings by two different instruments when the gas is drawn from exactly the same source, such as from a Tedlar gas bag.

Sample Tubing, Filters and Adsorption Losses

When a sample is drawn from a distance, the sample tubing can cause a delay in response and losses due to adsorption. Adsorption of VOCs is significant for most types of plastic or rubber tubing, even though such tubing may be supplied with standard confined space entry kits and is adequate for sampling CO, H_2S, CH_4, and O_2. For VOCs, metal or perfluorinated plastic (Teflon or PTFE, PFA, etc.) tubing is highly recommended. A second choice, polyurethane tubing, is often adequate. The importance of the tubing material choice depends on the length of tubing, the absorbability of the compound and the flowrate. Ten feet (3 m) of Tygon tubing will completely absorb low-volatility compounds like jet fuels. Several inches of Tygon has no effect on volatiles like benzene or isobutylene; 100 feet (30 m) of Teflon tubing has little effect on isobutylene, but does cause enough adsorption to delay the response by a few seconds more than that required to displace the air in the tubing.

For very high molecular weight compounds, even the inlet probe and sensor block can cause enough adsorption to affect the readings. Typically, compounds with a boiling point above about 300°C are not possible to measure quantitatively with most portable PIDs, unless the entire system is heated. For example, MDI, an isocyanate used in polymer manufacturing, has a boiling point of about 370°C. On a MiniRAE 2000 or ppbRAE, its response time to full response is very slow (>15 minutes), but these instruments have proven useful for detecting leaks on heated MDI pipelines.

The effect of adsorption losses can be reduced by setting the instrument to the highest flow rate available, thus saturating the adsorption capacity more quickly. In addition removing filters may reduce adsorption. Some PIDs use filters made of cellulose or other materials that can absorb or react with some chemicals. For example, cellulose reacts with hexamethyldisilazane and acyl chlorides, making these compounds difficult or impossible to measure quantitatively with the filters in place. Removing the filters usually is at the cost of shortening the pump life or more frequent lamp cleanings, but it may be necessary for proper measurement.

Sample Tubing Volume and Delay Time

Tables 3.4.1 to 3.4.3 give the wait times that need to be considered when using extension tubing, to allow the gas sample to reach the instrument, at typical flows of 300, 500 and 650 cc/min. The times assume that the sample line has not been pre-filled with the air sample of interest. Smaller diameter tubing has the least delay time, but causes a pressure drop for long tubing. Only the smallest-diameter tubing (1/8" o.d.) exhibits a reduced flow rate due to pressure drop. For many instruments wider tubing is recommended to reduce strain on the pump, avoid leaks, and give better consistency.

Pump Flow Curves

Figure 3.3.3 below shows curves of flow vs inlet vacuum for RAEGuard and ppbRAE. MiniRAE 2000 has the same flow characteristics as the ppbRAE. Although the pumps can draw down to about 100" of H2O (74 mm Hg) without leaks, this creates a significantly reduced flow rate. To avoid excessive strain on the pump and to reduce the chance of leaks developing when parts are worn, typically no more than 40 inches of H2O (30 mm Hg) vacuum should be applied.

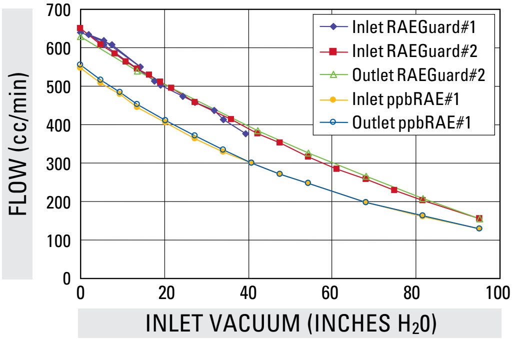

FIGURE 3.3.3. Flow-vacuum curves for ppbRAE (lower curve) and RAEGuard (upper curve)

TABLE 3.4.1. Sample tubing delay times at 300 cc/min

Nominal Tubing Size					Volume			Delay Time @ 300 cc/min				
in	in		cm		cc per			Seconds per				
OD	OD	ID	OD	ID	cm	m	ft	1′	10′	30′	100′	300′
1/8	0.125	0.063	0.318	0.159	0.020	2.0	0.60	0.1	1	5*	29*	--
4 mm	0.157	0.110	0.400	0.280	0.062	6.2	1.88	0.4	4	11	38	113
3/16	0.188	0.127	0.476	0.323	0.082	8.2	2.49	0.5	5	15	50	149
1/4	0.250	0.190	0.635	0.483	0.183	18.3	5.58	1.1	11	33	112	335
5/16	0.313	0.248	0.794	0.630	0.312	31.2	9.50	1.9	19	57	190	570
3/8	0.375	0.311	0.953	0.790	0.490	49.0	14.94	3.0	30	90	299	896
1/2	0.500	0.436	1.270	1.107	0.963	96.3	29.36	5.9	59	176	587	1762

* Corrected for decrease in flow rate due to pressure drop in tubing

TABLE 3.4.2. Sample tubing delay times at 500 cc/min

Nominal Tubing Size					Volume			Delay Time @ 500 cc/min				
in	in		cm		cc per			Seconds per				
OD	OD	ID	OD	ID	cm	m	ft	1′	10′	30′	100′	300′
1/8	0.125	0.063	0.318	0.159	0.020	2.0	0.60	0.1	1	2	7	22
4 mm	0.157	0.110	0.400	0.280	0.062	6.2	1.88	0.2	2	7	23	68
3/16	0.188	0.127	0.476	0.323	0.082	8.2	2.49	0.3	3	9	30	90
1/4	0.250	0.190	0.635	0.483	0.183	18.3	5.58	0.7	7	20	67	201
5/16	0.313	0.248	0.794	0.630	0.312	31.2	9.50	1.1	11	34	114	342
3/8	0.375	0.311	0.953	0.790	0.490	49.0	14.94	1.8	18	54	179	538
1/2	0.500	0.436	1.270	1.107	0.963	96.3	29.36	3.5	35	106	352	1057

TABLE 3.4.3. Sample tubing delay times at 650 cc/min

Nominal Tubing Size					Volume			Delay Time @ 650 cc/min				
in	in		cm		cc per			Seconds per				
OD	OD	ID	OD	ID	cm	m	ft	1′	10′	30′	100′	300′
1/8	0.125	0.063	0.318	0.159	0.020	2.0	0.60	0.1	1	3*	13*	--
4 mm	0.157	0.110	0.400	0.280	0.062	6.2	1.88	0.17	1.7	5	17	52
3/16	0.188	0.127	0.476	0.323	0.082	8.2	2.49	0.23	2.3	7	23	69
1/4	0.250	0.190	0.635	0.483	0.183	18.3	5.58	0.5	5	15	51	154
5/16	0.313	0.248	0.794	0.630	0.312	31.2	9.50	0.9	9	26	88	263
3/8	0.375	0.311	0.953	0.790	0.490	49.0	14.94	1.4	14	41	138	414
1/2	0.500	0.436	1.270	1.107	0.963	96.3	29.36	2.7	27	81	271	813

Pressure Drop in Tubing

Pressure drop in extension tubing depends on the inner diameter, the number and severity of bends, and total flow rate. Typical pressure drop for different types of tubing and flow rates are summarized in Table 3.4.4 below. The “Max Flows” in Table 3.4.4 are the nominal flows with no tubing or only short sections. To calculate the flow rate with tubing attached, use the value in Table 3.4.4 to estimate the vacuum in the tubing and then read the flow drop off of Figure 3.3.3. For example, a 10′ section of 1/16" i.d. tubing will cause a pressure drop of 1.3 x 10 = 13" of water in a ppbRAE or MiniRAE with nominal flow rate of 500 cc/min. Figure 3.3.3 shows that at a vacuum of 13" H_2O the flow rate drops from 540 to 450 cc/min. For 100′ of 2.8-mm i.d. tubing a RAEGuard with nominal 650 cc/min flow will result in 0.1 x 100 = 10" H_2O vacuum, and thus a flow drop from 650 to about 550 cc/min. These estimates give only a rough idea of the flow rates expected and vary with the user's exact configuration. Because of the high pressure drop in 1/16" i.d. tubing, we recommend using this tubing only if the length is less than a few meters, and using wider-bore tubing for longer distances.

TABLE 3.4.4. Pressure drop in various sizes of tubing

Tubing ID (inches)	Tubing ID (mm)	Max flow 500 cc/min	Max flow 650 cc/min
1/16"	1.6	1.3" H_2O/ft.	1.6" H_2O/ft.
1/9"	2.8	0.10" H_2O/ft.	0.13" H_2O/ft.
1/8"	3.2	0.083" H_2O/ft.	0.10" H_2O/ft.

Maximum Vacuum or Pressure

The maximum vacuum obtained on most PIDs with a built-in pump is about 280 mm Hg (150" of H_2O). On the outlet side, these instruments can push against a pressure of up to about 6 psi or 170" of H_2O (310 mm Hg). Note that the flow will be close to zero or very low at these maximum values, and it is not recommend to operate the pump for long periods under such conditions.

Aerosols, Mists and Dusts

Most PIDs are not designed to measure mists and dusts. Dusts tend to be trapped in instrument filters or the inlet sample train and thus do not reach the sensor efficiently. If dust particles do reach the sensor, they may ionize. However, they are so large as to have exceedingly poor mobility in the sensor and thus are poorly detected. In some cases high-molecular-weight chemicals such as dioxins and PAHs exist to a large extent adsorbed onto dusts in ambient air. It is possible that chemicals in the adsorbed phase ionize in the sensor chamber, but again, the ions are unlikely to be collected at the electrodes before being neutralized or swept out of the chamber.

Aerosols and mists are tiny droplets of pure liquid. They likewise tend to be trapped in the filters or the inlet sample train and are poorly detected. In addition, they tend to coat the lamp, causing reduced real response and increased current leakage.

Pressure Operation

If a sample is drawn from a pipe or vessel that is not at ambient pressure, high or low readings can be obtained if no precautions are taken. In addition to the pressure effects on the readings described in the previous chapter, sampling procedures may need to be modified.

For a high-pressure vessel or pipe, a valve can be attached to release a limited flow of the sample gas. The flow should be higher than the instrument pump draw, but not so high that the pump or sample train is damaged, preferably in the range of 110% to 200% of the pump draw. A safe way to achieve this is through an open cup, releasing excess flow past the inlet probe of the PID. As a rule of thumb, if the open cup diameter is no more than 4 times the diameter of the probe, then inserting the probe by at least 2 cm is adequate when the flow is at least 110% of the sample draw. If the cup is wider than that, air entrainment into the sample is possible unless flow is increased or the probe inserted further.

If emission of the sample gas to the ambient air is dangerous or otherwise undesirable, it is often possible to plumb the effluent from the PID back into the sample train. This option is usually available only for low-pressure systems, because of possible damage when the entire PID sample train will be pressurized.

Vacuum Operation

Sampling from vessels under vacuum is often limited by the capacity of the pump to draw against a vacuum. Most PID pumps are not designed to draw against more than a few inches of Hg negative pressure. To avoid these pump limitations, the effluent can be plumbed back into the sample train. However, the leaks into the sensor can still occur because the instrument is under negative pressure. Without leaks, the pressure dependence curves such as in Figure 3.3.2 are followed. Again, it is desirable to calibrate at the same pressure as the measurement in order to avoid the need for pressure corrections.

4. SPECIFIC APPLICATIONS

4.1 Environmental Applications for PIDs

One of the earliest uses of portable PIDs was to screen for organic compounds emitted from potentially contaminated soils and leaking storage drums. Environmental contractors and consultants use PIDs to monitor the remediation of industrial waste sites and closed military bases. Other environmental applications include perimeter monitoring and fugitive emissions monitoring.

4.1.1 Hazardous Waste Monitoring

Toxic Hazardous Waste Monitoring

Hazardous waste contractors and industrial hygienists concerned with occupational health determine levels of toxic vapors or volatile organic compounds. PIDs allow pinpointing of the most hazardous areas at old disposal sites, disused industrial plants, and closed military bases, and during hazardous waste transportation. PIDs can help determine the correct level of personal protective equipment (PPE) to use, and whether a self-contained breathing apparatus (SCBA) is necessary.

Drum Monitoring

Hazardous waste contractors and environmental engineers can easily determine drum and other container contents at old disposal, landfill and garbage sites, as well as closed industrial plants and military bases.

4.1.2 PIDs for EPA Method 21 Compliance

EPA Method 21 is a standard for monitoring leaks, calibrating field monitoring equipment, and principles for monitoring fugitive emissions in pipelines and chemical processing equipment. Properly designed PIDs meet the specifications for leak-monitoring equipment called for in Method 21. For more information on Method 21, see Chapter 4.9.

4.1.3 Soil Remediation

Leaking Underground Storage Tanks

Portable PIDs are ideal for detecting BTEX (benzene, toluene, ethylbenzene, and xylene) and TPH (total petroleum hydrocarbons) in gasoline, diesel and jet fuel that may be present at leaking underground storage tanks. Both environmental engineers and the petroleum industry use PIDs to monitor gas stations, industrial sites, commercial transportation refueling sites and defense bases.

Real Estate Transfers

Environmental engineers and consultants can use PIDs for environmental soil contamination monitoring at industrial real estate sites and military base closures. A PID enables them to determine, before the sale of land, whether the soil is contaminated by VOCs. Due diligence and environmental impact studies, prior to purchase, allow for safe rezoning to homes, shops and parks.

Environmental Remediation and Contaminated Air Treatment

A common method of treating contaminated sites is to use a soil vapor extraction system that pumps air laden with organic contaminants out of the ground using a large vacuum pump. In most states, the generated air must be treated before it can be released to the atmosphere. Contaminated air streams are also produced in a large variety of industrial processes. Common treatment processes include liquid scrubber absorption, activated carbon adsorption, thermal oxidation, and incineration. PIDs are useful in determining the treatment process by measuring the VOC content before and after.
In some cases, a dilution is necessary on the influent to bring the sample concentration into the linear PID range and reduce the humidity to acceptable levels.

4.1.4 Headspace Screening

Although PIDs cannot be used to measure VOCs in water or soil directly, they are often employed indirectly to measure concentrations in these media by measuring the vapors emitted from them. For example, Hewitt and Lukash (1999) reported linear correlations between headspace PID response and soil concentrations of benzene, toluene, xylenes, dichloroethylenes, trichloroethylene and perchloroethylene. The concentration in the headspace, measured in ppmv, does not equal the soil or water concentration, measured in mg/kg or mg/L. The vapor concentration depends on such factors as soil-to-headspace weight and volume ratio, soil permeability, affinity of the compound to the soil, temperature, equilibration time, and dilution during the measurement procedure. Therefore, it is important that these factors are controlled as closely as possible if quantitative soil or water concentrations are desired.

Toxic VOCs in Drinking Water Sources

Hydrologists and environmental engineers often use PIDs to monitor chlorinated solvents (e.g., carbon tetrachloride) and VOCs (e.g., toluene) in groundwater at drill and well sites or closed industrial plants, military bases or nuclear facilities, etc. PIDs can also be used to monitor water stripper effluents and off-gases from wastewaters.

Soil and Water Headspace Screening

In a typical procedure, a sample of soil or water is filled approximately halfway into a jar with a ring-type lid. A piece of aluminum foil is placed over the mouth of the jar and held in place with the lid ring. The jar and its contents are brought to room temperature. The influent probe (and effluent line) of the portable PID is then poked through the foil and the VOC concentration measured in the headspace of the jar.

Procedures for Optimum Performance of PIDs

Soil and water headspace sampling requires special attention beyond that needed for typical ambient air monitoring. Stripper effluents and soil vapor extraction streams are typically near 100% RH (relative humidity), and soil samples are often dusty and humid. Such conditions can cause high, drifting readings on many PIDs if not properly maintained. Interferences are usually traceable to condensation in the sensor, causing a current leakage across the electrodes and thus a false-positive signal. This situation is exacerbated when the sensor is contaminated by soil dust or condensed, high-boiling organic compounds.

a) Keep the sensor clean using high-purity methanol, preferably using an ultrasound bath. Flush the residual solvent from the sensor with a rapid stream of clean air, and clean the lamp housing area that contacts the sensor when in place.
b) On sensors with interdigital fingers, check that the metal electrode fingers do not contact the Teflon sensor walls. Bend them out carefully if necessary. Replace the sensor if the electrodes are corroded.
c) Keep the lamp clean using high-purity methanol. Never use acetone on 11.7 eV lamps.
d) Perform frequent changes of the dust filters (daily to monthly, depending on usage and dirtiness).
e) Use additional external filters (e.g., Teflon "water trap") as an extra precaution, especially in dusty or moist environments.
f) Start sampling by using a dilution attachment, especially for highly contaminated soils. This minimizes the amount of dust, water, and high-boiling organics condensing on the sensor and lamp. If the concentrations are too low to give a reading, remove the attachment to obtain an undiluted reading.
g) Avoid situations in which the PID is colder than the soil being sampled, such as heating the soil samples to increase the headspace organic concentration, or bringing a cold PID into a warm room without allowing time for temperature equilibration. If anything, try to keep the PID warmer than the soil samples.
h) To obtain more stable readings, plumb the effluent flow from the PID back into the sample container to prevent diluting the sample. Use Teflon or metal tubing for this purpose so as to prevent adsorption to Tygon or other plastic tubing. Losses will not be stopped altogether but will be greatly reduced.
i) If humidity problems persist, use a humidity filtering tube to absorb moisture (see Chapter 4.13).

Response of PIDs and FIDs to Semi-volatiles on Soils

Often repeated is the statement that PIDs do not respond to semi-volatile organic compounds. This statement seems to be an old piece of "common knowledge" that may have been true at one time for an old PID used for soil headspace measurements, but is no longer true in general. The larger the organic molecule (and thus less volatile), the lower the IE and the greater the PID sensitivity. However, there is a point of diminishing sensitivity when adsorption losses in the instrument sample lines and filters begin to dominate over this sensitivity increase. This is true for any instrument including FIDs and PIDs if they are not specifically designed to handle semi-volatile compounds. New PIDs have higher flow rates and better sensor designs that reduce such losses, and therefore most compounds up to a boiling point of about 300°C can be detected on the MiniRAE 2000. Boiling points for fuel oils, diesels, and kerosenes range from about 170°C for #2 Fuel Oil to 260°C for #5-6 Fuel Oils. As the oil weathers and the light ends evaporate, the response time increases and the overall response drops because less organic vapor is present. The response may drop to zero before all the oil is removed from a soil sample, because only non-volatile components remain. Again, this effect is the same for FIDs and PIDs. In such cases, a direct measurement of the oil contamination may be needed – for example, using a solvent extraction procedure followed by laboratory gas chromatography. For such high-boiling compounds it is also important not to use any rubber or Tygon tubing to draw in samples, as several inches of such tubing can completely absorb heavy fuels. Teflon or metal tubing is preferred.

4.2 PIDs for Industrial Hygiene

The recent advent of PIDs with small size and weight and with datalogging capability has opened a host of new applications for industrial hygiene. The small size allows workers to wear the monitor while freely moving about, including climbing on ladders and scaffolding, and entering narrow, confined spaces. Advanced programming features are commonly available that allow the hygienist to set up the monitor parameters and calibrate it, using password protection to prevent tampering by the user. Programming of alarm limits allows the user to set one or more alarm levels, usually giving warning by both visual and audio alarms. Some manufacturers supply vibration alarms for operations in high-noise environments.

4.2.1 Definition of TWA, STEL and Ceiling

This section discusses the terms TWA (time-weighted average), STEL (Short-Term Exposure Limit), Ceiling, and running average, because these parameters are often misunderstood.

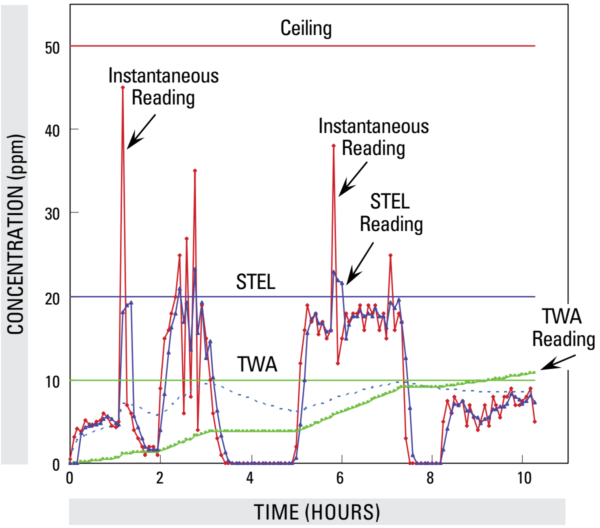

FIGURE 4.2.1. Exposure limit illustration: TWA vs. running average

Figure 4.2.1 illustrates these concepts for a hypothetical compound with a TWA of 10 ppm, STEL of 20 ppm, and Ceiling of 50 ppm. The Ceiling value is the concentration that should never be exceeded, even for an instant. An instantaneous reading may exceed the TWA and STEL as long as it never exceeds the Ceiling. A STEL reading may exceed the TWA, but action must be taken when the STEL limit is reached. A STEL is the average concentration over the immediately previous 15-minute period.

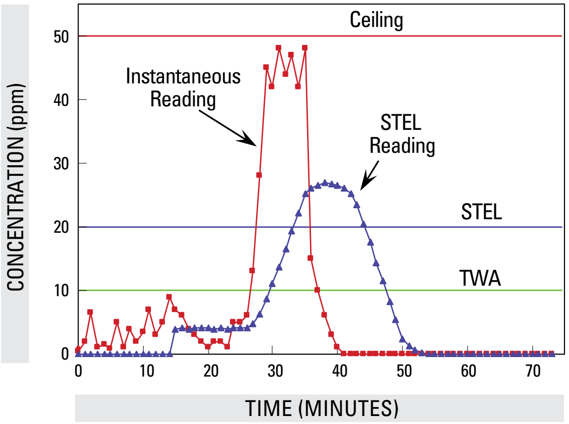

FIGURE 4.2.2. Exposure limit illustration: STEL

Figure 4.2.2 shows that the STEL reading tracks the instantaneous reading, except that it has a lag and is dampened. Once the STEL reading exceeds the STEL limit (at about 33 minutes in Figure 4.2.2), the exposure must be removed until the STEL reading drops below the limit again. At most, four such exposures may occur in a given working day, as long as there is at least one hour between consecutive cases exceeding the STEL limit. Note also in Figure 4.2.2 that the STEL reading is undefined until a 15-minute period has elapsed, and thus the reading is reported as zero.

The TWA is very different from all the other parameters because it is an accumulated exposure dose instead of an instantaneous concentration. Although the TWA is usually listed in units of ppm, which is a concentration unit, it is understood that the actual units are equivalent to ppm-days. It is calculated as the running average concentration times the number of hours exposed, divided by the hours in a working day. OSHA and ACGIH define the number of hours in a working day as 8 hours, while NIOSH uses 10 hours to define its recommended TWAs. Thus, if one is exposed to 20 ppm of a substance for two hours, the TWA reading is calculated as:

$$\text{TWA} = (2\text{ h exposed } \times 20\text{ ppm}) / (8\text{ h/day}) = 5\text{ ppm-days}$$

Figure 4.2.3 illustrates the difference between running average and the TWA readings. Like the STEL reading, the running average concentration (dashed line in Figure 4.2.3) tracks the instantaneous readings and can rise and fall. In contrast, the TWA is a cumulative dose that can never fall until it is reset to zero when the worker leaves work for the day. In Figure 4.2.3, it can be seen that the TWA reading rises steadily during the first 3.5 hours when some exposure occurs, and then from 3.5 to 5 hours, the concentration is zero and the TWA reading remains constant.

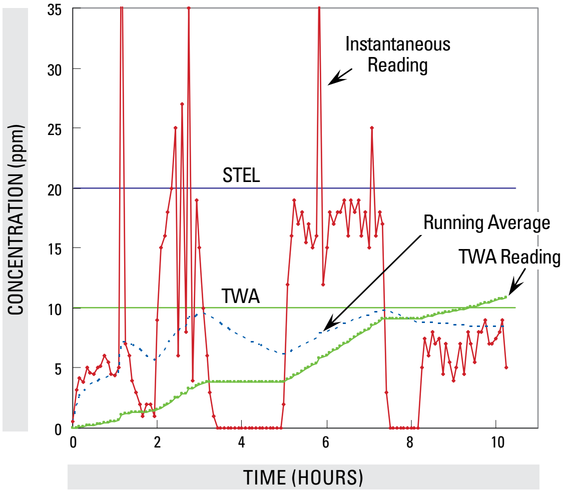

FIGURE 4.2.3. Exposure limit illustration: TWA vs. running average

After a full day (typically 8 hours), the TWA reading is equal to the running average. However, if work continues beyond the 8 hours, the TWA reading continues to accumulate and will exceed the running average. For very long exposures, it is even possible that the TWA reading is greater than the peak concentration for the exposure period, as shown in Figure 4.2.4.

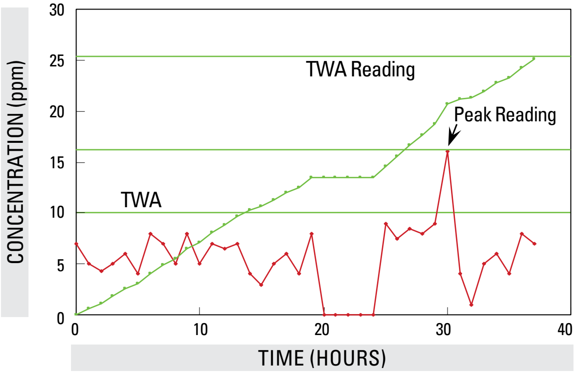

FIGURE 4.2.4. Exposure limit illustration: TWA exceeds peak

TWA and instantaneous concentrations are analogous to a recommended daily allowance of a food component such as fat and the rate at which it is eaten. Let's say the daily allowance is 100 grams. During breakfast one might eat 20 grams, lunch 35 grams, and dinner 45 grams. During meals the rate of intake (i.e., concentration) is relatively high, and the amount eaten (TWA reading) rises steadily. Between meals, the rate of intake (concentration) drops to zero but the amount consumed (TWA reading) during the day remains constant. If a heavy lunch is taken and the amount of fat eaten (TWA reading) exceeds 100 g (TWA) already, then one needs to stop eating (remove the exposure).

4.2.2 TWA and STEL Datalogging

This section gives details on how TWAs, STELs and other concentration data are determined and datalogged by a PID.

The ability to datalog exposure concentrations, calculate TWA and STEL values, and download them to a personal computer affords a permanent record of the exposures that can be used for hygiene improvements and legal protection. It is also useful in correlating exposure levels with work activities and thus to modify work behavior to reduce subsequent exposure. Figure 4.2.5 and Table 4.2.1 show examples of datalog records for a miniature PID worn in the workers' breathing zone.

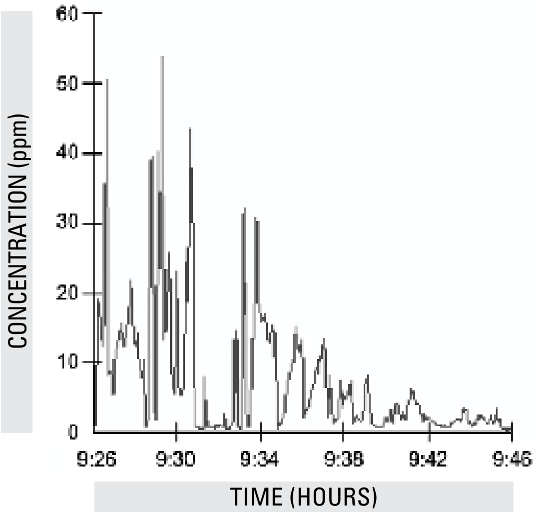

FIGURE 4.2.5. Real-time datalogging of vapor concentrations

TABLE 4.2.1 Example of logged data

Instrument: ToxiRAE (PGM30) Serial Number: 001410

User ID: 1 Site ID: 1
Data Points: 28 Sample Period: 120 sec
Last Calibration Time: 09/05/2001 18:31 Value: 100.0 ppm
Last Check Time: 09/05/2001 18:47 Value: 100.1 ppm

Measurement Type:	Min (ppm)	Avg (ppm)	Max (ppm)
High Alarm Levels:	100.0	100.0	100.0
Low Alarm Levels:	50.0	50.0	50.0

Line#	Date	Time	Min (ppm)	Avg (ppm)	Max (ppm)
1	09/06/01	08:36	0.5	1.6	2.0
2	09/06/01	08:38	0.6	1.4	1.9
3	09/06/01	08:40	0.5	0.7	0.9
4	09/06/01	08:42	0.2	2.2	4.0
5	09/06/01	08:44	0.6	0.7	0.8
6	09/06/01	08:46	3.9	5.5	6.9
7	09/06/01	08:48	0.2	0.6	0.8
8	09/06/01	08:50	0.0	0.5	2.5
9	09/06/01	08:52	0.9	0.9	0.9
10	09/06/01	08:54	0.2	0.7	0.9
11	09/06/01	08:56	0.9	0.9	1.0
12	09/06/01	08:58	0.3	0.7	0.9
13	09/06/01	09:00	3.6	5.3	7.1
14	09/06/01	09:02	3.5	7.3	15.2
15	09/06/01	09:04	1.8	2.1	5.2
16	09/06/01	09:06	0.8	0.8	0.9
17	09/06/01	09:08	0.7	1.3	15.1
18	09/06/01	09:10	1.3	7.9	28.0
19	09/06/01	09:12	0.7	1.2	3.5
20	09/06/01	09:14	1.1	9.7	58.5L
21	09/06/01	09:16	0.7	14.0	51.3L
22	09/06/01	09:18	23.7	30.3	35.0
23	09/06/01	09:20	32.2	36.1	39.8
24	09/06/01	09:22	41.2	44.9	49.0
25	09/06/01	09:24	51.1L	75.4L	103.1H
26	09/06/01	09:26	4.8	74.3L	102.2H
27	09/06/01	09:28	0.6	1.0	4.6
28	09/06/01	09:30	0.6	0.7	0.8

Figure 4.2.5 shows that a worker is more severely exposed during the first 10 minutes of the datalog event than in the second 10 minutes, a fact that might be missed with badge measurements or if relying on the worker to record unusual concentrations manually. Table 4.2.1 is an example of data taken at a 2-minute sampling interval, showing that minimum, average, and maximum values during each interval can be recorded. The "L" and "H" next to some values warn the reader that the low and high alarm limits were exceeded. In this case, the record can be used to prove that these limits were exceeded only for short periods.

Example 1: Instantaneous warning for transient exposures

Adsorptive tests using activated charcoal or passive samplers average-out changes in concentration and therefore may underestimate short-term exposures. For example, suppose a nail salon is located in a storefront under a law office. Vapors periodically filter into the law office with every new nail salon customer. These transient exposures may exceed the 15-minute STEL, but the averaging by adsorptive sampling techniques would miss this short-term exposure. A PID can datalog these quick, high transient responses and help IAQ investigators quickly identify and solve the problem.

Example 2: Datalogging PIDs document exposure versus time

PID datalogged results can be used in conjunction with worker schedules or even video tracking to correlate elevated VOC levels with the type of worker operations. For example, consider an office building with a small print shop in the basement. During the winter, the building manager decided to save money by decreasing the amount of outside air introduced into the HVAC system so that the air in the building was recirculated. Over the course of a workday, the solvent vapors from the print shop built up in the building until they reached levels over the TWA limit. Workers in the building didn't smell the vapors because they had grown accustomed to them over the course of the workday (olfactory fatigue). The logged PID data elucidated the low solvent exposures in the morning coupled with the high exposures in the afternoon. Therefore, it was only necessary to increase ventilation in the afternoon when outdoor temperatures were higher, thus maintaining some energy and cost savings.

4.2.3 TWA and STEL Data Processing

This section gives details on how TWAs, STELs and other concentration data are determined and datalogged by a PID. The algorithms apply specifically to the ToxiRAE PID, Model PGM-30, but are similar on most other portable PIDs with datalogging features. Depending on the datalogging options chosen, there may be differences between the instantaneously displayed values and the final datalogged values, as described below. All averages are calculated as arithmetic, rather than geometric, averages.

Displayed Values

- Second Values: Every second, the signal is sampled for several milliseconds, and the data are averaged to give the instantaneous reading. This value is used for calculation of the Minute Value and then overwritten when the next instantaneous reading is made.
- Minute Average: The Second Values are added to a running sum, and every minute this sum is divided by 60 to obtain a minute average. The Minute Average is not displayed, but is used to calculate the TWA and STEL.
- STEL: The Minute Average values are stored in a rolling buffer for 15 minutes to calculate the STELs and then overwritten. The STEL is updated every minute as an average of the most recent fifteen Minute Averages.
- TWA: The Minute Average values are also used to update the TWA every minute, by adding to a running sum and dividing by the number of minutes in an 8-hour day (480). The TWA is the value accumulated from the time the instrument is turned on until the time of the last Minute Average; it assumes no further exposure from then on. The TWA continues to accumulate after eight hours until the instrument is turned off.
- Peak Value: The Peak Value is updated every second and is the highest measured Second Value since the unit was turned on.
- Running Average: Some instruments store a running average in addition to (or instead of) a TWA. The running average is simply the arithmetic average of the concentration since the instrument or datalogging session was turned on.

Logged Values

The instrument software downloads minimum, average, and/or maximum values within a defined datalogging period. The datalogging period is defined as a time interval within the total datalogging event. The user programs the datalogging period, typically in one-second increments from one second up to one hour.

- The Minimum Value is the lowest Second Value measured during each datalogging period.
- The Average Value is the arithmetic average of all Second Values measured during each datalogging period.
- The Maximum Value is the highest Second Value measured during each datalogging period.
- The STEL is calculated as the average of the maximum logged results of the previous fifteen-minute window:

$$\frac{\sum \text{(All max logged values in last 15 min)}}{\text{\# values in 15 min} = (15 * 60) / \text{period (sec)}}$$

- The TWA is calculated as:

$$\frac{\text{Previous TWA} + \text{max logged value} * \text{period (sec)}}{480 * 60}$$

STEL and TWA values are sometimes not downloaded directly, but may be recalculated from the downloaded minimums, averages or maximums. Therefore, the logged values can be different from the displayed values if inappropriate datalogging parameters are chosen. The program often uses the highest values available to calculate the TWA and STEL. To ensure that the displayed and logged values are identical, the user should chose a datalogging period of 15 minutes or less. It is also suggested that the user log average only or average and minimum values, but not peak values.

Example 3: Typical Results

Table 4.2.2. gives an example of datalogged results showing TWA and STEL values. TWA values always increase because they are cumulative values, even though average concentrations may decrease. STEL values are calculated

correctly because the datalog period is <7.5 minutes and divides evenly into fifteen. The first 14 minutes of STEL values are not valid and always increase because they assume zero concentration before the first time-point. After 15 minutes, STEL values are correct.

Example 4: Datalog Period Too Short

Table 4.2.3 shows datalogged values that give incorrect STEL values due to data processing. In this example, the STEL does not average the most recent 15-minute window correctly. This is because STEL cannot be back-calculated correctly from the stored values when the datalog period is >7.5 minutes.

TABLE 4.2.2. Datalogged results showing TWA and STEL values

S/N: 001403 Year: 2001	User ID: 1 Period(s): 60	Site ID: 1 Data Pts: 20	Cal: 9/20 16:56 Chk: 9/20 14:40	00.4 ppm 100.5 ppm				
Date	**Time**	**Min**	**Avg ppm**	**Max**	**High 100.0**	**Low 50.0**	**STEL 25.0**	**TWA 10.0**
11/05	10:52	-	10.7	-			0.7	0.0
	10:53	-	9.7	-			1.4	0.0
	10:54	-	8.7	-			1.9	0.1
	10:55	-	8.0	-			2.5	0.1
	10:56	-	7.4	-			3.0	0.1
	10:57	-	7.0	-			3.4	0.1
	10:58	-	6.7	-			3.9	0.1
	10:59	-	6.4	-			4.3	0.1
	11:00	-	6.2	-			4.7	0.1
	11:01	-	6.0	-			5.1	0.2
	11:02	-	5.8	-			5.5	0.2
	11:03	-	5.7	-			5.9	0.2
	11:04	-	5.5	-			6.3	0.2
	11:05	-	5.4	-			6.6	0.2
	11:06	-	5.3	-			7.0	0.2
	11:07	-	5.2	-			6.6	0.2
	11:08	-	5.1	-			6.3	0.2
	11:09	-	5.0	-			6.0	0.2
	11:10	-	4.9	-			5.8	0.3
	11:11	-	4.8	-			5.7	0.3

TABLE 4.2.3. Datalogged results showing incorrect STEL values

S/N: 001403 Year: 2001	User ID: 1 Period(s): 600	Site ID: 1 Data Pts: 10	Cal: 6/20 45:29 Chk: 4/3 15:41	106.6 ppm 100.3 ppm				
Date	**Time**	**Min**	**Avg ppm**	**Max**	**High 100.0**	**Low 50.0**	**STEL 25.0**	**TWA 10.0**
5/10	11:24	-	2.7	3.6			3.6	0.1
	11:34	-	1.7	2.7			2.7	0.2
	11:44	-	1.6	2.7			2.7	0.2
	11:54	-	2.2	4.4			4.4	0.3
	12:04	-	3.9	4.6			4.6	0.4
	12:14	-	4.1	5.4			5.4	0.5
	12:24	-	2.9	3.8			3.8	0.6
	12:34	-	1.4	1.9			1.9	0.6
	12:44	-	2.2	4.0			4.0	0.7
	12:54	-	3.0	3.9			3.9	0.8

4.3 PIDs for Hazardous Materials Spill Response

Many HazMat (Hazardous Material) incidents involve spills or releases of VOCs that vaporize. Until recently, emergency responders were primarily concerned with the immediate hazards of the release or fire, including oxygen depletion, CO toxicity, and explosivity. Therefore, most responders relied on CO and O_2 electrochemical sensors and combustible gas detectors for broadband organic vapor detection. However, increasing awareness of the long-term toxicity of the many VOCs has led to a rapid growth in use of PIDs for HazMat response, either as stand-alone instruments or in combination with the other sensors listed above. PIDs measure VOCs at low ppm levels that can be toxic but are not detectable by standard LEL sensors. Also, recent improvements in PID ruggedness, reliability and affordability have made them more accessible to local HazMat teams. PID's are a valuable tool for making HazMat decisions including:

- Initial PPE assessment
- Leak detection
- Perimeter establishment and maintenance
- Spill delineation
- Decontamination
- Remediation

Because of these developments, more HazMat responders may want to consider adding PIDs to their inventory of gas monitors.

Common HazMat VOCs

Chemicals commonly encountered in hazardous material releases are the same as those that are commonly used in industry, including:

- Fuels
- Solvents, paints
- Heat transfer fluids
- Degreasers
- Plastics, resins and their precursors
- Oils, lubricants

Initial PPE Assessment

When approaching a potential HazMat incident, the responder must make a personal protective equipment (PPE) decision. Some potential incidents may not be an "incident" at all and may not require any PPE. Some incidents may initially appear to have no contamination yet require significant levels of PPE. PIDs are useful aids in this decision-making process.

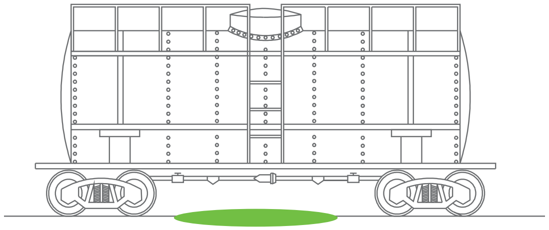

FIGURE 4.3.1. Apparently leaking benzene rail car

For example, a HazMat contractor was called by a railroad company to respond to a leaking tank car on a hot (95°F), humid (95%RH) summer day. According to the manifest, the tank car was loaded with benzene. Due to the carcinogenic nature of benzene (PEL of 1 ppm) the HazMat contractor chose to dress-out in Level A. However, because it was a hot summer day, this potentially exposed the responders to heat stress injuries. In the assessment of the "leaking" tank car it was found that the puddle under the car was coming from condensation, not dripping benzene. The car had been loaded at 65° F and the high relative humidity coming into contact with the cool rail car produced a puddle of water from condensation, which was mistaken as a benzene leak.

Using a PID would have helped the contractor quickly rule out the presence of benzene vapors, reducing the cost of the response and preventing the potential of heat-stress injuries from dressing in full Level A encapsulation.

Leak Detection with a PID

A leak is often not readily apparent and must first be located before it can be effectively stopped. As the gas or vapor disperses and dilutes, a concentration gradient is established with the highest concentration at the source and decreasing outwardly until it can no longer be detected. The PID can be used like a Geiger Counter to quickly follow the concentration gradient to the vapor source.

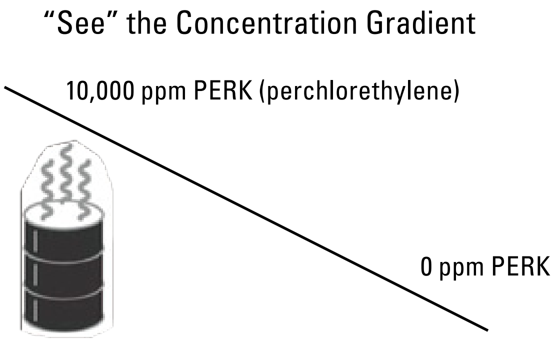

FIGURE 4.3.2. Concentration gradient from a vapor source

Perimeter Monitoring with a PID

HazMat technicians assess the incident and set a perimeter based upon the toxicity of the gas or vapor, the temperature, wind direction, and other factors. However, perimeters are usually manned by personnel without a high degree of experience.

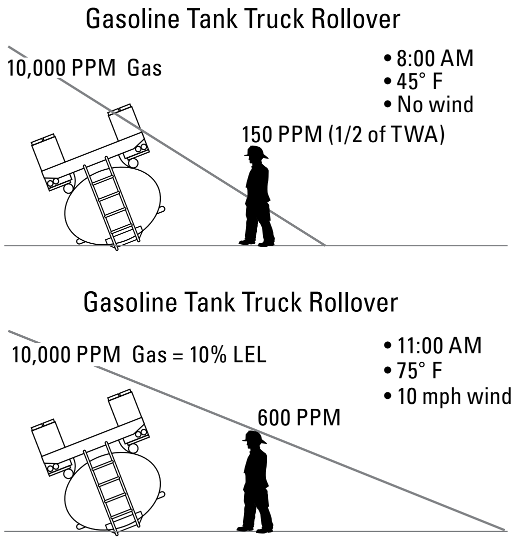

FIGURE 4.3.3. Perimeter variation due to changing weather conditions

As conditions change, perimeters often are not adjusted because perimeter workers do not have the experience to recognize that the conditions have changed. The experienced HazMat technicians are typically focused upon the problem of dealing with complications of the original spill. Therefore, perimeter workers are often unprotected from changing conditions that may require movement of a perimeter away from the spill site. For many HazMat incidents, a PID allows those manning a perimeter line to adjust the line in response to changing conditions. PIDs can provide instantaneous alarms that warn perimeter workers when to retreat from the incident.

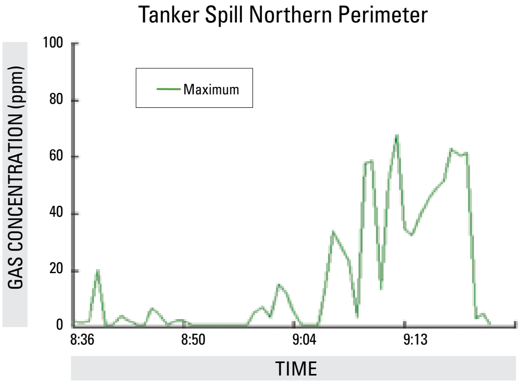

FIGURE 4.3.4. Datalogged PID response at a HazMat incident perimeter

Datalogging as a Tool

Datalogging PIDs provide supervisors with documentation of exposure levels and provide evidence to justify evacuations, should they be required. Some HazMat teams already datalog their incidents where there has been a chemical release.

However, most teams only datalog those incidents when the datalog showed positive results. This misses more than half of the value of datalogging. Many times a negative result on a datalog is more beneficial than a positive result, as it can later prove that a spill of an ionizable compound was promptly and properly contained. This can save time and money if the spill ever results in legal action.

PIDs for Spill Delineation

In the course of a HazMat incident many liquids can be present, such as water, fuel, engine fluids and firefighting foam. As described previously for the benzene rail car, PIDs allow responders to distinguish the released chemical from water, saving both time and absorbent. It also helps delineate a spill where the chemical adsorbed to surfaces and not clearly visible.

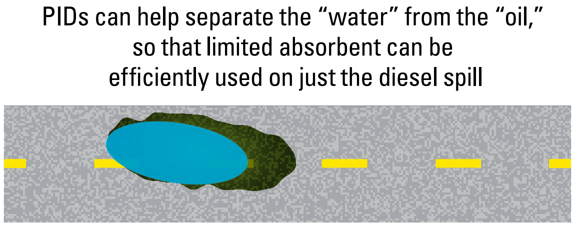
PIDs can help separate the "water" from the "oil,"
so that limited absorbent can be
efficiently used on just the diesel spill

FIGURE 4.3.5. Delineating a spill

Using a PID for Decontamination

After a HazMat incident clothing and PPE may require decontamination of the hazardous materials. For ionizable compounds like fuels and other VOCs, PIDs provide a quick and effective means of determining if materielle require decontamination, and if the decontamination is complete. A PID is swept over areas of suspected contamination will respond positively to areas that are contaminated with ionizable compounds and it will not respond to clean or properly decontaminated areas.

PIDs can help answer these questions:

- Is the worker contaminated?
- Is decontamination complete?
- Can we reuse the suit?
- Is my turn-out contaminated with fuel products?

FIGURE 4.3.6. PID for decontamination monitoring

Often a first responder to a fuel spill incident gets gasoline on his flame-retardant turnout clothing. Absorbed gasoline compromises the flame-retardant properties of turnout gear. A PID quickly responds to contamination and identifies this dangerous condition so that the turnout gear can be properly laundered before going into a structural firefighting situation. This same sensitivity to hydrocarbons makes PIDs ideally suited to arson investigations.

Using a PID for Remediation

While the goal of any HazMat response team is to contain and prevent spills, hazardous materials often evade containment, contaminating nearby soil and water. Many jurisdictions (counties, states, countries) have defined the concentration at which remediative action must take place. If there has been a fuel spill that has been contained to the road surface and it has been completely removed by absorbent, further remediative action may not be required. However, if fuel product has evaded the best efforts for containment, the fuel may have contaminated the surrounding soil or water. Some jurisdictions have an action level of 100 ppm TPH (Total Petroleum Hydrocarbons) in a sample headspace for further remediation. If soil samples show only 10 ppm of contamination in the headspace of a sample, remediation may not be required. Soil samples of 200 ppm would require further remediation. The usefulness of PIDs for environmental remediation is described in Chapter 4.1.

4.4 Using PIDs For LEL Measurements

One of the many requirements for entering confined spaces (OSHA Standard 29 CFR 1910.146) is that the level of flammable gases be below 10% of LEL (Lower Explosive Limit). The most common sensor used for measuring LEL is the Wheatstone bridge/catalytic bead/pellistor sensor. However, catalytic bead LEL sensors have poor sensitivity to high-molecular-weight compounds. Furthermore, they are subject to deactivation by commonly present chemicals including silicones, sulfur compounds, chlorinated solvents, leaded gasoline, and phosphorous compounds. In these circumstances, PIDs provide an alternate, accurate means of measuring 10% of LEL for confined space entry. A notable exception to this is that there is no response to methane, and a PID should not be used for LEL judgments if methane approaching LEL levels may be present. Some examples are described below.

Aircraft Maintenance: Jet Fuels & Solvents

Many commercial and military aircraft maintenance programs are standardizing on PIDs for confined space entry into wingtanks. Catalytic bead LEL sensors have poor sensitivity to low-vapor-pressure jet fuels, and are readily poisoned by the silicones present in many chemicals used, including hydraulic fluids and sealants. 10% of LEL for jet fuel is approximately 800 ppm. Because jet fuel standards are not readily available, PIDs can be calibrated with hexane or isobutylene and set to read in units of jet fuel by internally applying a correction factor. The PID alarm is set to 800 in units of jet fuel. This setting provides 10% LEL protection not only for jet fuels, but also for most other flammable liquids used in aircraft maintenance, including aromatics and ketones.

Pulp & Paper Plant: Turpentine

Turpentine is a low-vapor-pressure/high flash point flammable liquid that is difficult to measure with a catalytic bead LEL sensor. The mercaptans and sulfides present in pulp mills can deactivate the sensor. An experienced worker measured a confined space prior to a welding operation in a paper plant and detected no flammable vapors. However, the welding operation ignited turpentine vapors that went undetected by the properly functioning and calibrated catalytic bead LEL sensor. This facility subsequently standardized on PIDs with a high alarm set to 800 ppm (10% of LEL) for confined space entries.

Deodorant Filling Plant: Acute Silicone Poisoning

In addition to flammable solvents and propellants, deodorants contain sizable amounts of silicone compounds. Catalytic bead LEL sensors typically last days or weeks in these applications. PID optics are unaffected by these conditions and provide a reliable tool for 10% of LEL measurement. Due to the nature of some propellants, 11.7 eV lamps may be needed. While an 11.7 eV lamp does not last as long as the standard 10.6 eV PID lamp, it can last longer than catalytic bead sensors in these environments.

Gasoline Tank Remediation: TEL Poisoning

Tetraethyllead (TEL) historically was used as an octane booster in gasolines but is no longer allowed in the US because of its human toxicity. However, TEL still can be found in old underground storage tanks and contaminated sites. One contractor repeatedly replaced LEL sensors until it was determined that the old tanks contained trace amounts of TEL. For underground work it is important to use a catalytic bead LEL sensor because of the possible presence of methane, which PIDs cannot measure. But the most immediate threat during the tank remediation is gasoline flammability, and the PID provides consistent, reliable results even when TEL is present.

Styrene Plants: Chronic Styrene Poisoning

Styrene monomer can polymerize on hot catalytic bead LEL sensors, gradually rendering them inoperable. Exposure to clean air can help to reverse this process, but air that is completely free of styrene is rarely found in plants producing styrene. Therefore, catalytic bead LEL sensors have short lives in these facilities. PIDs have been used in many styrene plants to provide continuous monitoring of styrene vapors for daily exposure limits (20, 50, and 100 ppm for AGCIH, NIOSH, and OSHA, respectively). A high PID alarm of 900 ppm in styrene units provides a convenient, reliable alarm for 10% LEL also, without the need for a second instrument.

Setting PID Alarms for 10% LEL

Table 4.4.1 lists 128 NFPA 325 chemicals and 178 total flammable chemicals. The table shows the concentration of the compound in ppm at 10% of the LEL, in column 5. The rightmost column shows the equivalent PID reading when the unit is calibrated to isobutylene with a 10.6 eV lamp (calculated as 10% LEL/CF). When the alarm is set to the 10% LEL equivalent value for any chemical, it provides a warning also for all other chemicals on the list that are above it. The unit alarms at <10% LEL for these chemicals. A PID set to the following alarms and not beeping provides 10% of LEL protection for:

- 1000 ppm alarm: 75 NFPA 325 chemicals, including major solvents like xylene, toluene, acetone, and MEK, MPK.
- 500 ppm alarm: 96 NFPA 325 chemicals, from isobutyl acetate to vinyl bromide.
- 250 ppm alarm: 116 NFPA 325 chemicals, from n-hexane to vinyl bromide.
- 100 ppm alarm: 126 NFPA 325 chemicals, from naptha to vinyl bromide.

For most common industrial chemicals, a setpoint of 1000 ppm in isobutylene units is an appropriate alarm for 10% of LEL. This will provide a conservative setpoint for all liquid fuel products, aromatics (benzene, styrene, xylene, etc.), ketones (MEK, MIBK, etc) and many other common industrial chemicals. Some chemicals, like the alcohols, require more conservative setpoints. Of course, setting an alarm to 100 ppm would provide the highest level of protection, but also a greater tendency for false alarms.

TABLE 4.4.1. 10% LEL response for NFPA chemicals by PID

Note: NFPA 325 Chemicals are in Italics

Chemical Name	10.6 eV CF	LEL (Vol %)	LEL (ppm)	10% LEL (ppm)	10% LEL Response w/IBE Calibration
Vinyl bromide	*0.40*	*9*	*90000*	*9000*	*22500*
Dichloroethene, t-1,2-	0.45	9.7	97000	9700	21600
Trichloroethylene	*0.54*	*8*	*80000*	*8000*	*14800*
Dichloroethene, c-1,2-	0.8	9.7	97000	9700	12100
Vinylidene chloride	*0.82*	*6.5*	*65000*	*6500*	*7900*
Methyl mercaptan	*0.54*	*3.9*	*39000*	*3900*	*7200*
Tetraethyl lead (as Pb)	*0.3*	*1.8*	*18000*	*1800*	*6000*
Methyl bromide	1.7	10	100000	10000	5900
Dimethyl disulfide	0.20	1.1	11000	1100	5500
Trichlorobenzene, 1,2,4-	*0.46*	*2.5*	*25000*	*2500*	*5400*
Methyl sulfide	0.44	2.2	22000	2200	5000
Ethyl mercaptan	*0.56*	*2.8*	*28000*	*2800*	*5000*
Dichlorobenzene, o-	*0.47*	*2.2*	*22000*	*2200*	*4700*
Ethylamine	*0.8*	*3.5*	*35000*	*3500*	*4400*
Ethyl sulfide	0.51	2.2	22000	2200	4300
Methylamine	1.2	4.9	49000	4900	4100
Methylstyrene, alpha-	*0.50*	*1.9*	*19000*	*1900*	*3800*
Hexamethyldisilazane, 1,1,1,3,3,3-	0.24	0.8	8000	800	3300
Chlorobenzene	*0.40*	*1.3*	*13000*	*1300*	*3300*
Bromopropane,1-	1.5	4.6	46000	4600	3100
Dimethylformamide, N,N-	*0.7*	*2.2*	*22000*	*2200*	*3100*
3000 ppm Alarm ↑					
Toluidine, o-	0.50	1.5	15000	1500	3000
Mesitylene	0.35	1	10000	1000	2900
Xylene, p-	*0.39*	*1.1*	*11000*	*1100*	*2800*
Aniline	*0.48*	*1.3*	*13000*	*1300*	*2700*
Pyridine	*0.68*	*1.8*	*18000*	*1800*	*2600*
Pinene, a-	*0.31*	*0.8*	*8000*	*800*	*2600*
Diacetone alcohol	*0.70*	*1.8*	*18000*	*1800*	*2600*
Dimethylhydrazine, 1,1-	*0.78*	*2*	*20000*	*2000*	*2600*
Xylene, m-	*0.44*	*1.1*	*11000*	*1100*	*2500*
Isoprene	*0.63*	*1.5*	*15000*	*1500*	*2400*
Butadiene	*0.85*	*2*	*20000*	*2000*	*2400*
Trimethylamine	*0.85*	*2*	*20000*	*2000*	*2400*
Turpentine	*0.35*	*0.8*	*8000*	*800*	*2300*
Furfural	*0.92*	*2.1*	*21000*	*2100*	*2300*
Acetone	*1.1*	*2.5*	*25000*	*2500*	*2300*
Benzene	*0.53*	*1.2*	*12000*	*1200*	*2300*
Dimethyl acetamide, N,N-	*0.80*	*1.8*	*18000*	*1800*	*2300*
Styrene	*0.40*	*0.9*	*9000*	*900*	*2300*
Toluene	*0.50*	*1.1*	*11000*	*1100*	*2200*
Vinyl actetate	*1.2*	*2.6*	*26000*	*2600*	*2200*
Naphthalene	*0.42*	*0.9*	*9000*	*900*	*2100*
Monomethyl hydrazine	*1.2*	*2.5*	*25000*	*2500*	*2100*
Benzoyl chloride	*0.6*	*1.2*	*12000*	*1200*	*2000*
Xylene, o-	*0.46*	*0.9*	*9000*	*900*	*2000*
Dichloro-1-propene, 2,3-	1.3	2.6	26000	2600	2000
Diethylenetriamine	1.0	2	20000	2000	2000
Crotonaldehyde	*1.1*	*2.1*	*21000*	*2100*	*1900*
Ethanolamine	*1.6*	*3*	*30000*	*3000*	*1900*
Methyl t-butyl ether	0.91	1.7	17000	1700	1900
Dimethylamine	*1.5*	*2.8*	*28000*	*2800*	*1900*
Diethylamine	*0.97*	*1.8*	*18000*	*1800*	*1900*
Xylenes (o-, m-, p-isomers)	0.49	0.9	9000	900	1800
Benzyl chloride	*0.60*	*1.1*	*11000*	*1100*	*1800*
Ethyl silicate	0.71	1.3	13000	1300	1800
Dioxane, 1,4-	*1.1*	*2*	*20000*	*2000*	*1800*
Isobutylene	1.0	1.8	18000	1800	1800
Phenol	*1.0*	*1.8*	*18000*	*1800*	*1800*
Vinyl chloride	*2.0*	*3.6*	*36000*	*3600*	*1800*
Butene, 1-	*0.90*	*1.6*	*16000*	*1600*	*1800*
Isopropyl ether	*0.80*	*1.4*	*14000*	*1400*	*1750*
Vinyl-2-pyrrolidinone, 1-	*0.80*	*1.4*	*14000*	*1400*	*1750*
Diethyl ether	*1.1*	*1.9*	*19000*	*1900*	*1700*
Benzyl cyanide	*0.60*	*1*	*10000*	*1000*	*1700*
Dicyclopentadiene	0.48	0.8	8000	800	1700
Cumene	*0.54*	*0.9*	*9000*	*900*	*1700*
Gasoline #1	*0.85*	*1.4*	*14000*	*1400*	*1600*
Methyl ethyl ketone	*0.86*	*1.4*	*14000*	*1400*	*1600*
Cyclohexene	0.80	1.3	13000	1300	1600
Methyl-2-pyrrolidinone, N-	0.80	1.3	13000	1300	1600
Pentanone, 2- (Methyl propyl ketone)	*0.93*	*1.5*	*15000*	*1500*	*1600*
Propylene glycol monomethyl ether acetate (PGMEA)	*1.0*	*1.6*	*16000*	*1600*	*1600*
Petroleum distillates	0.7	1.1	11000	1100	1600
Ammonia	*9.7*	*15*	*150000*	*15000*	*1500*
Butylamine, n-	*1.1*	*1.7*	*17000*	*1700*	*1500*
Ethyl benzene	*0.52*	*0.8*	*8000*	*800*	*1500*

Chemical Name	10.6 eV CF	LEL (Vol %)	LEL (ppm)	10% LEL (ppm)	10% LEL Response w/IBE Calibration
1500 ppm Alarm ↑					
Hexene, 1-	0.80	1.2	12000	1200	1500
Methyl isobutyl ketone	0.80	1.2	12000	1200	1500
Diisopropylamine	*0.74*	*1.1*	*11000*	*1100*	*1500*
Piperylene, isomer mix	0.69	1	10000	1000	1400
Picoline, 3-	0.90	1.3	13000	1300	1400
Propene	*1.4*	*2*	*20000*	*2000*	*1400*
Gasoline #2, 92 octane	1.0	1.4	14000	1400	1400
Dichloro-1-propene, 1,3-	0.96	1.3	13000	1300	1400
Jet fuel JP-5	*0.6*	*0.8*	*8000*	*800*	*1300*
Jet fuel JP-8	*0.6*	*0.8*	*8000*	*800*	*1300*
Methoxyethoxyethanol, 2-	1.2	1.6	16000	1600	1300
Chloroprene, beta-	*3.0*	*4*	*40000*	*4000*	*1300*
Triethylamine	*0.90*	*1.2*	*12000*	*1200*	*1300*
Ethoxyethanol, 2- (Cellosolve)	1.3	1.7	17000	1700	1300
Jet fuel JP-4	*1.0*	*1.3*	*13000*	*1300*	*1300*
Cyclohexylamine	1.2	1.5	15000	1500	1300
Methylcyclohexane	0.97	1.2	12000	1200	1200
Cyclohexanone	*0.90*	*1.1*	*11000*	*1100*	*1200*
Hydrogen sulfide	*3.3*	*4*	*40000*	*4000*	*1200*
Diesel Fuel #2	*0.66*	*0.8*	*8000*	*800*	*1200*
Propionaldehyde	1.9	2.3	23000	2300	1200
Benzyl alcohol	*1.1*	*1.3*	*13000*	*1300*	*1200*
Tetrahydrofuran	*1.7*	*2*	*20000*	*2000*	*1200*
Kerosene (Jet Fuel)	*0.6*	*0.7*	*7000*	*700*	*1200*
Methyl isocyanate	*4.6*	*5.3*	*53000*	*5300*	*1200*
Propylene glycol monomethyl ether	*1.4*	*1.6*	*16000*	*1600*	*1100*
Methyl methacrylate	*1.5*	*1.7*	*17000*	*1700*	*1100*
Stoddard Solvent	*0.71*	*0.8*	*8000*	*800*	*1100*
Hydrazine	*2.6*	*2.9*	*29000*	*2900*	*1100*
Methyl ether	*3.1*	*3.4*	*34000*	*3400*	*1100*
Carbon disulfide	*1.2*	*1.3*	*13000*	*1300*	*1100*
Diethylaminopropylamine, 3-	1.3	1.4	14000	1400	1100
Isopar M Solvent	0.66	0.7	7000	700	1100
Allyl alcohol	*2.4*	*2.5*	*25000*	*2500*	*1000*
Nicotine	*0.70*	*0.7*	*7000*	*700*	*1000*
Phenyl ether	0.70	0.7	7000	700	1000
1000 ppm Alarm ↑					
Nitrobenzene	*1.9*	*1.8*	*18000*	*1800*	*950*
Cyclohexane	1.4	1.3	13000	1300	930
Butoxyethanol, 2-	1.2	1.1	11000	1100	920
Isooctane	1.2	1.1	11000	1100	920
Dichloroethyl ether	*3.0*	*2.7*	*27000*	*2700*	*900*
Benzonitrile	1.6	1.4	14000	1400	880
Diesel Fuel #1	0.93	0.8	8000	800	860
Diphenyl (Biphenyl)	*0.70*	*0.6*	*6000*	*600*	*860*
Bromobenzene	*0.60*	*0.5*	*5000*	*500*	*830*
Butyl alcohol, tert-	*2.9*	*2.4*	*24000*	*2400*	*830*
Diethanolamine	*2.0*	*1.6*	*16000*	*1600*	*800*
Methyl acrylate	*3.7*	*2.8*	*28000*	*2800*	*760*
Butyl acetate, tert-	2.0	1.5	15000	1500	750
Methoxyethanol, 2-	2.4	1.8	18000	1800	750
Ethyl hexyl acrylate, 2-	1.1	0.8	8000	800	730
Acrolein	*3.9*	*2.8*	*28000*	*2800*	*720*
Caprolactam	2.0	1.4	14000	1400	700
Isopropyl acetate	*2.6*	*1.8*	*18000*	*1800*	*690*
Allyl chloride	*4.3*	*2.9*	*29000*	*2900*	*670*
Acetaldehyde	*6.0*	*4*	*40000*	*4000*	*670*
Butyl acetate, n-	*2.6*	*1.7*	*17000*	*1700*	*650*
Toluene-2, 4-diisocyanate (TDI)	*1.4*	*0.9*	*9000*	*900*	*640*
Ethyl acrylate	*2.4*	*1.4*	*14000*	*1400*	*580*
Decane	1.4	0.8	8000	800	570
Nonane	*1.4*	*0.8*	*8000*	*800*	*570*
Butyl acetate, sec-	*3.0*	*1.7*	*17000*	*1700*	*570*
Octane, n-	*1.8*	*1*	*10000*	*1000*	*560*
Isobutyl acetate	*2.6*	*1.3*	*13000*	*1300*	*500*
500 ppm Alarm ↑					
Propyl acetate, n-	*3.5*	*1.7*	*17000*	*1700*	*490*
Hexanol, 1-	2.5	1.2	12000	1200	480
Amyl acetate, n-	*2.3*	*1.1*	*11000*	*1100*	*480*
Isoamyl acetate	*2.1*	*1*	*10000*	*1000*	*480*
Propylene glycol	*5.5*	*2.6*	*26000*	*2600*	*470*
Methyl acetate	*6.6*	*3.1*	*31000*	*3100*	*470*
Ethyl (S)-(-)-lactate	3.2	1.5	15000	1500	470
Phosphine	3.9	1.79	17900	1790	460
Isobutyl alcohol	*3.8*	*1.7*	*17000*	*1700*	*450*
Epichlorohydrin	*8.5*	*3.8*	*38000*	*3800*	*450*
Acetic Anhydride	*6.1*	*2.7*	*27000*	*2700*	*440*
Propyl alcohol, n-	*5*	*2.2*	*22000*	*2200*	*440*
Amyl acetate, sec-	*2.3*	*1*	*10000*	*1000*	*440*
Ethyl acetate	*4.6*	*2*	*20000*	*2000*	*440*

Chemical Name	10.6 eV CF	LEL (Vol %)	LEL (ppm)	10% LEL (ppm)	10% LEL Response w/IBE Calibration
Butyl alcohol, sec-	*4.0*	*1.7*	*17000*	*1700*	*430*
Heptane, n-	*2.8*	*1.05*	*10500*	*1050*	*380*
Propylene oxide	*6.5*	*2.3*	*23000*	*2300*	*350*
Isopropyl Alcohol	*6.0*	*2*	*20000*	*2000*	*330*
Ethyl alcohol	*10*	*3.3*	*33000*	*3300*	*330*
Naphtha (Coal tar) {10% aromatics}	*2.8*	*0.9*	*9000*	*900*	*320*
Undecane	2.0	0.6	6000	600	300
Butyl alcohol, n-	*4.7*	*1.4*	*14000*	*1400*	*300*
Ethene	*9*	*2.7*	*27000*	*2700*	*300*
Hexane, n-	*4.3*	*1.1*	*11000*	*1100*	*260*
250 ppm Alarm ↑					
Amyl alcohol	*5.0*	*1.2*	*12000*	*1200*	*240*
Amyl alcohol, sec-	*5.0*	*1.2*	*12000*	*1200*	*240*
Ethylene oxide	*13*	*3*	*30000*	*3000*	*230*
Acrylic Acid	*12*	*2.4*	*24000*	*2400*	*200*
Ethylene glycol	*16*	*3.2*	*32000*	*3200*	*200*
Acetic Acid	*22*	*4*	*40000*	*4000*	*180*
Dimethyl sulfate	*20*	*3.6*	*36000*	*3600*	*180*
Pentane	*8.4*	*1.5*	*15000*	*1500*	*180*
Isopentane, & all isomers	*8.2*	*1.4*	*14000*	*1400*	*170*
Naphtha (Coal tar) {purely aliphatic}	*5.7*	*0.9*	*9000*	*900*	*160*
100 ppm Alarm ↑					
Propylene carbonate	62	1.8	18000	1800	29
Butane	*67*	*1.6*	*16000*	*1600*	*24*
Isobutane	*100*	*1.6*	*16000*	*1600*	*16*

4.5 Dual Lamp Measurements for Enhanced Specificity in Variable Mixtures

In some cases of two-component mixtures whose component ratios may vary, it is possible to measure one component in the presence of another if they have different sensitivities on different lamps. The same principle applies to three-component mixtures using three lamps, although these will not be treated here because of their impracticality. The response to a mixture can be calculated as:

$$R_T^{9.8} = \frac{C_1}{CF_1^{9.8}} + \frac{C_2}{CF_2^{9.8}}$$

$$R_T^{10.6} = \frac{C_1}{CF_1^{10.6}} + \frac{C_2}{CF_2^{10.6}}$$

where R_T^n is the total response on lamp n in isobutylene equivalents and CF_x^n is the correction factor for compound X on lamp n. All the factors are known except for C_1 and C_2, and therefore the concentrations can be determined using simple algebra for two equations in two unknowns. Examples of this calculation are given in Appendix 7 and below in Example 1.

Example 1. Measuring CS_2 in the Presence of H_2S.

Both CS_2 and H_2S respond on a 10.6 eV lamp with CFs of 1.2 and 3.3, respectively (See Appendix 3). The CS_2 can be measured selectively using a 9.8 eV lamp (CF = 4) without interference from the H_2S. Thus, if only the concentration of CS_2 is needed, measuring with a 9.8 eV lamp alone is sufficient. However, both components can be determined by using both 9.8 and 10.6 eV on the same gas sample.

For example, if the total response with the 9.8 eV lamp is 3 ppm IBE equivalents, and the response on the 10.6 eV lamp is 18 ppm IBE equivalents, then:

- The concentration of CS_2 is $3 \times CF_{9.8} = 3 \times 4 = 12$ ppm CS_2.
- The contribution by CS_2 on the 10.6 eV lamp response is:
  $12/CF_{10.6} = 12/1.2 = 10$ ppm IBE equivalents
- The response of the H_2S on the 10.6 eV lamp is the remainder:
  $18 - 10 = 8$ ppm IBE equivalents
- The concentration of H_2S is $8 \times CF_{10.6} = 8 \times 3.3 = 26.4$ ppm H_2S.

In summary, the 12 ppm CS_2 plus 26.4 ppm H_2S give a response of 3 ppm on the 9.8 eV lamp and 18 ppm on the 10.6 eV lamp.

Note that it is not correct to simply subtract the response of the 9.8 eV lamp from that of the 10.6 eV lamp, even if both lamps were calibrated directly to CS_2, because H_2S has a different CF than CS_2 on both lamps.

4.6 Volatile Emissions from Paint

Paints are a special case of the mixtures described in previous sections, because they contain a large fraction of non-volatile materials, such as titania, silica, and organic polymers. These non-volatile components are the residues left behind on the painted surface that provide the protective and decorative coating. Typically a Material Safety Data Sheet (MSDS) for the paint will provide the percentage by weight of all the components, not just the volatile ones detectable by PID. In this section, we work through some examples of how to estimate correction factors and set alarm limits for paints based on the percentages provided on an MSDS.

In this analysis, it is often necessary to make some assumptions because the exact composition is often not defined in the MSDS.

Example 1 – Nonvolatile Paint Component

There is a spill of Part B of the topcoat Interthane 870, consisting of:

TABLE 4.6.1. Composition of Interthane 870 Part B

Component	MSDS Wt. %	Estimated Actual Weight % of Total	Weight % of Volatiles
Homopolymer of HMDI	50-100	70	-
Trimethylbenzene	10-25	15	50
Aromatic Hydrocarbons	10-25	10	33
Xylene	1-10	5	17
Total	72-160	100	100

TABLE 4.6.2. Conversion of Wt.% to Mole% for Part B volatiles

Component	Wt. %	m.w. (g/mol)	(Wt.%)/(m.w.) (mol/g liq)	mol %
Trimethylbenzene	50	120.2	0.416	47.9
Aromatic Hydrocarbons	33	~113	0.292	33.6
Xylene	17	106.2	0.16	18.4
Total	100	-	0.868	99.9

It is immediately clear that a number of assumptions need to be made. First, the isomers of trimethylbenzene and xylene are not specified. These have slightly different CFs and exposure limits and therefore an average or typical value must be assumed. Second, it is assumed that the aromatic hydrocarbons are different from trimethylbenzene and xylene, because they are listed separately. Third, in the absence of other information, it was assumed that the aromatics are other isomers of xylene and trimethylbenzene in approximately equal ratio, giving an average molecular weight between the two. Finally, it is assumed that the homopolymer of HMDI is completely non-volatile and thus can be ignored in the CF calculation. Using the mole percentages of the volatile components, one can then calculate the correction factor and alarm limits using the equations for mixtures from Chapter 3.1.6 (Table 4.6.3).

In this example, the painting operations are conducted using supplied air respirators; therefore, it is not necessary to meet OSHA TWA limits. Nevertheless, to avoid undue skin exposure, the factory regulations call for a shutdown of operations if the organic vapor levels reach 5 times the TWA for either ethylbenzene (100 ppm), xylene (100 ppm), or trimethylbenzene (25 ppm), or 500, 500 and 125 ppm, respectively. Table 4.6.3 shows that the overall CF for the mixture of volatiles is 0.40 with a 10.6 eV lamp and the action level is 205 ppm, or an equivalent PID response of 517 ppm when calibrated to isobutylene. In this calculation mesitylene (1,3,5-trimethylbenzene) was used to represent the MSDS "trimethylbenzene" and o-xylene was used to represent the MSDS "aromatics" because it has a slightly higher CF than other xylenes and therefore would tend to err on the conservative (safe) side.

TABLE 4.6.3. CF and action level alarm calculation for Part B volatiles

Compound	CF 9.8 eV	CF 10.6 eV	CF 11.7 eV	Mol. Fraction	Conc. (ppm)	Action Level (ppm)
Mesitylene	0.36	0.35	0.32	0.479	47.9	125
Xylene, o-	0.56	0.46	0.43	0.336	33.6	500
Xylene, m-	0.5	0.44	0.4	0.184	18.4	500
Mixture value:	0.43	0.40	0.36	1.00	100 ppm	205 ppm
Action alarm setpoint when calibrated to isobutylene:	472 ppm	517 ppm	562 ppm			

Example 2 – Formaldehyde in Paint Volatiles

A paint is applied containing the following VOCs and allowed to air-dry. The mole percentages were calculated from the weight percentages using the methods described above, and the mixture CF and alarm limits are calculated using the methods in Chapter 3.1.6.

TABLE 4.6.4. Composition of paint volatiles

Component	Mole % of Total	TWA
Formaldehyde	0.6	Ceiling 0.3
Toluene	1.5	50
PGMEA	1.5	~50
Isobutanol	14.6	50
p-Xylene	23.4	100
n-Butyl acetate	58.5	150

In this case, a TLV of 0.3 for formaldehyde was entered, which is actually the ceiling value, in the absence of a TWA value.

The CF and alarm limit calculation table is given in Appendix 4. With the above mixture one calculates an average CF of 1.1 for a 10.6 eV lamp, and 1.0 for 11.7. After calibration with isobutylene, the CF is set to 1.1, and the alarm to 33 ppm to equal the mixture TLV. This alarm setpoint is very sensitive to the TLV entered for formaldehyde. For example, if the formaldehyde TLV is doubled to 0.6 ppm, the CF remains at 1.1 while the alarm setpoint increases to 51 ppm for a 10.6 eV lamp. Even though the formaldehyde is not detected, the calculations account for its toxicity in the mixture. The other compounds act as a marker for CH_2O, while CH_2O dominates the toxicity. If the reading is less than 33 ppm total, one is assured that formaldehyde is <0.3 ppm, and the ceiling is not exceeded.

4.7 Ammonia Measurement by PID

Ammonia (NH_3) is a common alkaline gas, also referred to as anhydrous ammonia in the absence of water or in the gas phase. Lighter than air, it has a strong, distinctive smell and is highly corrosive. Its affinity for water causes it to cauterize respiratory tracts, resulting in death at concentrations of 5,000 ppm. It has the following relatively low exposure limits (NIOSH, 1994):

- TWA 25 ppm
- STEL 35 ppm
- IDLH 300 ppm
- LEL 15 Vol%

As an alternative to ozone-depleting chlorofluorocarbon refrigerants, the use of ammonia as a refrigerant (R717) has increased substantially over the past few years. Large quantities of ammonia can also be found in:

- Fertilizer plants
- Resin production using urea
- Explosives/munitions plants
- Nylon production
- Semiconductor production
- Water & wastewater facilities
- Clandestine drug labs

Why Measure Ammonia?

While ammonia's distinctive smell makes it relatively easy to identify, the human nose is not calibrated to measure its concentration. Therefore, real-time monitors are necessary to allow continuous determination of the Personal Protective Equipment (PPE) necessary to provide proper protection from ammonia. According to the NIOSH pocket guide (NIOSH, 1994), protection from low levels of ammonia (up to 250 to 300 ppm) can be as little as a respirator with the appropriate ammonia cartridges. Entries into concentrations above 300 ppm or into unknown concentrations require positive-pressure supplied-air or SCBAs. Even higher concentrations require full encapsulation suits (Level A) because of the highly reactive alkaline nature of ammonia gas. At concentrations above 15% (150,000 ppm), the ammonia atmosphere is potentially explosive. Accurate, reliable, and continuous portable ammonia monitors are useful to make these decisions.

LEL and EC Sensors for Measuring Ammonia

Catalytic bead LEL sensors can measure ammonia in the low volume % range, but do not have the low-ppm sensitivity necessary to make decisions at TWA or STEL levels. Also, ammonia can deactivate LEL sensors. So while they provide good initial warnings of very high ammonia levels (~10,000 ppm) their life in these high concentrations are limited to minutes or hours, depending on the concentration of ammonia.

Electrochemical sensors are an inexpensive way of making selective ammonia measurements in the low ppm range. However, common electrochemical ammonia sensors suffer from long response times (two to three minutes) and rapid burnout at high ammonia exposures (because the cell uses a sacrificial iodine reagent).

Measuring Ammonia with a PID

Ammonia has an ionization energy of 10.16 eV and can be readily measured with a PID using a standard 10.6 eV lamp. The CF for ammonia is about 10 with a 10.6 eV lamp (Appendix 3). Therefore, the detection limit is about 1 ppm ammonia, for a PID with 0.1 ppm isobutylene detection limit. This detection limit is about the same as for an electrochemical sensor. The sensitivity can be improved by a factor of 3 using an 11.7 eV lamp. However, it is questionable whether the improved response is necessary or desirable in light of the higher maintenance and replacement costs of the 11.7 eV lamp. The 10.6 eV lamp provides enough sensitivity for most applications. Portable PIDs have considerable advantages for measuring ammonia in ranges above the TWA and STEL of ammonia (25 to 35 ppm):

- PIDs have a broader range (up to 15,000 ppm) than EC sensors and therefore can be used for all PPE decisions and for leak detection.
- PIDs are not damaged by over-ranging.
- PIDs have much faster response time of <5 seconds, compared to 150 seconds for ammonia sensors. The fast response makes it easier to assess changing conditions and detect leaks.
- Isobutylene calibration gas for the PID is less expensive and more stable than the ammonia gas required for electrochemical sensors.
- Lower operating cost than EC sensors because the lamp is changed less frequently and at lower price than an NH_3 sensor.

PID Specificity to Ammonia

A PID is not specific to ammonia and it responds to a variety of other compounds (see Appendix 3). However, a major ammonia leak can often be determined by its distinctive smell. Use of a selective technique, such as gas detection tubes, can provide an inexpensive verification of the presence of ammonia, while the continuous measurement capability of the PID can be used to monitor with much greater speed and flexibility.

4.8 Measurement of Phosphine (PH_3) by PID In the Food Storage Industry

Introduction

Phosphine (PH_3) is used as a pesticide in food-storage units, especially in the agriculture and marine shipping industries. To ensure adequate pest control, a few hundred ppm are typically applied and the concentration verified by measurement. PH_3 has a low exposure limit (8-hour TWA of 0.3 ppm) and, when entering the storage vessels, must be measured at low levels to ensure worker safety. PH_3 has an IE of 9.87 eV and can be measured by PID using different lamps:

TABLE 4.8.1. Phosphine correction factors and resolution for RAE PIDs

Lamp eV	9.8 eV	10.6 eV	11.7 eV
CF	28	3.9	1.1
Resolution	~3 ppm	~0.4 ppm	~0.2 ppm

In most cases, the 10.6 eV lamp is chosen because of its good sensitivity and durability. At high concentrations, the 9.8 eV lamp may be useful if cross-interferences are present.

Lamp Fogging Phenomenon

Phosphine is unique in its behavior with PIDs in that it reacts photochemically to form products that can coat the PID lamp. The products are surmised to be phosphorus oxides such as polyphosphates, although this has not been verified. This lamp coating occurs with all lamps and becomes more severe as concentration and exposure time increase. The situation is most obvious at a few hundred ppm, but even 20 ppm can cause a noticeable response drop within minutes. Short, intermittent exposures help minimize the buildup of such coatings. The coatings are easily removed by cleaning the lamp crystal with anhydrous methanol. Near the TWA level, the coating deposits are negligible.

There is also some evidence that the sensor electrodes can become coated, again reducing response. Therefore, sensor cleanings may help reverse the problem.

Measurement Recommendations

1. Calibrate using isobutylene gas instead of a phosphine standard.
2. Use as short an exposure duration as possible (e.g., 10 seconds, with a PID having t90 response time of <5 seconds).
3. Expose to the lowest concentration possible, i.e., use a dilution system if available and still allows enough gas to measure accurately.
4. Use an old lamp or turn down the lamp drive, if possible (on a MiniRAE 2000, use 150).
5. Recalibrate frequently, possibly after every few measurements.
6. Clean the lamp frequently. For a MiniRAE 2000, leave the unit on the charger overnight to allow self-cleaning.
7. Leave the pump on between measurements to help flush out the coating.
8. Clean the sensor frequently.

Gas Detection Tube Combinations

It may be desirable to measure the high-end PH_3 concentrations using an alternate method such as colorimetric gas detection tubes, to avoid exposure of the PID lamps to high concentrations. The PID can be used more effectively at the low concentration range where the tubes lack sensitivity. Gas detection tubes for phosphine are readily available in the 500 to 1,000 ppm range often used for initial fumigation.

4.9 PIDs for EPA Method 21 Leak Detection

Introduction

EPA Method 21 (40 CFR, Ch.1, Pt. 60 Appendix A) is a standard for selecting and using monitors for leak detection and monitoring fugitive emissions. PIDs are listed among the common instruments appropriate for making the measurements. Method 21 does not define leak thresholds; these are defined in other regulations. Tougher requirements have resulted in better monitoring equipment for determining VOC leaks. Method 21 is designed primarily to limit emissions of hydrocarbons that result in tropospheric ozone generation in sunlight. For this purpose, the term VOC includes most organic compounds but excludes such non-ozone-generating compounds as methane, ethane, acetone, methyl acetate, methylene chloride, 1,1,1-trichloroethane, most Freon refrigerants (CFCs and HCFCs), and methylated siloxanes.

Calibration at 10,000 ppm?

It is a common misconception that Method 21 requires calibration at 10,000 ppm methane. It does not; it simply uses 10,000 ppm in an example of where a leak definition might be set. In the definitions, it states:

> "For example, If a leak definition concentration is 10,000 ppmv as methane, then any source emission that results in a local concentration that yields a meter reading of 10,000 on an instrument calibrated with methane would be classified as a leak. In this example the leak definition is 10,000 ppmv, and the reference compound is methane."

The "leak definition" is defined in another regulation specific to the industry or application. The reference compound is "The VOC species selected as an instrument calibration basis for specification of the leak definition concentration." It can be any compound appropriate for the type of instrument used.

What is the Recommended Calibration Gas Concentration?

Under the Definitions, the calibration gas is defined as:

> "The VOC compound used to adjust the instrument meter reading to a known value. The calibration gas is usually the reference compound at a concentration approximately equal to the leak definition concentration."

This statement does not define the gas type or concentration. These are best defined by the regulation controlling the leak threshold. Under Title V, most leak definitions fell to 500 ppmv or less. For example, in Subpart VV – Standards of Performance for Equipment Leaks of VOC in the Synthetic Organic Chemicals Manufacturing Industry (EPA 40 CFR Part 60), the calibration gas is defined as approximately 10,000 ppm methane or n-hexane, and the leak definition is 500 or 10,000 ppm, depending on the device being tested.

Can a Different Calibration Gas be Used?

Under Reagents and Standards, Method 21 states:

> "Calibrations may be performed using a compound other than the reference compound. In this case, a conversion factor must be determined for the alternative compound such that the resulting meter readings during source surveys can be converted to reference compound results."

For example, if the leak definition is given in methane equivalents, then the PID response needs to be converted to methane equivalents to set the leak alarm on the PID. Clearly the PID cannot be calibrated directly with methane, because it does not respond to methane. In other words, compound A can be used to calibrate the instrument to measure the emission of compound B (the VOC) in equivalents of compound C (reference gas – usually methane or hexane equivalents).

Calibration on Isobutylene is Permitted if the CF is <10

The only limitation on the use of calibration gas different from the reference gas is that correction factors for the measurement VOCs are always less than 10. Thus, one could calibrate on isobutylene and measure toluene leaks (CF = 0.5) but not ethylene oxide leaks (CF = 13). However, one could use an 11.7 eV lamp, where the CF = 3.5, or use hexane or ethylene to calibrate and thus reduce the ethylene oxide CF to 3.0 or 1.3, respectively (see Chapter 3.1.4 to convert CFs).

PID Compliance with Method 21

Several other specifications are required to be met when selecting an instrument for use under Method 21. The following table shows how several PIDs comply to the specifications. (The data for MultiRAE assume that a PID is installed.)

TABLE 4.9.1 PID compliance with EPA Method 21

Method 21 Specification	MiniRAE 3000	ppbRAE 3000
Detects compound	Responds to a broad range of organic compounds	Responds to a broad range of organic compounds
Instrument Range Encompasses leak definition	0 to 15,000 ppm	0 to 10,000 ppm
Range w/Dilution Probe Encompasses leak definition	No dilution probe	No dilution probe
Instrument Resolution ±2.5 % of leak definition	0.1 ppm (0 to 999.9 ppm) 1 ppm (1,000 to 15,000 ppm)	1 ppb (1 to 9999 ppb) 10 ppb (10 to 99 ppm) 0.1 ppm (100 to 999.9 ppm) 1 ppm (1000 to 9999 ppm)
Pump Flow Rate 0.1 to 3.0 L/min	0.45 to 0.55 L/min	0.45 to 0.55 L/min
Probe Dimensions ≤1/4" O.D.	3/16" O.D.	3/16" O.D.
Intrinsic Safety for Chemical Vapors Class I, Division 1	Class I, Division 1 Approved	Class I, Division 1 Approved
Correction Factor available for measured compound	Over 350 compound CFs available for RAE PIDs	Over 350 compound CFs available for RAE PIDs
Response Factor Value <10	<10 for most compounds, using isobutylene cal. gas	<10 for most compounds, using isobutylene cal. gas
Response Factor for Test Compound Measurable or Available	Pre-programmed with 222 compounds Available for >350 compounds	Pre-programmed with 222 compounds Available for >350 compounds
Cal. Precision Test Freq. Initial and every 3 months	Simple daily calibration	Simple daily calibration
Calibration Precision ±10% of Cal. gas value	±2% of cal. gas value	±2% of cal. gas value
Response Time ≤30 seconds to 90%	≤3 seconds to 90%	≤3 seconds to 90%

Please refer to TN 122 on our website.

4.10 Natural Gas Leak Detection by PID

Natural gas consists primarily of methane, but may contain significant amounts of higher hydrocarbons, as listed in Table 4.10.1. PIDs cannot detect methane, but do respond to the minor components. Biogenic methane produced in anaerobic waters does not contain higher hydrocarbons. Therefore, a PID with 10.6 or 11.7 eV lamp can be used to distinguish a natural gas leak in an underground pipeline from background biogenic methane such as in groundwater or landfills. By contrast, an FID or LEL catalytic bead sensor could not make this distinction.

TABLE 4.10.1. Composition of a "rich" natural gas sample

Gas component	Mole %
CO_2	1.181
Nitrogen	0.405
Methane	83.000
Ethane	7.754
Propane	4.250
Isobutane	0.858
n-Butane	1.776
Isopentane	0.332
n-Pentane	0.305
n-Hexane	0.101
Heptane & C_7+	0.038
H_2S	0.012
Total Mol %	100.000

PIDs for EPA Method 21 Natural Gas Leak Detection

Table 4.10.2 lists measurement parameters for various instruments for EPA Method 21 leak detection. Using the equations described in Chapter 3.1.6 Part 3, an isobutylene CF of 220 can be calculated for this mixture with a 10.6 eV lamp, and a CF of 15 with an 11.7 eV lamp. Accordingly, the detection limits for these lamps are about 22 and 3 ppm, respectively. Method 21 has a requirement that the instrument used be able to resolve at least down to 2.5% of the leak definition. Common leak definitions are 10,000 ppm and 500 ppm.

TABLE 4.10.2. EPA Method 21 criteria for various sensors

Sensor	% of Gas Detected	CF	Detection Limit (DL)	DL Required for 10,000 ppm Leak Definition	DL Required for 500 ppm Leak Definition
FID Cal to Methane	99%	1	1 ppm	250 ppm	12.5 ppm
PID 11.7 eV Cal to Ethane	7.70%	1	3 ppm	250 ppm	12.5 ppm
PID 10.6 eV	0.80%	220	22 ppm	250 ppm	12.5 ppm
Cal to IBE					
LEL Cal to Pentane	99%	2.3	1% LEL or 140 ppm	250 ppm	12.5 ppm
LEL Cal to Methane	99%	1	1% LEL or 500 ppm	250 ppm	12.5 ppm

Table 4.10.2 shows that the PID with 11.7 eV lamp and FID can both be used for either a 500 ppm or 10,000 ppm leak definition, because their detection limits are below the minimum requirements of 12.5 and 250 ppm, respectively. PIDs with either 10.6 or 11.7 eV lamps are more sensitive to natural gas than a catalytic bead LEL sensor, despite the fact that the LEL sensor responds to essentially all of the natural gas and the PID only responds to a small fraction. The standard LEL sensor calibrated to methane cannot meet the sensitivity criterion for either a 10,000 ppm or 500 ppm leak definition. It is barely acceptable for the 10,000 ppm leak definition if calibrated with pentane (the sensitivity changes because the display usually limits the detection limit when calibrating with methane).

Note that the PID with an 11.7 eV lamp is nearly as sensitive as a portable FID, but is much smaller and easier to operate. The operating cost may be a bit higher due to lamp-replacement needs, but the initial purchase price is lower and FIDs are often considered too complicated.

Another criterion in EPA Method 21 is that the CF for the measured gas compared to the calibration gas be less than or equal to 10. The PIDs have greater CFs when calibrated with isobutylene, but can pass the criterion by calibrating with another gas such as ethane (CF = 15) for the 11.7 eV lamp and butane (CF = 67) for the 10.6 eV lamp. The new factors are obtained by division (Chapter 3.1.4) and are 1.0 and 3.3, respectively. The detection limit does not change when calibrating to these different gases.

A further consideration for complying with Method 21 is that, in principle, methane and ethane are not considered ozone precursor VOCs and thus may not need to be taken into consideration in the leak definitions. In this case, the calculated correction factors and leak definitions would change and would likely favor the use of a PID with 10.6 eV lamp.

4.11 ppb Level Detection by PID

4.11.1 Indoor Air Quality

The advent of ppb-level PIDs at the turn of the millennium has opened a new range of applications that are just now being characterized. One of these is the measurement of indoor air quality (IAQ). Outdoor air generally contains a few tens of ppb or less of organic vapors (excluding methane). Indoor air can contain tens to hundreds of ppb. Previously, these concentrations were in the noise level of most PIDs and often were canceled out during instrument zeroing. Current ppb-level PIDs have resolution down to a few ppb and can now distinguish the different levels of VOCs in indoor air.

General Indoor Air Quality (IAQ)

It has been shown that people in industrialized societies typically spend greater than 95% of the time indoors. The drive for HVAC (Heating, Ventilation and Air Conditioning) energy conservation has led to buildings with lower fresh air replacement rates and thus higher indoor contaminant concentrations (Godish, 1995). These two factors combined have led to a rise in “sick building syndrome” (SBS) complaints. According to the American Lung Association, the top five indoor air pollutants (in alphabetical order) are:

- Carbon monoxide
- Formaldehyde
- Microbial contaminants (mold, dust mites, etc.)
- Second-hand tobacco Smoke
- Volatile organic compounds (VOCs)

VOCs have a wide range of effects including, eye and respiratory tract irritation, headaches, dizziness, visual disorders and memory impairment. In addition to their negative health affects, high levels of indoor VOCs have even been blamed as a cause of increased computer failures in offices. VOCs in an indoor environment can come from a wide variety of sources. They can be found in or caused by, among others:

- Human occupancy (exhalation, smoking, perfumes, etc.)
- Carpets, fabrics, finishes and furniture
- Office equipment (copiers, printers, plastic materials)
- Cleaning and maintenance supplies
- Renovations (plasters, paints, etc.)
- Microbial activity
- Vocational Training shops and art rooms
- Pesticides

PIDs with ppb capability can detect most of the major indoor contaminants except CO and formaldehyde.

VOC Types

VOCs in indoor air include alkanes, aromatics, alcohols, aldehydes, esters, ketones, ethers, organic acids, and halogenated compounds. For example, a study by the Japanese Department of Health & Welfare (2000) identified the following VOCs:

Major Compounds Found	Average Conc.
Ethanol	~150 ppb
BTEX & Trimethylbenzenes	~50 ppb
p-Dichlorobenzene	~21 ppb
Acetone, Butyl acetate	~16 ppb
$C_8 - C_{12}$ Alkanes	~14 ppb
Limonene, α-Pinene	~7 ppb
Average Total	~280 ppb
Contaminated Building Total	~5,500 ppb

The average CF for the mixture above is calculated as 1.4, using the techniques described earlier. This CF suggests that an isobutylene calibration can be used to give an approximate measure of the total VOCs. Other indoor air mixtures have similar low estimated CFs, but not identical.

CO_2: An Indirect Measure of IAQ

ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) standards historically use CO_2 levels as a marker for indoor air quality. Levels of CO_2 in excess of 700 ppm over outdoor levels (typically 350 ppm), or usually over 1,000 ppm total, are an indication of “poor” indoor air quality. Such levels of CO_2 can indicate that air is not being refreshed enough so that CO_2 is built up from the exhaled breath of the building occupants. At the levels typically found in IAQ investigations, CO_2 is not a toxicity concern (OHSA PEL = 5,000 ppm), only a gross indicator of possible contamination from one of the five sources listed above. If the building is ventilated enough to reduce CO_2 levels, it often solves the IAQ problem by dilution. PIDs complement CO_2 monitors by providing a direct measurement of VOCs and help locate their sources.

tVOCs Correlate With SBS but not CO_2

tVOC concentration has been found to correlate with the prevalence of sick build syndrome (SBS) symptoms (Norback et al., 1990). However, CO_2 levels do not correlate with total VOCs (tVOCs) in IAQ measurements. In an informal study at a wide variety of sites worldwide, including offices, conference rooms, hotel rooms, homes, etc., tVOCs, as measured by a ppbRAE calibrated on an Isobutylene scale did not significantly correlate (r = 0.11) with CO_2 readings taken with a gas detection tube. This result reflects the fact that tVOCs and CO_2 come from different sources. Although human breath contains measureable levels of acetone and other hydrocarbons, these apparently do not contribute significantly to the tVOCs in indoor air. It is clear that CO_2 as a survey tool for IAQ assessments can (and does) miss elevated VOC levels.

Options for Measuring VOCs

For Indoor Air Quality assessment, one can use the following methods to measure VOCs (Volatile Organic Compounds) at low levels:

- **Adsorbent Media (e.g., activated carbon) followed by GC/MS Lab Analysis:** Accurate, specific, and highly sensitive, but are expensive and lack real-time feedback (1 day to 2 weeks).
- **Metal Oxide Sensors (MOS):** Low cost, but have limited sensitivity, slow response (minutes), respond to moisture, CO_2 and temperature changes.
- **PID:** Rapid, broad-band, highly sensitive with intermediate cost, but having limited selectivity.

Laboratory analyses by GC/MS are expensive and can take days or weeks to return from the lab. By the time that the results are available, a minor Indoor Air Quality problem can grow into a major incident. PIDs provide rapid, direct measurement of VOCs so that problems can be quickly identified and fixed. They can be used for both portable IAQ surveys and permanent IAQ subsystems of a building HVAC system.

In a Japanese study, Hara (2000) found "significant correlation" between samples tested with a TenaxTA-thermal desorption-GC/MS and a ppbRAE PID (Figure 4.11.1).

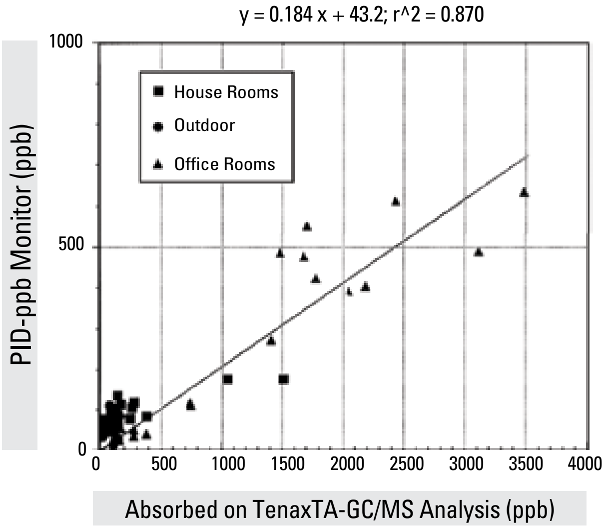

FIGURE 4.11.1. Correlation of ppbRAE response with laboratory GC/MS

tVOCs Concept

The urgency and complexity of the Sick Building Syndrome problem triggered a search for a practical (time/cost-effective) assessment method using tVOC levels as practical standards (Godish, 1995). Such a "total component" concept has already gained acceptance in other health related disciplines, such as TSP (Total Suspended Particles) and TdB (Total deciBel) as screening standards for particle and sound pollution, respectively. Pioneering work on using tVOC level as practical overall standard are not complete (Seifert, 1990; Molhave, 1991) and require further epidemiological research. Even so, tVOCs are emerging as a more direct approach of surveying indoor environments for contamination, and several organizations have recommended tVOC limits (Table 4.11.1).

TABLE 4.11.1 tVOC limit recommendations

Agency	Recommended Limit	
	µg/m³	ppb
Scandinavian Construction Materials Assoc.	300-1300	~75-325
Japan Ministry of Health	400-1000	~100-250
ASHRAE/ACGIH	<1000	~200
Texas General Services Commission	500	~100
Australian National Health & MRC	500	~100
Finnish Society of IAQ & Climate	200-600	~50-150
German Guideline (Seifert, 1999)	300	~75
Denmark Institute of Hygiene	250	~50

Global consensus has resulted in the emergence of preliminary guidelines for tVOC standards for IAQ (Australian NHMRC, 1993; Finnish Society of IAQ, 1995; Seifert, 1999; Hong Kong EPA, 1999; Japan Ministry of Health, 2000). Depending on location (home, school, etc.), recommended levels range from 200 to 1300 µg/m³, or about 50 to 325 ppb (toluene units) or approximately 100 to 650 ppb isobutylene units. By all accounts, the IAQ tVOC threshold for normal environments should not exceed 500 ppb (0.5 ppm) toluene units, which is equivalent to 1000 ppb (1 ppm) isobutylene equivalents. Field experience suggest the following guide for the use of PIDs to assess indoor environments:

- <100 ppb Isobutylene Units: normal outdoor air
- 100-400 ppb Isobutylene Units: normal indoor air
- 500+ ppb Isobutylene Units: indicates potential of IAQ contaminants

PIDs Identify Copier Odors

A school district had many older photocopiers in operation using liquid toner. The liquid toner had an exposure limit of 100 ppm. Heavy copier use released significant concentrations of toner vapor in the small copier rooms, where there was little ventilation. A PID was used to initially identify the problem and subsequently to help "tune" the new ventilation system to vent the copier odor away from workers.

Mold (mVOCs)

Molds release allergens, spores and mold particles that cause a variety of human health problems (Godish, 1995). A number of operators have reported that ppb-level PIDs can be used to indirectly determine the presence of molds and fungi on surfaces (Knobel, 2001; McGuinness, 2002). The major compounds released by molds can all be detected using a PID with a 10.6 eV lamp:

- Heptane, octane, nonane (CFs = 1 - 3)
- Benzene, toluene, styrene (CFs ~0.5)
- C_5 - C_{10} Alcohols (CFs 2 - 5)
- Octenols (Major odor compound) (CF ~1)
- C_8 - C_9 Ketones, acetophenone (CFs 0.5-1)
- C_4 - C_8 Acetates (CFs 2 - 5)

These compounds are not primarily of direct toxic concern because of their low concentrations, but act as indicators of the mold toxins. Concentrations are usually below 1,000 ppb immediately adjacent to a living mold culture. PID detection works well for locating "hot spots" for further testing, by categorizing the culture as dead or alive.

Recent studies on chemistry of VOCs in Indoor Air (secondary emission and reactive species) and the human health effects of microbial VOCs (Wolkoff, 2000; Salthammer, 2000; Hess, 2001) call for need of further research. Until complete understanding is reached, researchers (Seifert, 1999; Salthammer, 2000; Hara 2000) are refining a tVOC approach as a practical screening method for exposure risk assessment to total VOCs in working and living environments.

4.11.2 Other ppb-PID Applications

Electronics Manufacturing Clean Rooms

Many electronic components such as silicon wafers and flat panel displays suffer from poor yields when organic vapors deposit on them. A common contaminant is di-octylphthalate and other phthalate esters used as plasticizers in many synthetic materials. Conventional methods such as contact angle determinations require hours to accumulate enough surface deposits for accurate measurement. Continuous PID detection in the ppb range can be of use to monitor the level of VOC contamination in the clean room or test bay, or to screen materials before entry. To date, attempts to correlate PID response to product yields have met with partial success.

IVF Facilities

In contrast to *in vivo* embryos, which are protected within the body, *in vitro* fertilization allows potential exposure of the gametes and embryos to the ambient air. Sudden loss of fertility rates has been attributed to exposure to ambient VOCs and other contaminants (Cohen, *et. al,* 2002). Studies are currently underway to assess the ability of ppb-level PID response to warn IVF facilities of potentially harmful VOC levels in the incubators.

4.12 Measuring PID Correction Factors

This chapter gives practical details on how to measure correction factors (CFs) for new compounds. Correction factors are used to allow measurement of a large variety of compounds while calibrating with only a single standard gas, commonly isobutylene.

In general, CFs are independent of the type of instrument as long as the lamp chemistry and crystal are qualitatively the same. Often it is easiest to use a PID with a built-in pump. In this case it is preferable to use the same type of gas supply to both calibrate the PID and measure the unknown (i.e., using a gas bag –such as one made of Tedlar – for both or a pressurized cylinder for both), in order to nullify the effects of pressure or flow variations.

The matrix of the gas has important effects on the PID response. CFs listed in Appendix 3 are measured in dry air and apply only to this condition. High humidity generally decreases the response by 30% to 50%, while measurements in pure nitrogen may give roughly a 10% to 30% increase in signal over dry air when an 11.7 eV lamp is used. Therefore it is important to measure the calibration gas and the sample gas in the same matrix. A correction factor measured with room air may be more representative of the actual use conditions, but is a less convenient reference point.

Correction Factor Definition

The correction factor is defined as the response of the isobutylene (IBE) calibrated PID to an equal concentration (ppmv) of the compound of interest (Gas Y):

$$\text{CF} = \frac{\text{Instrument's IBE Reading * Gas Y Concentration (ppmv)}}{\text{IBE Concentration (ppmv) * Gas Y Instrument Response}}$$

Thus, the higher the correction factor, the lower the sensitivity to the compound of interest. To account for any drift during the measurements, one can make isobutylene measurements before and after the sample measurements and take the average response to the isobutylene standard. With a standard PID having a measurement range of 0.1 to a few thousand ppm, it is preferable to use a gas standard of at least 50 to 100 ppmv in order to be well above the noise level of the instrument.

CF Measurement Using Gas Standards

If a cylinder of standard gas in dry air is available, simply calibrate the instrument with isobutylene and then measure the gas standard in the same way. Use the equation above to calculate the CF.

CF Measurement For Liquid Samples

If the gas standard is to be prepared from a liquid sample, proceed as follows:

- Obtain a large vessel such as a 5-gallon glass water jug or a 1-gallon glass bottle, and calibrate its volume. One simple way to do this is to fill the bottle with water and measure the difference in weight with an accurate balance. The volume equals the weight in grams of the water. Thoroughly dry the vessel before use. Alternately, use a Tedlar gas bag. A 3-L or 5-L gas bag is convenient if a 1 μL syringe is avaliable for liquid injections.
- If a glass jug is used, place some small inert objects (e.g., PTFE pieces) inside or use a magnetic stirrer to aid in mixing. Bore two holes in the cap to insert the instrument influent and effluent sample lines. Use PTFE tubing for these lines to minimize losses due to adsorption.
- Flush the sample vessel with dry air. If a gas bag is used, fill the bag to a known volume using a high-volume syringe (e.g., 1.5 L) or a mass flow controller system. Do not fill the gas bag completely, to allow for easier mixing in a subsequent step.
- Calibrate the instrument with isobutylene or other reference gas.
- Using a microliter syringe, inject a volume of liquid calculated to give the desired concentration:

$$\text{Concentration (ppmv)} = \frac{\text{24.4 (L/mol) * Volume injected } (\mu\text{L}) \text{ * Liquid density (g/mL) * 106}}{\text{1000 (mg/g) * Molecular weight (g/mol) * Vessel volume (L)}}$$

- Allow time for the liquid to evaporate and mix. Assist mixing with magnetic stirring or agitation of the inert objects inside the closed vessel. If the compound is high-boiling, it may be necessary to apply heat (e.g., heat gun) to the vessel wall to speed evaporation. For a Tedlar bag, massage the bag gently to mix the air.
- Uncap the vessel and quickly insert the PID influent and effluent lines (recap or reseal it as quickly as possible), or attach the PID influent probe to the gas bag using a minimum of flexible tubing.
- Allow a minute or so for equilibration, record the sample measurement, and remove the sample lines. Calculate the CF using the equation above.
- Repeat a few more times at different concentrations to obtain a calibration curve and several CF values to average.

If desired, a known volume of liquid water can also be injected to achieve a desired relative humidity and CF under humid conditions. For such measurements it is important that the sensor be very clean, or else the readings may drift upward.

4.13 Dessicant Tubes for Removing Humidity During Continuous PID Measurements

Introduction

PID response can be reduced by high humidity (Figure 4.13.1). In addition, a false-positive reading can result if the sensor is dirty or if water condenses in the sample line and the sensor (Figure 4.13.2). For false positives, the preferred solution is good sensor cleanliness and instrument maintenance. The humidity filtering tubes described in this section address both types of humidity issues and allow more accurate measurements for many chemicals.

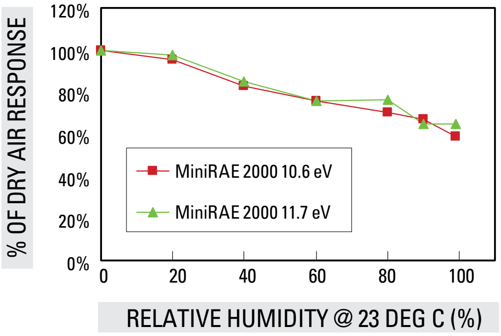

FIGURE 4.13.1. Response to test gas with clean sensor

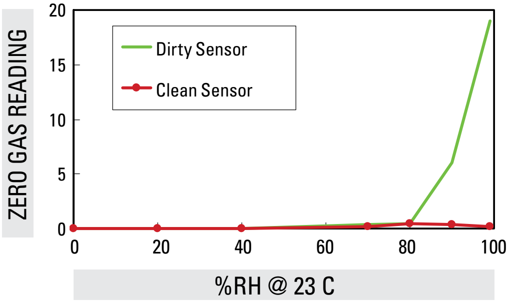

FIGURE 4.13.2. Response to zero gas vs. humidity on "dirty" vs "clean" sensor

High-humidity situations that can cause problems include:

- Soil vapor extraction systems
- Combustion stack gases
- Moving from a cool location to a hot, humid area, such as calibrating in an air-conditioned lab and moving outdoors.

Humidity Filtering II Tubes

The RAE Humidity Filtering II tube, attached to the inlet of a PID, can reduce humidity for the times listed in Table 4.13.1. The tube can be used while measuring organic vapors, with some precautions (see below).

TABLE 4.13.1. Run times for the Humidity Filtering II tubes.

T (°C)	T (°F)	RH (%)	10% RH Breakthrough time (min @ 500 mL/min)	20% RH Breakthrough time (min @ 500 mL/min)
45	113	100	12	14
		75	17	18
		50	35	>40
		25	>40	>40
40	104	100	18	20
		75	25	30
		50	40	>40
30	86	100	22	26
		75	28	32
		50	40	>40
20	68	100	23	~30
		75	34	>40
		50	40	>40

At extreme sample conditions such as 45°C (113°F), 100% RH and 500 mL/min flow rate, the humidity filtering tube can maintain <20% RH downstream for at least 14 minutes, as shown in Table 4.13.1. At this low RH, the effects shown in Figures 4.13.1 and 4.13.2 are almost completely removed. Under more typical conditions, the protection time can be expected to be much longer (see Table 4.13.1). A worst-case humidity breakthrough curve is shown in Figure 4.13.3.

The tubes are sealed and broken open immediately before use. They are intended for single use, but might be used for a few samples if within a short time or if the tube ends are capped. There is no color change in the tube, but a spent tube can be identified by a glassy gel formation on the solid absorbent. Caution: The tube contents may liquify after very long sampling or if a tube is left open in ambient air for several days. Dispose of tubes soon after use to avoid leakage or having liquid sucked into the instrument.

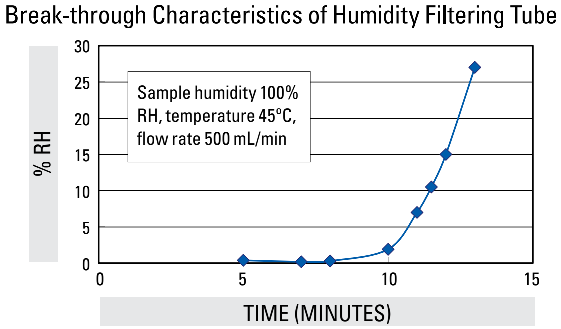

FIGURE 4.13.3. Worst-case breakthrough curve(Note: 45°C is higher than some instrument ratings)

Effect of Mist

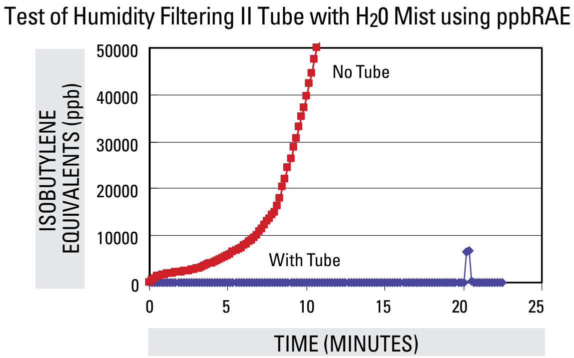

FIGURE 4.13.4. Test of humidity filtering II tube in the presence of water mist using a ppbRAE

The tubes can be used to measure VOCs in the presence of water mist. As shown in Figure 4.13.4, when mist is drawn into a PID with no tube, a false positive reading occurs similar to that in Figure 4.13.2. The Humidity Filtering II tube (diamonds on Fig. 4.13.4) prevents this and keeps the readings very close to ambient response for at least 20 minutes. The bump check at the end of the test with the tube with about 7 ppm (7,000 ppb) shows that the tube still responds to VOCs even when it is almost completely saturated with water.

Precautions

- Use the tube immediately after opening to avoid loss of absorption capacity.
- Use with caution when making PID measurements with the tube in place, as some compounds may be lost or exhibit delayed response (See Table 4.13.2). Contact manufacturer if the compound to be measured is not listed in Table 4.13.2 or the data sheet shipped with the tube.
- Use particular caution at low temperatures and low concentrations because adsorption losses can be relatively more severe. Extended sampling times may be required.
- If unexpectedly low readings are obtained, remove the tube and measure again to check for absorption losses. A rapid rise in a few seconds indicates VOC presence, while a slow rise suggests a false humidity response.
- Be sure that all connections are tight, or the sample gas will not be properly dried and may be diluted.
- The tube forms a gel and then liquid after excessive moisture has been drawn through. Remove the tube before such a gel fills the tube, or the liquid may be sucked into the PID, causing possible damage.
- It is still desirable to maintain a clean sensor to prevent drifting readings during measurements in high humidity.
- The contents of the tube are non-toxic and can be disposed of in a landfill. However, the tube may absorb some toxic compounds during use and become contaminated.

Effect on VOC Response

TABLE 4.13.2. Effect of Humidity Filtering II Tube on VOC response

Compound	Concentration (ppm)	T (°C)	^{t}90 (sec)	HCF*
Isobutylene	100	22	3	1
Isobutylene	10	0	5	1.17
Cyclohexane	10	22	3	1
Octane	100	22	3	1
Undecane	100	22	60	1.1
Benzene	5	22	3	1
Toluene	10	22	3	1
Xylenes	100	22	10	1.05
Styrene	50	22	10	1
Gasoline	100	22	15	1.05
Gasoline	10	22	15	1
Gasoline	10	0	28	1.6
Jet Fuel JP-5	10	22	65	1
Diesel Fuel	100	22	110	1.3
Vinyl Chloride	10	22	3	1
Trichloroethylene	10	22	3	1
Trichloroethylene	10	0	5	1.2
Perchloroethylene	10	22	4	1
Glutaraldehyde	10	22	NR** (480)	NR** (1.05)
Ethanol	1000	22	3	1
Ethanol	100	22	40	1
Isopropanol	10	22	90	1.15
Acetone	1000	22	3	1
Acetone	100	22	20	1
Acetone	10	22	80	1
Acetone	10	0	115	1.17
PGMEA (propylene glycol methyl ether acetate)	10	22	240	1.1
Phenol	20	22	150	1
Methyl methacrylate	10	22	150	1.05
Dimethyl sulfide	10	22	3	1
Ethyl mercaptan	10	22	4	1.05
Butyl mercaptan	10	22	5	1.05
Hydrogen sulfide	7	22	3	1
Ethylamine	high	22	NR*	NR*
Ammonia	50	22	NR*	NR*

*HCF = Humidity Correction Factor. Multiply by reading to get true concentration to correct for some loss. If calibrating with isobutylene, must also multiply by the Correction Factor in Appendix 3 to get true concentration. *

**Not recommended because of severe losses.

Note: The data in Table 4.13.2 were generated in dry air at about 22°C (72°C). Tests showed that 50% RH does not affect the response time to isobutylene, benzene, PGMEA, dimethyl sulfide, phenol, acetone or ethanol, but causes total loss of ammonia. 80% RH does not affect the response time of isobutylene, benzene, or H_2S. The response time for polar compounds is not significantly different between a fresh tube and a partially used tube up to 20% humidity breakthrough.

Other compounds: Volatile ethers, esters, haloalkanes, and olefins should not be affected except for possible slower response. Glycols, aldehydes and alcoholamines are expected to have slower and/or lower response. Acids and bases maybe lost on the tube. Compounds that hydrolyze easily, such as acetic anhydride, isocyanates or hexamethydisilazane may be lost.

The tubes can be used to measure a variety of volatile organic compounds (VOCs). The tubes have no effect on the response of nonpolar compounds such as isobutylene, hexane, benzene, and vinyl chloride but may affect the response time and efficiency of other compounds (see Table 4.13.2). Response time is faster at higher concentrations and higher temperature; therefore at low levels or low temperatures extra measurement time may be required.

Procedures

1. Insert the tip of the instrument probe into the smaller end of the tube adapter;
2. Break the two ends of a humidity filtering tube using the smaller side hole of the tube adapter;
3. Immediately insert one end (an arrow on the tube indicates the direction) of the open humidity filtering tube into the bigger end of the adapter;
4. Measure the sample gas;
5. Discard the used humidity filtering tube after the maximum time has elapsed as shown in Table 1, or when the tube becomes saturated as shown by a glassy gel formation.

If moving from a cool to a hot, humid environment:

4a. Run the instruments for at least 15 min with the humidity filtering in place to warm up the sample line and the instrument sensor. This is useful even if the sensor is clean and shows no humidity effect, in order to prevent liquid condensation.

4.14 Moisture Exchange Tubes for Humidity Control of Calibration and Test Gases

Introduction

As described earlier, many PIDs have a reduced response in humid air compared to the dry air that is often used for calibration. A convenient way to correct for this effect is to humidify the calibration gas to the same humidity as the air to be measured. Humidity corrections are usually negligible for PIDs below 40% RH at room temperature and for electrochemical sensors (although the latter may have transient responses to humidity changes).

Moisture Exchange Tube

Some PID manufacturers supply a 12" (30cm) or 24" (61cm) moisture exchange tube that can be connected directly between the calibration gas and instrument calibration cup or other connector. The tube consists of a membrane that allows moisture to pass, but retains organic vapors. Thus, moisture from ambient air enters the gas stream inside the tube without losing the organic compound. The tube works best for low-molecular-weight, nonpolar compounds like propane and isobutylene. Heavier compounds like toluene can be adsorbed onto the tube, and polar compounds such as alcohols, aldehydes, amines, and ketones can be lost by absorption into the moist pores of the tube.

In principle, the tube could also be used to dry a humid measurement stream, if the tube is jacketed with a dry air stream or other drying agent such as a silica gel pack. However, it is simpler to humidify the calibration gas than to dehumidify the measurement gas, because (1) the calibration gas can be selected to avoid adsorption losses on the tube, whereas the measurement gases may vary and unknown losses may occur, (2) the humidification needs to be performed only once during calibration, assuming the RH does not change significantly during measurement, and (3) large amounts of drying agents are typically required to provide drying capacity for more than a few minutes, creating handling and disposal complexity.

Operation

To operate the tube, first allow it to equilibrate for at least five minutes at the humidity desired for subsequent measurements. Then simply connect it between the calibration gas cylinder and the instrument inlet probe or calibration cup, and calibrate as usual (see Figure 4.14.1). The direction of flow through the tube is not important.

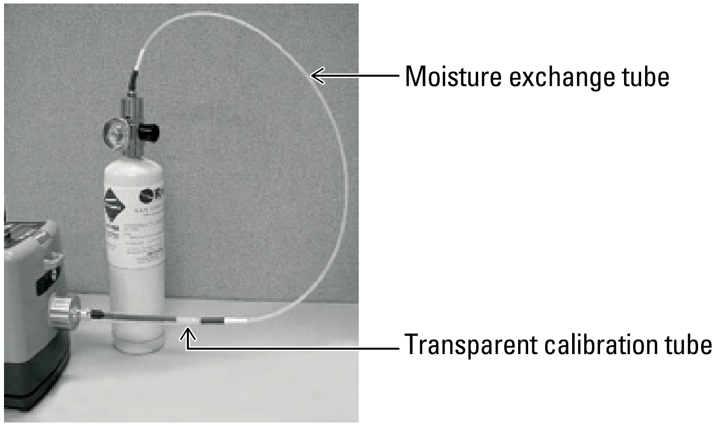

FIGURE 4.14.1. Connection of moisture exchange tube to gas cylinder and open calibration tube

Figure 4.14.2 shows the humidification efficiency as a function of gas flow rate. At 0.5 L/min., the tube is able to equilibrate a dry gas stream to ambient humidity for an extended period of at least 10 minutes. At 1.0 L/min., it is recommended that the calibration be completed within two minutes of starting the gas flow in order that the humidity not drop by more than 10% (by <5% RH at 50% RH).

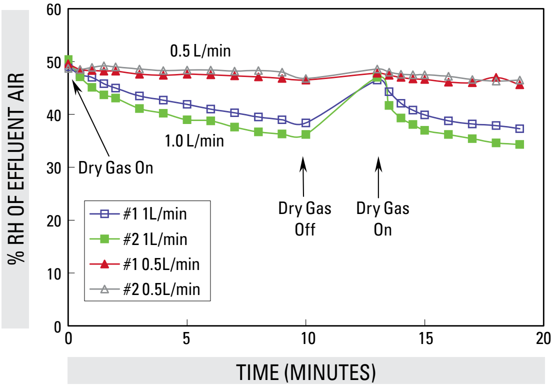

FIGURE 4.14.2. Humidification of dry air using a 24" moisture exchange tube

Figure 4.14.2 shows that when the dry gas is turned off, the tube recovers by absorbing moisture from the ambient air. The tube appears to have a reservoir of moisture in its pores that requires replenishment after being used to humidify a dry gas sample. Therefore, if multiple calibrations are to be performed with a single tube at 1 L/min. or more, at least five minutes' humidity equilibration time should be allowed with the gas off between calibrations. The tube is rated for flows up to 2 L/min., but will show reduced performance at this higher flow rate.

Other Matrix Gas Effects

The Moisture Exchange Tube will not compensate for other matrix gas effects, such as the suppression of PID signals due to methane, because methane does not pass through the membrane.

4.15 Chemical Warfare Agent Detection by PID

Introduction

Many chemical warfare agents (CWAs, i.e., nerve agents and related compounds) can be detected by PID. Table 4.14.1 lists some common agents and several of their physical properties and PID correction factors (CF).

Nerve Agent Response on PIDs

All the listed compounds can be detected with a 10.6 eV lamp, except phosgene, which requires an 11.7 eV lamp, and HCN and ClCN, which cannot be detected by PID. VX has inherent sensitivity, but it is too heavy a compound to get to the PID sensor and thus cannot be reliably measured. The 8-hr TWAs and IDLHs are extremely low, and the PID cannot measure nerve agents at these levels, except in a few cases with a ppbRAE. However, it can locate sources and detect the agents at levels well below those that are lethal in one minute (see LCt50 in Table 4.15.1). Compounds with low vapor pressures tend to respond more slowly on the PID, in some cases requiring several minutes. In the case of VX, the lethal dose is above its vapor pressure at room temperature; therefore, the lethal one-minute dose can be attained only if the air is hot or the chemical is sprayed as an aerosol. At the maximum room temperature concentration of VX, more than one minute of exposure is required for lethal effects.

Table 4.15.2 shows that many of the common decomposition products of aged warfare agents can also be detected by PID. These are often more volatile than the agent itself (especially for VX), and thus the products serve as a more easily detectable surrogate than the original material.

TABLE 4.15.1. Properties of chemical warfare agents and simulants including detectability by PID

Compound	Structure	m.w.	Lamp (eV)	CF	8-hr TWA (mg/m³) (WPL)	8-hr TWA (ppbv)	IDLH (ppbv)	LCt50 (ppmv-min)	Vapor Press. (ppmv)
Blood Agents									
Arsine (SA)	AsH_3	78	10.6	1.9	0.16	0.05	3,000		Gas
Hydrogen Cyanide (AC)	HCN	27	ND**	ND**	11	10,000	50,000	270	Gas
Cyanogen Chloride (CK)	ClCN	61.5	ND**	ND**	0.6 Cξ	300 Cξ			Gas
Blister Agents									
Lewisite (L1)	$ClCH{=}CHAsCl_2$	207	10.6	~1*	0.003	0.35		140	460
Mustard (H or HD)	$S(EtCl)_2$	159	10.6	0.6	0.0004	0.061	0.11	>230	95
N Mustard (HN-1)	$N(Et)(EtCl)_2$	172	10.6	~1*					320
HT	60% HD & 40% T $(O(Et.S.EtCl)_2)$		See HD; T part is non-volatile and poses low						
Phosgene Oxime (CX)	$HON{=}CCl_2$	114	11.7	~5*				685	15000
Choking Agent									
Phosgene (CG)	$O{=}CCl_2$	99	11.7	8.5	0.4	100	2,000	790	Gas
Nerve Agents									
Sarin (GB)	O=PF(Me)(OiPr)	140	10.6	~10	0.0001	0.017	17	12	3800
Soman (GD)	O=PF(Me)(OCH(Me)(tBu))	182	10.6	~3*	0.00003	0.004	6.7	9	530
Tabun (GA)	$O{=}P(CN)(OEt)(NMe_2)$	162	10.6	0.8	0.0001	0.015	15	20	92
VX	$O{=}P(Me)(OEt)(S.Et.N(iPr)_2)$	267	10.6	~0.5*	0.00001	0.00091	0.27	2.7	0.92
GF	O=PF(Me)(O-Cyclohex)	180	10.6	~3*	0.00003	0.004	6.8		79
Simulants									
DMMP	$O{=}P(Me)(OMe)_2$	124	10.6	4.3					
Triethyl phosphate	$O{=}P(OEt)_3$	182	10.6	3.1					
Methyl salicylate	$2\text{-}(HO)C_6H_4CO_2Me$	152	10.6	0.9					

** Estimated value. ** ND = Not Detectable by PID. ξC = ceiling value.*

TABLE 4.15.2. Estimated response of warfare agent degradation products by PID

Agent & Products	CAS No.	IE* (eV)	CF Estimate 10.6 eV Lamp	CF Estimate 11.7 eV Lamp
Lewisite(L1)	541-25-3	?	~1	~1
2-Chlorovinyl arsenic oxide	123089-28-1	?	~1	~1
2-Chlorovinylarsonic acid	64038-44-4	?	~1	~1
Dihydroxy-2-chlorovinylarsine	85090-33-1	?	~1	~1
Sodium arsenite	11137-68-1		ND	ND
Acetylene	74-86-2	11.4	ND	2
Hydrogen chloride	7647-01-0	12.8	ND	ND
Arsenic trichloride		10.55	~10	~1
Mustard (HD)	505-60-2		0.6	~0.5
1,4-Dithiane	505-29-3	~8.5	~0.5	~0.4
1,4-Oxathiane	15980-15-1	~9	~0.5	~0.4
2-Chloroethyl vinyl sulfide	81142-02-1	~9	~1	~1
2-Chloroethyl vinyl sulfoxide	40709-82-8	~10	~1	~1
Bis-2(bis(2-hydroxyethyl)-sulfonium ethyl)		?	?	?
Bis (2-hydroxyethyl)-2-(2-chloroethylthio) ethyl sulfonium	64036-91-5	?	?	?
Divinyl sulfoxide	1115-15-7	~10	~1	~1
Hemi Mustard	693-30-1		~1	~1
Mustard sulfone	471-03-4	~10	~5	~1
Mustard sulfoxide	5819-08-9	~8.8	~1.5	~1
Thiodiglycol	111-48-8	<9	~1	~1

** IE = Ionization Energy, the minimum lamp energy needed to detect the compound by PID*

Agent & Products	CAS No.	IE* (eV)	CF Estimate 10.6 eV Lamp	CF Estimate 11.7 eV Lamp
Mustard (HD) (continued)				
Dichloroethane	73-34-3	11.06	ND	0.6
1,1,2,2-Tetrachloroethane	79-34-5	11.1	ND	0.6
Tetrachloroethylene (PCE)	127-18-4	9.32	0.57	0.31
Trichloroethylene (TCE)	79-01-6	9.45	0.54	0.43
1,3-Butadiene	106-99-0	9.07	0.85	1.1
2-Butene	107-01-7	~9.6	~1	~1
Vinyl chloride	75-01-4	9.99	2	0.6
Phosgene (CG)	75-44-5	11.55	ND	8.5
Carbon dioxide	124-38-9	13.8	ND	ND
Hydrochloric acid	7647-01-0	12.8	ND	ND
PhosgeneOxime(CX)		~11.5	ND	~5
Carbon dioxide	124-38-9	13.8	ND	ND
Hydrochloric acid	7647-01-0	12.8	ND	ND
Hydroxylamine	7803-49-8	~10.0	~10	~3
Sarin (GB)	107-44-8	<10.6	3	~1
Diisopropyl methylphosphonate (DIMP)	1445-75-6	<10.6	~3	~1
Hydrogen fluoride	7664-39-3	16	ND	ND
Isopropanol (IPA)	67-63-0	10.12	6	2.7
Isopropyl fluoride	420-26-8	11.1	ND	~3

** IE = Ionization Energy, the minimum lamp energy needed to detect the compound by PID*

Agent & Products	CAS No.	IE* (eV)	CF Estimate 10.6 eV Lamp	CF Estimate 11.7 eV Lamp
Isopropyl methylphosphonic acid (IMPA)	1832-54-8	?	?	?
Sarin (GB)				
Methylphosphonofluoridic acid	1511-67-7	?	?	?
Methyl phosphonic acid	993-13-3	?	?	?
Soman (GD)	96-64-0	<10.6	~3	~1
Methyl phosphonic acid	993-13-3	?	?	?
Pinacolyl methylphosphonic acid	616-52-4	<10.6	~3	~1
Tabun (GA)	77-81-6	?	~0.8	~0.6
Dimethylphosphoramidate	33876-51-6	?	~2	~1
Dimethyl phosphoramideocyanidate	63917-41-9	?	~2	~1
O-ethyl N,N-dimethylphosphoramidate		?	~2	~1
O-ethyl phosphorocyanidate	23852-43-9	?	?	?
VX	50782-69-9	?	~0.5	~0.4
Bis(2-diisopropylaminoethyl) disulfide	65332-44-7	?	~0.5	~0.4
Bis(2-diisopropylaminoethyl) sulfide	110501-56-9	?	~0.5	~0.4
Diisopropylaminoethanol	96-80-0	?	~0.5	~0.4
Diisopropylaminoethyl mercaptan	1308490	?	~0.5	~0.4
Diisopropylaminoethyl methylphosphonic acid	73207-98-4	?	~0.5	~0.4
Ethyl methylphosphonothioic acid isopropyl	18005-40-8	?	?	?
Methyl phosphonic acid	993-13-3	?	?	?
S-(Diisopropylaminoethyl) methylphosphonothioate	73207-98-4	?	~0.5	~0.4

** IE = Ionization Energy, the minimum lamp energy needed to detect the compound by PID*

4.16 Heat Transfer Fluids by PID

Introduction

Heat transfer fluids are used in many processing applications to carry heat to or from a source, such as a boiler, or a target process, such as a chemical-processing vessel. While hardly volatile at room temperature, some heat transfer fluids contain highly toxic substances that can become volatile when heated. Heat transfer fluids typically are contained in a closed-loop system so that they do not come in contact with personnel or the process. However, leaks can and do occur. Because of the high toxicity of some heat transfer fluids, it is desirable to measure them for leak detection and to assure that levels are low enough to allow workers to operate safely. PIDs are very sensitive to the compounds that make up many heat transfer fluids and offer an effective means of providing real-time measurement for worker health and safety and for leak detection.

Example 1 – DowTherm® A

DowTherm® A, commonly referred to as DowTherm® or Therminol®*, is made up of 73% Diphenyl Oxide (Phenyl Ether) and 27% Diphenyl (Biphenyl). Both of these constituents have relatively low exposure limits:

TABLE 4.16.1. Dowtherm® A toxicity

Threshold	Diphenyl Oxide	Biphenyl	DowTherm® A (total)
Odor	0.001-0.01 ppm	0.0095 ppm	<0.001 ppm
PEL (OSHA)	1 ppm (7 mg/m^3)	0.2 ppm (1 mg/m^3)	0.48 ppm
IDLH	100 ppm	20 ppm (100 mg/m^3)	48 ppm

The TLV for the DowTherm® A mixture is calculated by the formula given in Chapter 3.1.6:

$$TLV_{mix} = 1 / (X_1/TLV_1 + X_2/TLV_2)$$

where X_i, TLV_i, are the mole fraction (percentage) of total VOCs, TLVs, of the individual components, respectively.

Therefore, the calculated limits for DowTherm® A are:

$$\text{TLV} = 1 / (0.73/1 + 0.27/0.2) = 0.48$$
$$\text{IDLH} = 1 / (0.73/100 + 0.27/20) = 48$$

DowTherm® A has a characteristic "sweet" odor. It can be readily detected by smell well below its exposure limit but cannot be quantitated this way. Grab samples and lab analysis provide accuracy, but they take too long for the results. PIDs provide rapid measurements of DowTherm® A that allow workers to immediately make PPE decisions.

Measuring at Lower Temperatures

DowTherm® A's high boiling temperature of 495°F (257°C) and vapor pressure of 0.025 mm Hg at 25°C means that at normal ambient temperatures, few DowTherm® A vapors are produced. For example, sampling the vapors above a bucket of DowTherm® A well below room temperature (41°F, 5°C) should produce little or no reading on a PID. At room temperature (68°F, 20°C) the saturated air space above a bucket of DowTherm® A could be expected to contain 33 ppm. However, because DowTherm® A is used as a heat transfer fluid, it is often used at elevated temperatures that can produce significant vapors.

Calibrating a PID to DowTherm®

Because DowTherm® A has a high boiling point, it is impossible to make a compressed gas standard for it, and a surrogate calibration with isobutylene is recommended. Because the TLV is low, a 10 ppm isobutylene calibration is preferred over 100 ppm. A CF of 0.4 is often appropriate for a 10.6 eV lamp (check with manufacturer).

Unusual Characteristics of DowTherm® A

DowTherm® A has a high boiling point and tends to adsorb to surfaces and be absorbed by some materials. Therefore, when using a PID to sample for leaks, it is recommended that the probe be extended by slipping a drinking straw over it. If liquid DowTherm® A comes into contact with the straw, the straw can be thrown away. If DowTherm® A comes into contact with the sample probe of a PID, it must be thoroughly solvent cleaned before further sampling.

Never Use Tygon® Tubing with DowTherm® A

Because Tygon® sample tubing quickly absorbs heat transfer fluids, it should never be used when sampling for them. Long sample lines can cause heat transfer fluid vapors to condense; therefore, it is recommended that all sampling be conducted without additional sampling hose. In-line filters can also promote condensation of heat transfer fluid, so they should be eliminated or reduced.

Sampling High Concentrations of DowTherm® A

When DowTherm® A can be seen in plumes, this is an indication that high concentrations (25 to 100 ppm) are present, which can lead to condensation in the sampling train. If the PID does not clear with five minutes' exposure to fresh air, then clean the components of the PID using a methanol wash in the following order:

1. Sample probe
2. Filters (replace them if they cannot be cleaned)
3. Sensor and PID lamp

*** Note:** Therminol® is a registered Trademark of Solutia, Inc.

4.17 Additional Portable PID Applications

Introduction

Many other PID applications are known. A few key ones are described below.

Aircraft Wing Tank Entry

Aircraft maintenance requires workers to enter confined spaces that contain jet fuel vapors, which need to be monitored for both explosive and toxic levels. LEL sensors used in conventional confined space monitors have poor sensitivity to jet fuel vapors. Workers can often see or smell jet fuel when in a wing tank, without the meter detecting it. The LEL of jet fuels is on the order of 0.8 vol.% (8000 ppm), and therefore it can easily be detected by PID even at the 10% LEL level (800 ppm). Unlike LEL sensors, PIDs are not poisoned by chemicals commonly used in aircraft maintenance, including low-ppm levels of silicon compounds found in lubricants, adhesives, silicone rubbers (including caulking and sealant compounds), and others. Chlorinated hydrocarbons are another common group of chemicals that degrade LEL sensor performance. They are frequently found in solvents, including degreasing and cleaning agents used in and around aircraft.

Turpentine in Pulp Mills

The pulping process produces two major products: (1) paper and (2) chemicals for applications as diverse as paints and foods. Turpentine is one of these chemicals; it has a low LEL of 0.8% by volume (8000 ppm) and an OSHA PEL of 100 ppm. Because of its relatively high molecular weight, turpentine's vapors are difficult to measure with a conventional LEL sensor in the combustible range, and are undetectable in the PEL range. PIDs provide a simple way to measure both PEL and LEL levels. In addition, PIDs are not subject to the poisoning by sulfur compounds often present, as catalytic bead LEL sensors are. Turpentine is especially sensitive, having a CF of only 0.3 on a 10.6 eV lamp.

Marine Applications

A variety of instruments are needed aboard ships, depending on the tank and vessel type. The three main considerations are usually to monitor for enough oxygen, explosive vapors, and toxic gases based on the hygiene limits. Oxygen and explosive vapors are done with standard electrochemical and LEL sensors. The instrument for toxic gases depends of the tank and vessel type.

Cargo tanks can carry a wide variety of liquids, depending on the vessel's IMO (International Marine Organization) classification. There are three levels of IMO classification. IMO class 1 covers the least corrosive or toxic liquids while IMO class 3 covers the most corrosive or toxic liquids.

IMO 1 – Transport of vegetable oils
  – LEL and O_2 sensors recommended
IMO 2 – Transport of crude oil and oil products
  – LEL, O_2, and H_2S sensors recommended
IMO 3 – Transport of various chemicals (BTEX to MTBE)
  – Colorimetric detection tubes are often used for entry into these spaces, but a portable PID monitor is often more cost efficient and provides greater safety in the form of continuous monitoring.

Slup Tanks are normally used for carrying water to clean the cargo tanks. Entry into these spaces requires at least an O_2 sensor. Slup tanks are sometimes also approved for use as additional cargo tanks.

Fuels Tanks for the transport of fuel. Entry into these tanks requires a gas monitor with at least LEL and O_2 sensors.

Ballast Tanks use seawater to aid navigation. The seawater is drawn from the harbor and is usually full of plants, mussels, and even fish that start to rot inside the tank. LEL, O_2, and H_2S sensors are standard for entry into these spaces.

Container Vessels account for more than 3,000 of the marine industry's vessels. These vessels require the standard LEL and O_2 sensors to clean, repair, and inspect the fuel and ballast tanks. There are fumigants (methyl bromide), coolants (ammonia), and many additional applications on container vessels that require a monitor capable of monitoring both the basics (LEL, O_2, and H_2S) and a broad range of chemicals (PID).

Seaport Inspections often require detecting VOC levels before unloading is allowed, or loading new materials in cleaned tanks is permitted.

4.18 Common Fixed PID Applications

Introduction

Fixed-system PIDs can be used to monitor VOCs on a continuous, 24-hour basis. Continuous measurement can be useful for both industrial hygiene monitoring of VOCs and for process control to increase productivity and efficiency. Typically, such PIDs must be hard-wired to a power supply to allow intrinsically safe (from causing explosion) operation. Portable instruments can be used for the same function, but lose their intrinsically safe rating when plugged into a charger, as is necessary for long-term operation. Therefore, when a portable PID is used in a fixed application where intrinsic safety is required, it must either be contained in an explosion-proof housing or used remotely from the hazardous area with extension tubing reaching to the sampling location.

Fixed PIDs are best suited for operation with long-life lamps such as 9.8 eV and 10.6 eV lamps. Because of their relatively short life, 11.7 eV lamps are generally not recommended for continuous operation. In-line filters are recommended to extend the calibration intervals.

Paint Booths

Paints may contain a variety of solvents including methyl ethyl ketone (MEK) and simple hydrocarbons, which are easily detected with a PID. During spray painting and paint drying, these solvents are emitted to the air. Large operations such as in the automobile and aviation industries may require one monitor for each paint booth.

Printing Processes

Printing and silkscreening processes use solvents like toluene to dissolve and apply inks. These solvents are then emitted to the atmosphere during drying. Fixed PIDs have been successfully installed in the effluent ducting to determine the drying process' completion.

Degreasing Operations

Vapor degreasers employ large amounts of solvents such as perchloroethylene (PCE) to remove cutting oils and greases used in machining and assembling metal parts. Major applications include automobile and aviation industries.

Indoor Air Quality Monitoring

PIDs can be used for continuous indoor air quality (IAQ) monitoring, including non-manufacturing facilities. VOC sources include those from newly installed carpets or painted surfaces or where air intakes are located near potential outside sources. One example is an airport in which the incoming air is potentially contaminated with jet fuels. In some cases, the PID is packaged with other IAQ monitors to provide complete IAQ monitoring systems.

Air Treatment System Performance

Many fixed PIDs have been successfully installed to monitor the performance of treatment systems, such as activated carbon or thermal oxidation. Contaminated air streams arise from manufacturing operations and environmental clean-up activities, such as soil vapor extraction. Common treatment systems include activated carbon adsorption systems, catalytic oxidizers, and liquid scrubbers. In some cases, a PID is placed both before and after the treatment system to determine treatment effectiveness. PIDs can also be used to measure VOC emissions from incinerators, if the gases are allowed to cool below 60°C before entering the unit.

Refrigeration

Ammonia is frequently used as a refrigerant, especially in the food industry. Ammonia can be measured with a PID, which has advantages over electrochemical sensors in that the response is much faster and there are no overload concerns. Some of the newer Freon replacements are simple hydrocarbons that may also be measureable with a PID.

4.19 Pre-filter Applications

Silazanes

Semiconductor manufacturers often use hexamethyldisilazane and similar compounds as coating surfaces. When a PID is used, silicate deposits may form on the lamp and sensor, reducing sensitivity to other target vapors such as photoresists. Because of its highly reactive nature, hexamethyldisilazane can be removed selectively using cellulose filters. Such filtering has proved useful in at least one semiconductor plant even for long-term monitoring using a fixed PID.

UltraRAE

The UltraRAE uses an absorbent filter tube to remove interferences before PID measurement. Filter tubes are available to detect benzene in gasoline, butadiene in polymer manufacturing processes, and halocarbons such as methylene chloride in mixtures with common organic solvents. Readings are not continuous, as the co-present vapors consume the filter media. Time for one sample is on the order of 30 to 90 seconds.

The UltraRAE can also be operated in VOC mode for continuous measurements. Thus, it is a powerful tool for continuously monitoring general VOCs until a significant concentration is reached, followed by specific determination of a particularly toxic component of the mixture. Figure 4.19.1 shows the apparent response to low levels of butadiene in the presence of 100 ppm n-hexane using an UltraRAE.

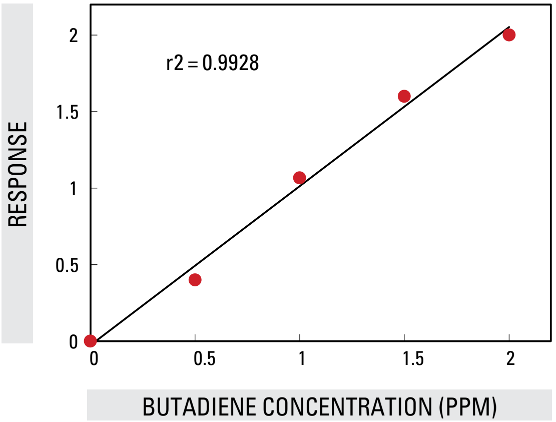

FIGURE 4.19.1. UltraRAE butadiene response in the presence of 100 ppm hexane using a RAE-Sep butadiene tube and 9.8 eV lamp

Table 4.19.1 lists the apparent response to a variety of compounds that may interfere in benzene measurements. Thus, appropriate filtering can provide selective measurements in the presence of large excesses of other responding compounds in certain applications.

TABLE 4.19.1. UltraRAE response to potential benzene interferences using RAE-Sep benzene tube with 9.8 Ev lamp

Compound	Test Concentration (ppmv)*	Apparent Benzene Response
Toluene	400	0.1
p-Xylene	200	0.0
Ethylbenzene	200	0.0
Styrene	100	0.0
Nitrobenzene	100	0.0
Phenol	100#	0.0
Chlorobenzene	20	2.5
Dichlorobenzene	50	0.1
Hydrogen Sulfide	150	0.0
Methane	25,000**	0.0
Propane	1000	0.0
Isobutane	100	0.0
Isobutylene	500	0.0
n-Pentane	1,500	0.0
1,3-Butadiene	300	0.0
n-Hexane	100#	0.0
Cyclohexane	10	0.4
n-Octane	300	0.1
β-Pinene	50	0.0
Ethanol	50	0.0
Isopropanol	100	0.0
Acetone	100	0.0
Cyclohexanone	200	0.0
Tetrahydrofuran	100	0.0
Ethyl acetate	100	0.0
Acrylonitrile	100	0.0
Epichlorohydrin	100	0.0
Trichloroethylene	100	66
Perchloroethylene	50	38

*Not necessarily the maximum allowable concentration.

**No effect on tube capacity. Propane and higher hydrocarbons do affect capacity.

#Higher concentrations may cause a reduced benzene response.

5. APPENDICES

5.1 Appendix 1: References

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5.2 Appendix 2. Glossary

ACGIH: American Conference of Governmental Industrial Hygienists. A non-regulatory professional society of hygienists that provides recommendations for human exposure limits, among other things.

Aldehydes: Compounds that contain a carbon bonded to a hydrogen, another carbon, and double bonded to an oxygen atom.

Aliphatics: Compounds containing only carbon and hydrogen and no double or triple bonds.

Alkanes: see Aliphatics.

Alkyl Halides: Aliphatics containing halogens.

Amines: Compounds with an $-NH_2$ group with alkalinity and corrosivity similar to ammonia.

Aromatics: Cyclic compounds that contain double bonds and have special stability, and sensitivity to PIDs. A common example is benzene, comprising 6 carbons and 6 hydrogens, but may contain nitrogen, oxygen, or other heteroatoms.

BTEX: Benzene, toluene, ethylbenzene, and xylenes. Aromatic hydrocarbons, usually as part of a fuel mixture.

CF: Correction Factor. This value is multiplied by the observed reading when the PID is calibrated to a surrogate gas (e.g., isobutylene), to obtain the true concentration of the compound measured. Higher values mean lower sensitivity of the compound.

Ceiling: Worker exposure concentration that should not be exceeded during any part of the working period.

CFC: Chlorofluorocarbon containing no hydrogen atoms. Condensable gas compounds commonly used as refrigerants, but causing potential damage to the ozone layer.

EC Sensor: Electrochemical sensor.

Ethers: Organic compounds containing an oxygen atom bonded to two carbon atoms.

FID: Flame Ionization Detector. Responds to a broad range of combustible compounds including methane, but not CO or CO_2.

GC: Gas Chromatography.

GAC: Granular Activated Carbon. Used as an adsorbent to collect vapor components for subsequent analysis.

Halogens: Compounds containing fluorine, chlorine, bromine or iodine.

HVAC: Heating, Ventilation and Air Conditioning.

HCFC: Hydrogen-containing chlorofluorocarbon. Condensible gas compounds commonly used as refrigerants, causing less potential damage to the stratospheric ozone layer than CFCs.

$h\nu$ Symbol for a photon of unspecified energy. The photon energy is the product of Planck's constant h (6.63 x 10^{-34} joule-seconds) and the frequency ν in cycles per second.

Hydrocarbons: Compounds containing carbon and hydrogen.

IAQ: Indoor Air Quality.

IBE: Isobutylene, a common calibration gas for PIDs.

IDLH: Immediately Dangerous to Life and Health.

IE or IP: Ionization Energy or Ionization Potential. More correctly termed ionization energy and commonly given in units of electron-volts (eV). This is the lowest photon energy capable of ejecting an electron from a target molecule.

Inorganics: Compounds that contain fewer than two carbon atoms.

ISEA: International Safety Equipment Association.

Ketones: Organic compounds containing a carbon bonded to two other carbons and a double-bonded oxygen.

LC50: The concentration of a gas or vapor that causes a 50% chance of death within a defined exposure time (used herein as 1 minute).

LED: Light-emitting diode. Commonly used for PID alarms.

LEL or LFL: Lower Explosive Limit or Lower Flammability Limit. The lowest vapor concentration that will sustain a flame when ignited in air.

Li-ion: Lithium ion battery. High power density batteries not subject to memory effects.

MAK: Exposure limits defined by the Federal Republic of Germany.

MDI: 4,4'-Methylenebis(phenyl isocyanate), an agent used in polymer manufacturing.

MEK: Methyl ethyl ketone (i.e., 2-butanone).

MIBK: Methyl isobutyl ketone.

MSDS: Material Safety Data Sheet.

NFPA: National Fire Protection Association.

NiCd: Nickel-Cadmium battery. Medium power density batteries that exhibit a memory effect when recharged before complete discharge.

NiMH: Nickel-Metal Hydride battery.

NIOSH: National Institute for Occupational Safety and Health. A U.S. government agency making non-enforceable exposure limit recommendations (RELs).

Olefins: Hydrocarbons containing double bonds.

Organics: Compounds containing more than one carbon atom and typically containing hydrogen.

OSHA: Occupational Safety and Health Administration, a U.S. government agency defining enforceable exposure limits (PELs).

PAH: Polycyclic Aromatic Hydrocarbons. Carcinogenic compounds formed in combustion processes, especially on fly-ash.

PC: Personal computer.

PEL: An OSHA-defined permissible exposure limit, legally enforceable.

PFA: A derivative of Teflon having perfluoroalkoxy copolymer blocks and similar chemical properties.

PGME: Propylene glycol monomethyl ether.

PGMEA: Propylene glycol methyl ether acetate.

PID: Photoionization Detector.

ppb or ppbv: Parts-per-billion or parts-per-billion by volume (used synonymously in this work).

PPE: Personal Protective Equipment

ppm or ppmv: Parts-per-million or parts-per-million by volume (used synonymously in this work).

PTFE: Teflon or polytetrafluoroethane, a chemically inert polymer.

REL: Recommended Exposure Limit as suggested by NIOSH.

RF: Response Factor. The reading is divided by the RF to obtain the true concentration. Inverse of the CF.

SCBA: Self-Contained Breathing Apparatus.

SBS: Sick Building Syndrome. Used to describe a variety of indoor-related symptoms of which the cause is not clearly identified.

STEL: Short Term Exposure Limit. The maximum allowable exposure concentration averaged over a 15-minute period for at most 4 times per 8-hour day separated by at least one hour exposure below the TWA.

Sulfides: Organic compounds containing a sulfur atom bonded to two carbon atoms.

TLV: Threshold Limit Value. An ACGIH-recommended exposure limit (not legally enforceable).

TVOCs: Total VOCs, typically used as an IAQ parameter.

TWA: Time Weighted Average. A cumulative exposure dose, generally over an 8-hour period. TWA is calculated as the average concentration times the fraction of the (8-hr) time period elapsed.

VOC: Volatile Organic Compound. In general use this acronym refers to all organic compounds that have significant vapor pressure. The US EPA also defines VOCs according to their tropospheric ozone-forming potential and includes most carbon-hydrogen containing compounds but excludes such compounds as methane, ethane, acetone, methyl acetate, methylene chloride, and most CFCs and HCFCs.

VOC*: VOC in a short-lived, excited electronic state.

VOC^+: Ionized VOC with a positive charge.

5.3 Appendix 3: Correction Factors, Ionization Energies and Exposure Limits

See Table at www.raesystems.com: Technical Note TN-106

5.4 Appendix 4: Sample Calculation for Gas Mixture CFs

Examples of Automatic Calculation of Correction Factors, TLVs and Alarm Limits for Mixtures

(Calculations performed using Excel version of this database, available on request)

Example 1: Solvent Mixture

Compound	CF 9.8 eV	CF 10.6 eV	CF 11.7eV	Mole Fraction	Conc. ppm	TLV-TWA ppm	STEL ppm
Benzene	0.55	0.53	0.6	0.01	1	0.5	2.5
Toluene	0.54	0.5	0.51	0.06	10	50	150
Hexane, n-	300	4.3	0.54	0.06	10	50	150
Heptane, n-	45	2.8	0.6	0.28	50	400	500
Styrene	0.45	0.4	0.42	0.06	10	20	40
Acetone	1.2	1.1	1.4	0.28	50	750	1000
Isopropanol	500	6	2.7	0.28	50	400	500
None	1	1	1	0	0	1	
Mixture value:	2.1	1.5	0.89	1	181 ppm	56 ppm	172 ppm
TLV alarm setpoint when calibrated to isobutylene:	26 ppm	37 ppm	62 ppm				
STEL alarm setpoint, when calibrated to isobutylene:	86 ppm	115 ppm	193 ppm				

Example 2: Paint Solvents

Compound	CF 10.6 eV	CF 11.7eV	Mole Fraction	Conc. ppm	TLV-TWA ppm
Formaldehyde	NR	1.6	0.006	0.5	~0.3
Toluene	0.50	0.50	0.015	1.25	50
PGMEA	1.0	0.82	0.015	1.25	~50
Isobutanol	3.8	1.5	0.14	12.5	50
Xylene, p-	0.39	0.38	0.23	20	100
Butyl acetate, n-	2.6	~1.5	0.59	50	150
Mixture value:	1.1	0.87	1.00	86 ppm	36 ppm
TLV alarm setpoint when calibrated to isobutylene:	33 ppm	42 ppm			

5.5 Appendix 5: Mixture Alarm Limits

Note: OSHA Z-listed chemicals are in italics.

Compound	CF @10.6 eV	OSHA PEL (ppm)	IBE-Equiv. Alarm
Acetone	1.1	1000	909
Petroleum distillates	0.71	500	704
Stoddard Solvent	0.71	500	704
Isopropyl ether	0.80	500	625
Methylcyclohexane	0.97	500	515
Dichloroethene, t-1,2-	0.45	200	444
Toluene	*0.50*	*200*	*400*
Cyclohexene	*0.80*	*300*	*375*
Diethyl ether	*1.1*	*400*	*364*
Gasoline #1	0.85	300	353
Pinene, α-	0.31	100	323
Gasoline #2, 92 octane	1.0	300	300
Turpentine	*0.35*	*100*	*286*
Octane, n-	*1.8*	*500*	*278*
Pinene, β-	0.37	100	270
Xylene, p-	*0.39*	*100*	*256*
Dichloroethene, c-1,2-	0.8	200	250
Styrene	*0.40*	*100*	*250*
Methyl ethyl ketone	*0.86*	*200*	*233*
Xylene, m-	*0.44*	*100*	*227*
Xylene, o-	*0.46*	*100*	*217*
Methyl propyl ketone	*0.93*	*200*	*215*
Cyclohexane	*1.4*	*300*	*214*
Xylenes (o-, m-, p-)	*0.49*	*100*	*204*
Methyl styrene (alpha-)	*0.50*	*100*	*200*
Ethyl benzene	*0.52*	*100*	*192*
Chlorobenzene	*0.40*	*75*	*187*
Heptane, n-	*2.8*	*500*	*179*
Ethoxyethanol (2-)	*1.3*	*200*	*154*
Piperylene, isomer mix	0.69	100	145
Nonane	1.4	200	143
Ethyl silicate	*0.71*	*100*	*141*
Methyl isobutyl ketone	*0.80*	*100*	*125*
Pentane	*8.4*	*1000*	*119*
Tetrahydrofuran	*1.7*	*200*	*118*
Hexane, n-	*4.3*	*500*	*116*
Dichlorobenzene (o-)	*0.47*	*50*	*106*
Butyl acetate, (tert-)	*2.0*	*200*	*100*
Ethyl alcohol	*10*	*1000*	*100*
Chlorotoluene, o-	0.50	50	100
Propylene glycol methyl ether acetate	1.0	100	100
100 PPM Alarm ↑			
Isopropyl acetate	*2.6*	*250*	*96*
Cumene	*0.54*	*50*	*93*
Trichloroethylene	*0.54*	*50*	*93*
Dioxane, 1,4-	*1.1*	*100*	*91*
Ethyl acetate	*4.6*	*400*	*87*
Isopentane, & isomers	8.2	600	73
Diacetone alcohol	*0.70*	*50*	*71*
Mesitylene	0.35	25	71
Propylene glycol monomethyl ether	1.4	100	71
Butyl acetate, (sec-)	3.0	200	67
Isopropyl Alcohol	*6.0*	*400*	*67*
Methyl methacrylate	*1.5*	*100*	*67*
Butyl acetate, (n-)	*2.6*	*150*	*58*
Isobutyl acetate	*2.6*	*150*	*58*
Propyl acetate, n-	*3.5*	*200*	*57*
Cyclohexanone	*0.90*	*50*	*56*
Amyl acetate (sec-)	*2.3*	*125*	*54*
Kerosene	0.6	30	50
Jet fuel JP-8	0.6	30	50
50 PPM Alarm ↑			
Jet fuel JP-5	0.6	29	48
Isoamyl acetate	*2.1*	*100*	*48*
Methyl t-butyl ether	0.91	40	44
Perchloroethene	*0.57*	*25*	*44*
Amyl acetate (n-)	*2.3*	*100*	*43*
Butoxyethanol, 2-	*1.2*	*50*	*42*
Butyl alcohol (sec-)	*4.0*	*150*	*38*
Hexene, 1-	0.80	30	38
Naphtha (Coal tar) {10% aromatics}	*2.8*	*100*	*36*
Butyl alcohol (tert-)	*2.9*	*100*	*34*
Acetaldehyde	*6.0*	*200*	*33*

Compound	CF @10.6 eV	OSHA PEL (ppm)	IBE-Equiv. Alarm
Propyl alcohol (n-)	*6.0*	*200*	*33*
Jet fuel JP-4	1.0	30	30
Methyl acetate	*6.6*	*200*	*30*
Triethylamine	*0.90*	*25*	*28*
Isobutyl alcohol	*3.8*	*100*	*26*
Diethylamine	*0.97*	*25*	*26*
25 ppm Alarm ↑			
Naphthalene	*0.42*	*10*	*24*
Methyl iodide	*0.22*	*5*	*23*
Butyl alcohol (n-)	*4.7*	*100*	*21*
Hexamethyldisilazane, 1,1,1,3,3,3-	0.24	5	21
Naphtha (Coal tar) {purely aliphatic}	*5.7*	*100*	*18*
Butyl mercaptan	*0.60*	*10*	*17*
Carbon disulfide	*1.2*	*20*	*17*
Ethyl mercaptan	*0.60*	*10*	*17*
Methyl mercaptan	*0.60*	*10*	*17*
Diesel Fuel #2 (Automotive)	0.66	11	17
Propylene oxide	*6.5*	*100*	*15*
Dimethyl acetamide, N,N-	*0.80*	*10*	*13*
Dimethylformamide, N,N-	*0.80*	*10*	*13*
Ethylamine	*0.80*	*10*	*13*
Vinyl bromide	0.40	5	13
Butane	67	800	12
Dibromoethane, 1,2-	*1.7*	*20*	*12*
Methyl bromide	*1.7*	*20*	*12*
Diesel Fuel #1	0.93	11	12
Trimethylamine	0.85	10	12
Trichlorobenzene (1,2,4-)	0.46	5	11
Aniline	*0.48*	*5*	*10*
Dicyclopentadiene	0.48	5	10
Ethyl acrylate	*2.4*	*25*	*10*
Methoxyethanol, 2-	*2.4*	*25*	*10*
Toluidine, o-	*0.50*	*5*	*10*
10 PPM Alarm ↑			
Chloroprene (beta-)	*3.0*	*25*	*8.3*
Cyclohexylamine	1.2	10	8.3
Methylamine	*1.2*	*10*	*8.3*
Vinyl actetate	1.2	10	8.3

Compound	CF @10.6 eV	OSHA PEL (ppm)	IBE-Equiv. Alarm
Isobutane	100	800	8.0
Pyridine	*0.68*	*5*	*7.4*
Diisopropylamine	*0.74*	*5*	*6.7*
Allyl glycidyl ether	*1.5*	*10*	*6.7*
Dimethylamine	*1.5*	*10*	*6.7*
Butyl acrylate, n-	1.6	10	6.3
Furfural	*0.92*	*5*	*5.4*
Ammonia	*9.7*	*50*	*5.2*
Dichloroethyl ether	*3.0*	*15*	*5.0*
Formamide	4.0	20	5.0
Phenol	*1.0*	*5*	*5.0*
Nitric oxide	*5.2*	*25*	*4.8*
Butylamine, n-	*1.1*	*5*	*4.6*
Benzaldehyde	0.50	2	4.0
Ethylene glycol	16	50	3.1
Hydrogen sulfide	*3.3*	*10*	*3.0*
Dimethylethylamine	1.0	3	3.0
Methyl acrylate	*3.7*	*10*	*2.7*
Caprolactam	2.0	5	2.5
Phenyl ether	*0.40*	*1*	*2.5*
Benzene	*0.53*	*1*	*1.9*
Ethanolamine	*1.6*	*3*	*1.9*
Crotonaldehyde	*1.1*	*2*	*1.8*
Benzyl cyanide	0.60	1.04	1.7
Benzyl chloride	*0.60*	*1*	*1.7*
Propylene imine	*1.3*	*2*	*1.5*
Diethanolamine	2.0	3	1.5
Bromobenzene	0.60	0.78	1.3
Vinyl-2-pyrrolidinone, 1-	0.80	1	1.3
Butadiene	*0.85*	*1*	*1.2*
Dichloro-1-propene, 1,3-	0.96	1	1.0
Diethylenetriamine	1.0	1	1.0
Iodine	*0.10*	*0.1*	*1.0*
1 PPM Alarm ↑			
Acrylic Acid	12	10	0.8
Allyl alcohol	*2.4*	*2*	*0.8*
Benzoyl chloride	0.6	0.5	0.8
Acetic Anahydride	*6.1*	*5*	*0.8*

Compound	CF @10.6 eV	OSHA PEL (ppm)	IBE-Equiv. Alarm
Dimethylhydrazine, 1,1-	*0.78*	*0.5*	*0.6*
Butyl hydroperoxide, t-	1.6	1	0.6
Glutaraldehyde	0.80	0.5	0.6
Epichlorohydrin	*8.5*	*5*	*0.6*
Nitrobenzene	*1.9*	*1*	*0.5*
Vinyl chloride	*2.0*	*1*	*0.5*
Acetic Acid	*22*	*10*	*0.5*
Diphenyl (Biphenyl)	*0.40*	*0.2*	*0.5*
Methyl ethyl ketone peroxide	2	0.7	0.4
Hydrazine	*3.0*	*1*	*0.3*
Nitrogen dioxide	*16*	*5*	*0.3*
Diketene	2.0	0.5	0.3
Allyl chloride	*4.3*	*1.0*	*0.2*
Bromoform	*2.5*	*0.5*	*0.2*
Methyl hydrazine (Monomethyl hydrazine)	*1.2*	*0.2*	*0.2*
Phosphorus trichloride	*4.0*	*0.5*	*0.1*
Nicotine	*0.70*	*0.075*	*0.1*
Bromine	*1.3*	*0.1*	*0.08*
Ethylene oxide	*13*	*1*	*0.08*
Phosphine	*3.9*	*0.3*	*0.08*
Below Common Air Background Values of 0.05 ppm (50 ppb)			
Dimethyl sulfate	*20*	*1*	*0.05*
Tetraethyl lead (as Pb)	*0.30*	*0.008*	*0.03*
Acrolein	*3.9*	*0.1*	*0.03*
Toluene-2,4-diisocyanate (TDI)	*1.4*	*0.02*	*0.01*
Mustard, Distilled (TWA) (LC50)*	0.6	0.00046 >230	0.0008 >385
Tabun (TWA) (LC50)*	0.8	0.000015 20	0.00002 25
Sarin (TWA) (LC50)*	3	0.000017 12	0.000006 4

* LCt50 = Lethal concentration for 50% chance of death in a one minute exposure

5.6 Appendix 6: PID to FID Conversion

TABLE 5.6.1. PID to FID correction factors for methane equivalents

Compound	C's	PID CF (10.6 eV)	Lab FID RF	PID-FID CF (Meas.)	PID-FID CF (C Atom Calc)
Acetaldehyde	2	6			12
Acetic acid	2	22			44
Acetone	3	1.1	1.8	2.0	3.3
Acetonitrile	2	NR		NR	NR
Acetylene	2	NR		NR	NR
Acrolein	3	3.9			11.7
Acrylonitrile	3	NR		NR	NR
Allyl alcohol	3	2.4			7.2
Allyl chloride	3	~4			~12
Aniline	6	3.0			18
Benzene	6	0.53	4.3	2.3	3.2
Benzyl chloride	7	0.6			4.2
Bromoethane	2	~1.6			~3.2
Bromoform	1	2.5			2.5
Bromopropane, 1-	3	1.5			4.5
Butadiene, 1,3-	4	0.85			3.4
Butane, iso-	4	~100			~400
Butane, n-	4	NR		NR	NR
Butanol, n-	4	4.7			18.8
Butanol, iso-	4	3.8			15.2
Butyl mercaptan	4	0.52			2.1
Carbon tetrachloride	1	NR	0.40	NR	NR
Chlorobenzene	6	0.40	4.0	1.6	2.4
Chloroethane	2	NR		NR	NR
Chloroform	1	NR	0.49	NR	NR
Cumene	9	0.54			4.9
Cyclohexane	6	1.4			8.4
Dichlorobenzene, 1,2-	6	0.47			2.8
Dichlorobenzene, 1,4-	6	~0.5			~3
Dichloroethylene, 1,1-	2	~0.9	1.9		~1.8
Dichloroethylene,c-1,2-	2	~0.8			~1.6
Dichloroethylene, t-1,2-	2	0.45			0.9
Dichloropropane, 1,2-	3	NR		NR	NR
Dimethylformamide, N,N-	3	~0.8			~2.4

Compound	C's	PID CF (10.6 eV)	Lab FID RF	PID-FID CF (Meas.)	PID-FID CF (C Atom Calc)
Dioxane, 1,4-	4	~1.3			~5.2
Epichlorohydrin	2	8.5			17.0
Ethane	2	NR		NR	NR
Ethanol	2	12			24.0
Ethoxyethanol, 2-					
(Ethyl cellosolve)	4	~1.3			~5.2
Ethyl acetate	4	4.6	2.0	9.0	18.4
Ethyl acrylate	5	2.4			12.0
Ethylbenzene	8	0.52			4.2
Ethylene dibromide (1,2-Dibromoethane)	2	1.7			3.4
Ethylene dichloride (1,2-Dichloroethane)	2	NR	1.5	NR	NR
Gasoline	8	~1			~8
Heptane, n-	7	2.6			18.2
Hexane, n-	6	4.3	4.7	20.2	25.8
Isobutylene	4	1.0			4.0
Isoprene	5	0.6			3.2
Isopropanol	3	6.0	1.6	9.9	18.0
Methane	1	NR	1.0	NR	NR
Methanol	1	NR	0.58	NR	NR
Methoxyethanol, 2- (Methyl cellosolve)	3	2.4			7.2
Methyl bromide	1	1.7			1.7
Methyl chloride	1	NR		NR	NR
Methyl ethyl ketone	4	0.86	2.2	1.9	3.4
Methyl isobutyl ketone	6	0.8			4.8
Methyl methacrylate	5	1.5			7.5
Methyl t-butyl ether	5	0.9	3.2	2.8	4.5
Methylene chloride	1	NR	0.94	NR	NR
Nonane, n-	9	~1.4			~13
Octane (mix)	8	1.8			14.4
Pentane, n-	5	8.4			42.0
Perchloroethylene	2	0.57	1.3	0.8	1.1
Propane	3	NR		NR	NR
Propionaldehyde	3	~1.9			~5.7
Propylene oxide	3	6.5			19.5

Compound	C's	PID CF (10.6 eV)	Lab FID RF	PID-FID CF (Meas.)	PID-FID CF (C Atom Calc)
Styrene	8	0.4			3.2
Tetrachloroethane, 1,1,2,2-	2	NR		NR	NR
Tetrahydrofuran	4	1.7	2.5	4.2	6.8
Toluene	7	0.5	5.1	2.6	3.5
Trichloroethane, 1,1,1-	2	NR	1.6	NR	NR
Trichloroethane, 1,1,2-	2	NR		NR	NR
Trichloroethylene	2	0.5			1.0
Triethylamine	3	0.9			2.7
Vinyl acetate	4	1.2			4.8
Vinyl bromide	2	0.4			0.8
Vinyl chloride	2	2.0	2.0	4.0	4.0
Xylene, o-	8	0.59	3.6	2.1	4.7
Xylene, m-	8	0.43			3.4
Xylene, p-	8	0.45			3.6

TABLE 5.6.2. PID to FID correction factors for hexane equivalents

Compound	C's	PID CF (10.6 eV)	Lab FID RF	PID-FID CF (Meas.)	PID-FID CF (C Atom Calc)
Acetaldehyde	2	6			2.0
Acetic acid	2	22			7.3
Acetone	3	1.1	0.39	0.42	0.55
Acetonitrile	2	NR		NR	NR
Acetylene	2	NR		NR	NR
Acrolein	3	3.9			2.0
Acrylonitrile	3	NR		NR	NR
Allyl alcohol	3	2.4			1.2
Allyl chloride	3	~4			~2
Aniline	6	3.0			3.0
Benzene	6	0.53	0.92	0.49	0.53
Benzyl chloride	7	0.6			0.7
Bromoethane	2	~1.6			~0.5
Bromoform	1	2.5			0.42
Bromopropane, 1-	3	1.5			0.75
Butadiene, 1,3-	4	0.85			0.57
Butane, iso-	4	~100			~67
Butane, n-	4	NR		NR	NR

Compound	C's	PID CF (10.6 eV)	Lab FID RF	PID-FID CF (Meas.)	PID-FID CF (C Atom Calc)
Butanol, n-	4	4.7			3.1
Butanol, iso-	4	3.8			2.5
Butyl mercaptan	4	0.52			0.35
Carbon tetrachloride	1	NR	0.08	NR	NR
Chlorobenzene	6	0.40	0.86	0.34	0.40
Chloroethane	2	NR		NR	NR
Chloroform	1	NR	0.10	NR	NR
Cumene	9	0.54			0.81
Cyclohexane	6	1.4			1.4
Dichlorobenzene, 1,2-	6	0.47			0.47
Dichlorobenzene, 1,4-	6	~0.5			~0.5
Dichloroethylene, 1,1-	2	~0.9	0.40		~0.3
Dichloroethylene,c-1,2-	2	~0.8			~0.3
Dichloroethylene, t-1,2-	2	0.45			0.15
Dichloropropane, 1,2-	3	NR		NR	NR
Dimethylformamide, N,N-	3	~0.8			~0.4
Dioxane, 1,4-	4	~1.3			~0.9
Epichlorohydrin	2	8.5			2.8
Ethane	2	NR		NR	NR
Ethanol	2	12			4.0
Ethoxyethanol, 2-					
(Ethyl cellosolve)	4	~1.3			~0.9
Ethyl acetate	4	4.6	0.42	1.9	3.1
Ethyl acrylate	5	2.4			2.0
Ethylbenzene	8	0.52			0.69
Ethylene dibromide (1,2-Dibromoethane)	2	1.7			0.57
Ethylene dichloride (1,2-Dichloroethane)	2	NR	0.32	NR	NR
Gasoline	8	~1			~1.3
Heptane, n-	7	2.6			3.0
Hexane, n-	6	4.3	1.00	4.3	4.3
Isobutylene	4	1.0			0.67
Isoprene	5	0.6			0.53
Methoxyethanol, 2- (Methyl cellosolve)	3	2.4			1.2
Methyl bromide	1	1.7			0.28
Methyl chloride	1	NR		NR	NR

Compound	C's	PID CF (10.6 eV)	Lab FID RF	PID-FID CF (Meas.)	PID-FID CF (C Atom Calc)
Methyl ethyl ketone	4	0.86	0.48	0.41	0.57
Methyl isobutyl ketone	6	0.8			0.80
Methyl methacrylate	5	1.5			1.3
Methyl t-butyl ether	5	0.9	0.67	0.61	0.75
Methylene chloride	1	NR	0.20	NR	NR
Nonane, n-	9	~1.4			~2
Octane (mix)	8	1.8			2.4
Pentane, n-	5	8.4			7.0
Perchloroethylene	2	0.57	0.29	0.16	0.19
Propane	3	NR		NR	NR
Propionaldehyde	3	~1.9			~0.95
Propylene oxide	3	6.5			3.3
Styrene	8	0.4			0.53
Tetrachloroethane, 1,1,2,2-	2	NR		NR	NR
Tetrahydrofuran	4	1.7	0.53	0.90	1.1
Toluene	7	0.5	1.1	0.55	0.58
Trichloroethane, 1,1,1-	2	NR	0.35	NR	NR
Trichloroethane, 1,1,2-	2	NR		NR	NR
Trichloroethylene	2	0.5			0.17
Trimethylbenzene, 1,2,4-	6	~0.35	0.22	~0.08	~0.35
Triethylamine	3	0.9			0.45
Vinyl acetate	4	1.2			0.80
Vinyl bromide	2	0.4			0.13
Vinyl chloride	2	2.0	0.43	0.86	0.67
Xylene, o-	8	0.59	0.76	0.45	0.79
Xylene, m-	8	0.43			0.57
Xylene, p-	8	0.45			0.60

5.7 Appendix 7: Calculation of CS_2 and H_2S Concentrations in a Dual 9.8/10.6 eV Lamp PID System

Definitions:

$[H_2S]$ = H_2S concentration in ppm
$[CS_2]$ = CS_2 concentration in ppm
$R_{9.8}$ = Reading with a 9.8 eV lamp in isobutylene equivalent ppm
$R_{10.6}$ = Reading with a 10.6 eV lamp in isobutylene equivalent ppm
$CF_{9.8\text{-}CS2}$ = Correction factor for CS_2 with a 9.8 eV lamp
$CF_{10.6\text{-}CS2}$ = Correction factor for CS_2 with a 10.6 eV lamp
$CF_{10.6\text{-}H2S}$ = Correction factor for H_2S with a 10.6 eV lamp

The response to the 9.8 eV lamp is only due to CS_2. Therefore,

$$R_{9.8} = \frac{[CS_2]}{CF_{9.8\text{-}CS2}} = \frac{[CS_2]}{4}$$

$$\therefore [CS_2] = 4R_{9.8}$$

The response to the 10.6 eV lamp is due to both CS_2 and H_2S. Therefore,

$$R_{10.6} = \frac{[CS_2]}{CF_{10.6\text{-}CS2}} + \frac{[H_2S]}{CF_{10.6\text{-}H2S}} = \frac{[CS_2]}{1.2} + \frac{[H_2S]}{3.3}$$

$$\therefore [H_2S] = 3.3\left(R_{10.6} - \frac{[CS_2]}{1.2}\right)$$

For example, if the total response on the 9.8 eV lamp is 2 ppm isobutylene equivalents, and the total response on the 10.6 eV lamp is 10 ppm isobutylene equivalents, then

$$[CS_2] = 4R_{9.8} = 4 \text{ x } 2 = 8 \text{ ppm}$$

and

$$[H_2S] = 3.3\left(R_{10.6} - \frac{[CS_2]}{1.2}\right) = 3.3\left(10 - \frac{8}{12}\right) = 11 \text{ ppm}$$

5.8 Appendix 8: RAE PID Lamp Traits

This appendix gives an example of recommendations for selection and care of PID lamps.

PID Lamp Selection

RAE Systems photoionization detectors (PIDs) offer lamps with three different photon energies: 9.8 eV, 10.6 eV and 11.7 eV. A special high-intensity version of the 10.6 eV lamp is also available. Instruments are shipped with the standard 10.6 eV lamp unless otherwise specified. Because the 11.7 eV lamp has a shorter life (see Table 5.9.1) and is more expensive, use of the 9.8 or 10.6 eV lamps is recommended whenever possible.

Lamp Output and Resolution

The larger (1/2") lamps used in the MiniRAE, ppbRAE and UltraRAE series have greater output than the smaller (1/4") lamps used in the ToxiRAE, MultiRAE and AreaRAE series. 10.6 eV lamps also have significantly stronger output than 11.7 eV lamps, and slightly stronger than 9.8 eV lamps. Higher output translates to better resolution and lower detection limits. The resolution also depends on the type of compound measured; generic values for isobutylene are listed below. The "super-bright" 10.6 eV lamps are required for ppb- level detection, and the ppbRAE cannot use 11.7 eV lamps. These stronger lamps are not recommended for other PIDs because they may saturate the sensor at high VOC concentrations.

Lamps Stored in Glass Ampules

Because lamps gradually lose power even when not in use, the warranty periods listed below apply even if the lamp is not turned on. New 1/4" 11.7 eV lamps shipped in sealed ampules are warranted for storage of 3 months. The one-month operating warranty begins at the earlier of the three-month storage period or when the when the gas-tight container is opened. In order to maintain the warranty, it is important that these dates be recorded.

Lamp Care

Store lamps under dry conditions to minimize attack on the lamp window. Keep the lamps clean using dry methanol or isopropanol; never use acetone on 11.7 eV lamps.

Lamp Replacement

RAE Systems PID lamps do not burn out suddenly because they have no filament. Thus, because of the shorter life, we recommend purchasing 11.7 eV lamps as close as possible to the date of use. The strength of the lamp and thus its expected life can be determined using the special Diagnostic Mode (See RAE Systems Technical Note TN-123).

TABLE 5.9.1. PID lamp characteristics

Lamp Energy	Lamp Diameter	Typical Resolution	Warranty Period	Typical Life
9.8 eV	1/2 inch	0.1 ppm	6 months	1 year
9.8 eV	1/4 inch	0.2 ppm	6 months	1 year
10.6 eV*	1/2 inch	0.1 ppm	1 year (3 yrs)*	2 - 3 years
10.6 eV super bright	1/2 inch	0.002 ppm	1 year	1 year
10.6 eV	1/4 inch	0.1-0.2 ppm	1 year	1 year
11.7 eV	1/2 inch	0.1-0.2 ppm	1 month	1 - 2 months
11.7 eV in ampule	1/4 inch	1.0 ppm	1 month	4 mo. in ampule 1 - 3 mo. in use

*10.6 eV lamps used in MiniRAE 3000 instruments are warranted for three years under normal operating conditions are used.

5.9 Appendix 9: Conversion Factors for Gas Concentrations

To convert from the units on the left to the units on top, multiply by:

To: from:	Vol. %	ppmv	ppbv	mg/m³	mg/L
vol. %	-	10^4	10^7	$\frac{10^4(mw\cdot P)}{MV}$	$\frac{10(mw\cdot P)}{MV}$
ppmv	10^{-4}	-	10^3	$\frac{(mw\cdot P)}{MV}$	$\frac{10^{-3}(mw\cdot P}{MV}$
ppbv	10^{-7}	10^{-3}	-	$\frac{10^{-3}(mw\cdot P)}{MV}$	$\frac{10^{-6}(mw\cdot P)}{MV}$
mg/m³	$\frac{10^{-4}MV}{(mw\cdot P)}$	$\frac{MV}{(mw\cdot P)}$	$\frac{10^3MV}{(mw\cdot P)}$	-	10^{-3}
mg/L	$\frac{0.1MV}{(mw\cdot P)}$	$\frac{10^3MV}{(mw\cdot P)}$	$\frac{10^6MV}{(mw\cdot P)}$	10^3	-

Key: P = pressure in atmospheres
MV = molar volume of gas (for air see table below)
mw = molecular weight of compound in g/mole

1 Atmosphere Equivalents
1013 hPa
101.3 kPa
1.013 bar
1013 mbar
760 mmHg
29.9 in. Hg
33.9 ft. H_2O
14.7 psia

Temp. (°C)	Temp. (°F)	Air Molar Volume (MV)
-10	14	21.59
-5	23	22.00
0	32	22.41
5	41	22.82
10	50	23.23
15	59	23.64
20	68	24.05
25	77	24.46
30	86	24.87
35	95	25.28
40	104	25.69
45	113	26.10
50	122	26.51

5.10 Appendix 10: RAE Systems Gas Detection Products

RAE Systems offers a broad array of products used to detect and monitor many different compounds. For the most up-to-date list of RAE Systems products, as well as technical notes, application notes, and other material, visit RAE Systems' website at: **www.raesystems.com.**

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Standard Operating Procedure

X-Ray Fluorescence

1.0 Purpose and Scope

The purpose of this document is to define the standard operating procedure (SOP) for analysis of soil samples using a portable x-ray fluorescence (XRF) analyzer. The following sections provide descriptions of equipment, field procedures, and quality assurance/quality control procedures to be implemented for the XRF field analysis of soil samples.

2.0 Equipment

The following items will be used for collecting soil samples and performing XRF analyses:

- Portable XRF analyzer and accessories
  - XRF analyzers that use an x-ray tube are the preferred instrument, as they minimize the need for isotope licensing and travel restrictions (Note: State registration may be required prior to use). The instrument's minimum detection limit must be below the cleanup goals established in the RAW.
- National Institute of Standards and Technology (NIST) traceable calibration standards for lead (standard reference material [SRM] for low, medium, and high concentrations)
- Field logbook
- Calculator, or equivalent
- Waterproof, black ink marker/pen
- Ruler or tape measurer
- Sealable 1-gallon plastic bags
- Packing tape
- Trowel or equivalent hand tool
- Hand auger
- Metal sieves
- Decon sprayer
- Camera and film or digital camera
- Soil moisture probe (optional)
- Reagent grade silica sand

3.0 Instrument Operation

Each make and model of XRF analyzer has its own specific start-up, calibration, and operating procedures. The user's manual will provide the information necessary to ensure the instrument is being used in the appropriate manner. XRF analyzer operators must follow the procedures listed in the user's manual when working with XRF analyzers.

3.1 Safety

XRF analyzers emit x-rays which can be harmful to human health. XRF analyzer operators must be trained in the use of XRF analyzers. In addition, the XRF analyzer operator should make field personnel aware of the following information:

- XRF analyzers emit radiation.
- Radiation exposure is negligible with the proper use of the XRF analyzer and low with the occasional incorrect use of the XRF analyzer.

Field staff working with, or in the vicinity of, an XRF analyzer must practice ALARA, which means that all radiation exposure should be As Low As Reasonably Achievable. This can be achieved by following these guidelines:

- Do not put fingers or any other body part in front of the analyzer window.
- Verify that no one stands within three paces of the analyzer window when the instrument is operating.
- Correct operation of the instrument involves leaving one hand on the handle and making sure the other hand is away from the window.

3.2 Battery Life

Battery life for the Innov-X analyzer (with rechargeable lithium-ion batteries) is approximately 4 to 8 hours. Due to the high volume of samples that will be analyzed during XRF field analysis activities, it is recommended that fully charged batteries be used at the start of each workday. If an instrument is being used for a full workday, the battery will likely need to be replaced once during that day. Therefore, a fully charged backup battery for each instrument in use will be kept on hand at all times. Instrument standardization and calibration verification must occur each time a battery is replaced. Record the date and time of each battery replacement in the field logbook. Standardization and calibration verification are discussed in Section 4.0.

4.0 Calibration and Verification

Instrument calibration verifications are necessary to ensure that the XRF analyzer is operating properly and to verify the accuracy of results. Field calibration checks will also be conducted while the XRF analyzer is being used during field activities. XRF analyzer calibration will follow the procedures listed in the user’s manual and in the following sections. Typically, rented XRF units will be calibrated by the vendor prior to delivery. Record the results of the included calibration sheet in the field logbook. Also record the results of calibration checks conducted by field staff in the field logbook. Additional calibration and method verification checks include the following:

- Start of Day
    - Energy Calibration (Section 4.1)
- Prior to XRF instrument use and shutdown
    - Instrument Blank (Section 4.2)
    - Calibration Verification with NIST standards (Section 4.3)

4.1 Energy Calibration

An energy calibration check will be performed each time an XRF analyzer is started. Innov-X analyzers automatically complete this energy calibration check when the unit is started (Innov-X, 2005). For non-Innov-X analyzers, consult the user’s manual for the energy calibration procedures. Record the results of the energy calibration check in the field logbook.

4.2 Instrument Blank

An instrument blank check must be conducted to verify that there is no contamination on the analyzer window. An instrument blank check will be conducted at least once per day or once per 20 samples. The instrument blank check will be conducted using the silicon dioxide blank provided with the analyzer. Record the results of the instrument blank checks in the field logbook. The minimum detection limit for handheld XRF varies by manufacturer and model. The instrument’s minimum detection limit must be below the cleanup goals established in the RAW.

4.3 Calibration Verification

A calibration verification test with NIST standards (SRM 2709, SRM 2710, and SRM 2711, or equivalent) must be conducted prior to XRF instrument use and shutdown (a minimum of at least once every 4 hours of analyzer use). To conduct the calibration verification, the operator should place the NIST standard in front of the XRF analyzer window and perform a standard test. The result of each test should be within 20 percent of the standard value. Record the results of the calibration verifications in the field logbook. If a test result is not within ± 20 percent of the NIST standard value, the test will be repeated. If test results are consistently outside of the 20 percent window, then the project manager will be notified, and corrective actions will be taken. It is also advisable to recalibrate throughout the day if there are significant variations in temperature. The target concentrations for the reference standards will vary depending on the XRF manufacturer.

5.0 XRF Sample Collection and Field Analysis

The steps listed below outline the collection and XRF field analysis procedures. Once a sample's location has been determined, the following list of procedures will be implemented:

1. Obtain and record the position of the ex-situ sample location using data from the robotic total station.
2. Using a permanent maker or pen, write the sample identifier and the time of sample collection on a plastic zipper-lock storage bag.
3. Don a clean pair of nitrile gloves.
4. Clear the sample location of any vegetation or debris.
5. Using a clean trowel, hand auger, or other appropriate tool, collect the sample in a 0.5-foot increment.
6. Record the sample location, date, and time of collection in the field logbook. Document any information about the sample location that is out of the ordinary (e.g., fill, discoloration, odor, the presence of man-made items, etc.).
7. If the soil is not homogeneous, a 60 mesh sieve will be used to sieve the sample into the plastic zipper-lock storage bag to homogenize and remove any non-soil materials, such as rocks and pebbles, twigs, or roots from the sample. Seal the bag and rotate it repeatedly to homogenize the sample.
8. Dry the sample if it appears to be too moist (i.e., greater than 20 percent moisture). A soil moisture probe may be used if site conditions are consistently damp or wet. The sample may be too moist if it appears to be clumpy or excessively cohesive. The drying process may include opening the plastic bag and exposing the sample to the open air in a warm environment such as a hot day or toaster oven, or spreading the sample out in a drying pan overnight (see Section 6.0 of this SOP).
9. Place the sealed plastic sample bag on a flat, non-metallic surface. Open the bag and obtain readings using a disposable Mylar screen to protect the XRF. Alternatively, flatten the sample in the plastic bag and obtain the reading through the plastic bag.
10. Obtain a minimum of three consecutive XRF readings. Each reading should be taken at a different location on the bag for a minimum of 30 seconds. Follow the procedures provided in the user's manual for operating that specific XRF analyzer. Sampling duration may be increased up to 120 seconds to improve the accuracy of the reading. The three consecutive readings must be within 50 percent for XRF values that are less than 50 parts per million (ppm). The three consecutive readings must be within 20 percent for XRF values that are greater than 50 ppm. If three consecutive readings within the 50/20 percent criteria are not obtained, the sample will be re-homogenized and reanalyzed according to steps 8 through 10. The three consecutive XRF readings will be averaged for the final copper and lead concentrations for each ex situ XRF sample analyzed. Additionally, note the presence of high levels of bromine, antimony, tin, or tantalum, as these may mask lead results.
11. Record the data in the field logbook.
12. Wipe off the XRF analyzer window.

6.0 Sample Drying

Soil samples with more than 20 percent moisture may create errors in the XRF field analysis results (United States Environmental Protection Agency [USEPA], 2007). However, most modern XRF analyzers have built in correction measures for moisture, which means that moisture should not have a significant impact on accuracy (Innov-X, 2005). In addition, studies indicate that the relative accuracy of XRF results is most strongly influenced by the degree of homogenization of the sample, yet high moisture content can cause soil to clump and inhibit the operator's ability to sufficiently homogenize the sample (USEPA, 2007). Based on this and site conditions, the project team should evaluate both the need for drying and the drying methodology. As a general guideline, if the soil is excessively clumpy or cohesive, it may need to be dried. A soil moisture probe may be used to determine the moisture content of the soil samples. If drying is required, the soil samples will be air dried by opening the plastic zipper lock bags or by spreading the samples out in clean drying pans or on disposable surfaces, such as waxed paper, and allowing them to air dry overnight or in a toaster oven, or until soil moisture is below 20 percent. The method used to dry soil samples (if necessary) will be recorded in the field logbook. Once the sample is dry enough for adequate homogenization, it should be placed in a sealed plastic bag for ex situ XRF analysis, as described in Section 5.0 of this SOP.

7.0 Correlation Sampling

Up to 10 percent of the XRF field analysis samples will be sent to a laboratory for analysis. The results for the laboratory analysis will be used to evaluate the correlation with the XRF filed analysis results.

8.0 References

Innov-X, 2005. *Instruction Manual: Innov-X Systems Alpha Series X-Ray Fluorescence Spectrometers*. August.

United States Environmental Protection Agency (USEPA), 2007. Method 6200. February.

EPA Method 5035

Field Preservation Kit

samplesmart

Collecting soil samples for volatile organic compounds can become very expensive and cumbersome. The **o2si** 5035 **samplesmart** kit provides significant cost savings. How? The **o2si samplesmart** kit saves time and money by reducing collection times and increasing holding times. For example, **o2si**'s 5035 **samplesmart** kit provides holding times up to 14 days. This simplifies work schedules and shipping requirements. Unlike other soil sampling kits, the need to weigh methanol in the field is eliminated through the introduction of methanol provided in a uniquely sealed Teflon® tube. Finally, the design of the **o2si** 5035 **samplesmart** kit requires only one label for each kit, thereby reducing collection time.

Provide Significant Cost Savings

- Meets CLP Sample Collecting Guidelines Options 1 and 2
- Meets EPA Method 5035 Sampling Requirements
- Eliminates Field Weighing
- Decreases Collection Time
- Increases Productivity in the Field and Laboratory
- Increases Holding Times
- Eliminates Multiple Labeling
- Reduces Laboratory Prep Cost

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o2si smart solutions is an ISO 9001:2000 certified company.

EPA Method 5035

Field Preservation Kit

Historically, the disadvantages of field preservation has been handling the vials, field weighing the methanol vial, methanol loss, and packaging the vials for shipping. The **o2si** 5035 **samplesmart** kit overcomes these problems!

Each Kit Contains:

- Disposable syringe sampling device, two pre-weighed low-level vials, one pre-weighed high-level vial, and an evaporative loss vial.
- Methanol preservative in a sealed Teflon® tube.
  - Eliminates the need for field weighing.
  - No chance for methanol loss prior to sampling.
  - Methanol can be supplied with surrogates to provide the most rigorous surrogate criteria.
  - Weight of methanol already added to methanol vial weight.
- Plastic rack which allows access to vials without having to remove them. The weatherproof rack holds the vials upright and allows all the lids to be easily removed and easily filled.
- Bar coded label with a unique number with corresponding numbers on each vial. A pull tab allows the bar code to be put on the chain-of-custody form.
  - Complete only one label for each kit instead of labeling each container.
- Sampling instructions printed on each kit.

Confidence Factor:

- All 5035 **samplesmart** kits include certified pre-cleaned vials that are reanalyzed by EPA Method 5035 heated-purge specifications following preservation to ensure cleanliness. A certificate of analysis is available upon request.
- Methanol is purge-and-trap grade that has been analyzed after packaging the tubes.
- All vials are tared with a calibrated balance checked against NIST traceable weights each day before use.
- Plastic rack provides excellent protection against breakage during shipping.

Appendix F

Responses to Regulatory Agency Comments

RESPONSES TO REGULATORY AGENCY COMMENTS
INTERIM REMOVAL ACTION WORK PLAN
SMUD 59TH STREET CORPORATION YARD
DRAFT, MARCH 2022

REVIEWER Dave Kremer, PG., Engineering Geologist, DSMOA Unit, Geological Services Unit (GSU), DATE May 18, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
1	General	Conclusions GSU reviewed the Work Plan and concluded that the proposed soil sampling and laboratory analysis are consistent with the SAP, the applicable cleanup goals were presented, and the proposed removal activities are consistent with industry standard practices. The elevated VOC concentrations discussed in Section 2 of the Work Plan establish the likely soil gas contamination source area where the proposed excavation activities will occur, however, this data is not representative of steady-state conditions due to the operation of the SVE system during or in close proximity to the sample collection dates.	Comment noted. The data obtained at the site prior to the initiation of SVE operations is consistent with respect to the determination of the likely soil gas contamination source area.

Notes:

GSU = Geological Services Unit
PG = Professional Geologist
SAP = Sampling and Analysis Plan
SMUD = Sacramento Municipal Utility District
SVE = soil vapor extraction
VOC = volatile organic compound

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REVIEWER Tom Booze, M.S. Ph.D., Senior Toxicologist, DSMOA Unit, Human and Ecological Risk Office (HERO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
1	Table of Contents, and Appendix D, Section D.6.3	There are two sections designated D.6.3. The second one (Action Levels) should be D.6.5.	The section numbering in Appendix D Table of Contents and text was corrected. Sections D.6.3 and D.6.5 are now D.5.3 and D.5.5, respectively.
2	Section 2.4.3	In the last sentence of the first paragraph please explain what is meant by “Children and pregnant women are believed to be at increased risk to arsenic exposures”. It’s not clear what the risk is that is being referred to.	The text referenced in the comment was deleted.
3	Section 2.5.1	Please discuss the potential risk from inhalation of PCE from vapor intrusion to potential residential receptors. Although the concentrations of PCE may be below the groundwater MCL residents may be exposed via vapor intrusion into indoor air. Also, please discuss the risk that might occur to trench or remediation workers that may be exposed to PCE in groundwater during construction or remediation.	Section 2.5 of the IRAW is a summary of the risk evaluation from the SCR Addendum. It is not the intent of the IRAW to provide further evaluation of future soil gas conditions at the site and therefore is not relevant to this document. This is not the final RAP and additional risk assessment is not needed for conducting this interim removal action. The following was added to Section 2.5: “This section summarizes the risk evaluation results from the SCR Addendum (AECOM, 2021a). No additional risk evaluation for future conditions is necessary for conducting this interim removal action. As described in Section 7.0, a site-specific health and safety plan will identify chemical and physical hazards to remediation workers associated with the planned activities and will specify minimum levels of training, protection, and safe operating guidelines for workers in compliance with Hazardous Waste Operations and Emergency Response (HAZWOPER) and California Occupational Safety and Health Administration (OSHA) regulations.” There is no risk to trench or remediation workers associated with direct exposure to PCE in groundwater because the depth to groundwater is 35 feet bgs and the maximum excavation depth is 15 feet bgs.

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REVIEWER Tom Booze, M.S. Ph.D., Senior Toxicologist, DSMOA Unit, Human and Ecological Risk Office (HERO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
4	Sections 2.5.1	Soil vapor data from three soil vapor extraction (SVE) wells were among the data used for the risk assessment. Please explain whether the SVE system was on and how it affected these and other nearby wells in terms of how if affected the VOC concentrations. If the system was not in operation, then please explain how long it had been on prior to sampling and whether equilibrium had been reached post-SVE.	Please see response to Comment 3. This IRAW summarizes the risk assessment results from the SCR Addendum. It is not the intent of the IRAW to provide detailed information on the data used in the SCR Addendum risk assessment. The soil gas risk assessment summary provided in the IRAW provides background site information that supports the selection of the interim removal action remedy of the source area. Although, SVE operations could provide a low bias for samples collected within influence of the SVE system, the results of low bias do not impact the interim remedy selection for the IRAW. The final remedy for the site will be selected in a future RAP.
5	Section 2.5.1	It appears that data from 4, 5, or 5.5' bgs only was used for the risk assessment. We recommend using the deeper samples from 14' bgs as well - which are closer to the source. The deeper near source data is not affected by current buildings as much as shallow soil gas may be, and the conditions in the shallow zone may be different post development which makes it important to use the near source data to provide a potentially better picture for evaluating future soi[l] gas conditions.	Please see response to Comment 3.
6	Section 2.5.1	We recommend that all organic chemicals detected, along with all inorganic chemicals not present as part of the naturally occurring background be considered chemicals of potential concern (COPC). We do not allow eliminating chemicals from the risk assessment based on screening such as that mentioned on the bottom of page 2-10. HERO notes the comment at the top of page 2-11 that says that chemicals detected below their screening level were carried through the risk assessment but wants to make sure that these chemicals stay in the risk assessment.	Please see response to Comment 3.
7	Section 2.5.2	This section says that the risk values for construction workers are summarized here but we could not find them. We recommend that they be included. We note that there is a comment in Section 2.5.1	Section 2.5 of the IRAW is a summary of the risk evaluation from the SCR Addendum, which did not quantify risk for construction workers. It is not the intent of the IRAW to provide further risk evaluation. This is not the final RAP

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REVIEWER Tom Booze, M.S. Ph.D., Senior Toxicologist, DSMOA Unit, Human and Ecological Risk Office (HERO), DATE May 3, 2022

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		that the construction worker was not evaluated quantitatively because there aren't any well established models for evaluating VOCs into a trench. We recommend using Virgina's construction worker trench model for evaluating this pathway (https://www.deq.virginia.gov/home/showpublisheddocument?id=4068).	and additional risk assessment is not needed for conducting this interim removal action. Section 2.5.2 was revised as follows: "The risk characterization from the SCR Addendum (AECOM, 2021a) for residential and~~,~~ commercial/industrial~~, and construction~~ worker receptors using SVSLs derived from AFs of 0.03 and 0.001 is summarized below." "~~No well-established models are available for estimating the migration of volatiles into an excavation trench.~~"
8	Section 3.2	We recommend adding metrics, or explanations, for some of the Remedial Action Objectives (RAOs) so that one can determine whether they have been met. The RAOs include the following. • Prevent direct human contact with and ingestion of soil COCs exceeding concentrations acceptable for human exposure, • Prevent human inhalation of soil COCs exceeding concentrations acceptable for residential exposure. • Prevent the migration of contaminants from soil COCs that would impact groundwater, and • Reduce VOC concentrations in the soil gas contamination area. However, there are cleanup concentrations for arsenic, lead, and TPH as hydraulic oil and motor oil only. It's not clear how some of the other chemicals of potential concern (COPC) in soil will be evaluated for cleanup, and there do not appear to be any cleanup concentrations based on migration of COCs to groundwater. Also, it's unclear to whether there is a numerical goal for VOCs in soil gas or how the concentrations will be reduced.	The RAOs were revised to state: "The following RAOs were developed for soil within the portions of the Site identified by the HHRA as having unacceptable carcinogenic risk and/or noncarcinogenic hazard. • Prevent direct human contact with, inhalation of, and ingestion of arsenic concentrations in soil exceeding the site-specific background concentration. • Prevent direct human contact with, inhalation of, and ingestion of lead concentrations in soil corresponding to a 1 microgram per deciliter source-specific incremental change in blood lead levels. Prevent direct human contact with, inhalation of, and ingestion of TPH$_{ho/mo}$ concentrations in soil corresponding to a hazard index of greater than 1. ~~• Prevent the migration of contaminants from soil COCs that would impact groundwater, and~~ • Reduce VOC concentrations in the soil gas contamination area by removing VOC mass from the source area identified at the north of the Tool Issue Building." The following was added to Section 2.5.1: "Based on the HHRA calculations, contaminants that pose unacceptable carcinogenic risk and/or noncarcinogenic hazard are identified as COCs."

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
			The following was added to Section 3.2: "COPCs are contaminants suspected of being site-related and were carried through the HHRA's quantitative risk calculations. Based on the HHRA calculations, contaminants that pose unacceptable carcinogenic risk and/or noncarcinogenic hazard are identified as COCs. The HHRA identified arsenic, lead, and TPHho/mo as COCs in soil within portions of the Site north of the light rail line (AECOM, 2021a)." Per the June 8, 2022 technical meeting with the DTSC, the potential for migration of lead from soil to groundwater should be evaluated utilizing the synthetic precipitation leaching procedure (SPLP) as further analysis of confirmation samples at the locations where lead is a COC. The SPLP data will be compared against a cleanup standard of 5 milligrams per liter (mg/L). Section 6.1 was revised to state "Confirmation samples for Area #3 will be analyzed for arsenic and lead by USEPA Method SW6020, lead by synthetic precipitation leaching procedure (SPLP) by USEPA Method 1312, and $TPH_{ho/mo}$ by USEPA Method SW8015M. The potential for migration of lead from soil to groundwater will be evaluated by comparing the SPLP data against a cleanup standard of 5 mg/L." A numerical goal for the removal of VOCs in soil gas is not provided. The plan is to excavate the potential source area in order to reduce the mass of VOCs in soil. Cleanup goals for soil gas will be provided in a future RAP or Removal Action Work Plan.
9	Sections 5.4.3.2 and 6.3	Please explain the basis for the 11 mg/kg arsenic in Virgin Class II aggregate base as being acceptable for backfill. This concentration is mentioned in both sections but there isn't a description of its origin.	The origin of the 11 mg/kg arsenic concentration was added to Sections 5.4.3.2 and 6.3, which were revised as follows: "or an arsenic concentration of 11 mg/kg for Virgin Class II aggregate base (Duvergé, 2011)," The following was added to Section 10.0 References: "Duvergé, Dylan Jacques, 2011. *Establishing Background Arsenic in Soil of the Urbanized San Francisco Bay Region*. December.

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REVIEWER Tom Booze, M.S. Ph.D., Senior Toxicologist, DSMOA Unit, Human and Ecological Risk Office (HERO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
			https://www.waterboards.ca.gov/sanfranciscobay/water_issues/available_documents/2011_Arsenic_Background_Duverge.pdf
10	Section 6.1	We recommend that at least two confirmation samples be collected from sidewalls and excavated bottoms of areas 2500-5000 ft^2 instead of the one sample recommended in this section which leaves large areas of excavations unverified.	The document was revised to indicate that two samples will be obtained from each sidewall and from the excavation bottom of areas 2500-5000 ft^2. Section 6.1 was revised to state: "Confirmation sampling for excavations less than 2,500 square feet will be conducted at an approximate frequency of one sample per sidewall (4 sidewall samples total) and excavation bottom. Confirmation sampling for excavations greater than 2,500 but less than 5,000 square feet will be conducted at an approximate frequency of ~~one~~two samples per sidewall (8 sidewall samples total) and excavation bottom (two bottom samples total).".
11	Table A1-2	We recommend that DTSC's Toxicity Criteria Rule (TCR) be added to Table A1-2 Potential State Chemical-Specific ARARs. In September 2018, the State of California adopted Title 22, California Code of Regulations sections 69021-69022 Toxicity Criteria for Human Health Risk Assessments, Screening Levels, and Remediation Goals rule (Toxicity Criteria Rule). The Rule provides a list of required toxicity criteria for specific chemicals to be used in human health risk assessments, human health risk-based screening levels and human health risk-based remediation goals (cleanup levels). These toxicity criteria can be found in DTSC's Human Health Risk Assessment Note 10 (https://dtsc.ca.gov/wp-content/uploads/sites/31/2019/02/HHRA-Note-10-2019-02-25.pdf).	Table A1-2 was updated to include the TCR.
12	Appendix D, Section D.6.3	Please provide the inputs/assumptions used to develop the community dust action level for arsenic. We did not obtain the same concentrations that were in the report and are trying to verify its appropriateness. There should also be community action levels for all of the COPCs that will be part of the excavation. DTSC's Community Air Monitoring Plan (CAMP) Guidance can be used to develop these action levels (https://dtsc.ca.gov/wp-	The other COPCs are not risk drivers. The proposed dust action levels developed for lead and arsenic are lower (i.e., more stringent) than the action levels for the COPCs. Therefore, the proposed dust levels are protective for all COPCs. The following text was added to Section D.6.5 (formerly Section D.6.3 Action Levels):

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REVIEWER Tom Booze, M.S. Ph.D., Senior Toxicologist, DSMOA Unit, Human and Ecological Risk Office (HERO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
		content/uploads/sites/31/2020/10/2020-CAMP-Guide-FINAL-w-appendices-072020-A.pdf).	“The community action levels were developed using DTSC’s Community Air Monitoring Plan (CAMP) Guidance. The non-cancer level was calculated using the CAMP Appendix E equation: $SSAL_{nc}$ = THQ x REL x (AT_{nc} / (ET x EF x ED)). Where, • $SSAL_{nc}$ = noncancer-based action limit of COC in air ($\mu g/m^3$) • THQ = target inhalation noncancer hazard quotient (unitless). The CAMP-recommended THQ value of 1.0 was used. • REL = Arsenic inhalation reference exposure level (per $\mu g/m^3$). The 1.5×10^{-02} $\mu g/m^3$ arsenic toxicity value from USEPA RSLs May 2022 (same as DTSC’s HHRA Note 10 [February 25, 2019]) was used. • AT_{nc} = averaging time for non-carcinogenic effects (hours). A value of 2016 hours (24 hours/day * 7 days/week * 12 weeks [based on 3-month exposure period]) was used. • ET = Exposure time (hours/day). A project-specific value of 9 hours/day was used. • EF = Exposure frequency (days/week). A project-specific value of 5 days/week was used. • ED = Exposure Duration (weeks). A project-specific value of 12 weeks was used. The cancer level was calculated using the CAMP Appendix E equation: $SSAL_c$ = TR x (1/IUR) x (AT_c / (ET x EF x ED)). Where, • $SSAL_c$ = cancer-based action limit of COC in air ($\mu g/m^3$) • TR = target inhalation cancer risk (unitless). The CAMP-recommended TR value of 1.0×10^{-06} was used. • IUR = Arsenic inhalation unit risk (per $\mu g/m^3$). The 4.3×10^{-03} $\mu g/m^3$ arsenic toxicity value from USEPA RSLs May 2022 (same as DTSC’s HHRA Note 10 [February 25, 2019]) was used.

REVIEWER Tom Booze, M.S. Ph.D., Senior Toxicologist, DSMOA Unit, Human and Ecological Risk Office (HERO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
			• AT_c = averaging time for carcinogenic effects (hours). A value of 613,200 hours (24 hours/day * 365 days/year * 70 years) was used. • ET = Exposure time (hours/day). A project-specific value of 9 hours/day was used. • EF = Exposure frequency (days/year). A project-specific value of 91 days/year was used. The project is expected to be less than 91 days. • ED = Exposure Duration (years). A project-specific value of 0.25 years was used.”

Notes:
mg/L = milligrams per liter
µg/m^3 = micrograms per cubic meter
CAMP = Community Air Monitoring Plan
COC = chemical of concern
COPC = chemical of potential concern
DTSC = Department of Toxic Substances Control
ft^2 = square feet
HERO = Human and Ecological Risk Office
HHRA = human health risk assessment
IRAW = Interim Removal Action Workplan
M.S. = Master of Science
Ph.D. = Philosophiae Doctor (doctor of philosophy)
PCE = tetrachloroethene
RAP = Remedial Action Plan
RAO = removal action objective
RSL = Regional Screening Level
SCR = Site Characterization Report
SMUD = Sacramento Municipal Utility District
SPLP= Synthetic Precipitation Leaching Procedure
SVE = soil vapor extraction
TCR = Toxicity Criteria Rule
TPH = total petroleum hydrocarbons
USEPA = United States Environmental Protection Agency
VOC = volatile organic compound

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DRAFT, MARCH 2022

REVIEWER Farrukh Ahmad Ph.D., P.E., Hazardous Substances Engineer, Engineering and Special Projects Office (ESPO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
1	List of Acronyms and Abbreviations (page vii)	Total petroleum hydrocarbons as hydraulic oil/motor oil (TPHho/mo) is not a recognized TPH fraction. *Please provide a normal alkane-based equivalent carbon number (ECN) range for this TPH fraction where it is defined in the list.*	The ECN range of C17 – C32 (aromatic high) was added to the TPHho/mo definition in the text and in the List of Acronyms and Abbreviations.
2	Executive Summary (pages ES-1 and ES-2)	The Executive Summary is missing several key pieces of information. *ESPO recommends the inclusion of the following items in the Executive Summary:* • *Reference to the DTSC Removal Action Workplan (RAW) sample (https://dtsc.ca.gov/wp-content/uploads/sites/31/2018/11/Appdx_C3_083108.pdf).* • *Information on future land use planned for the Site.* • *Removal action objectives (RAOs).* • *Mention that backfill (last paragraph) will be compliant with the DTSC Information Advisory on Clean Imported Fill (https://rfs-env.berkeley.edu/sites/default/files/dtscsmp_fs_cleanfill-schools.pdf). Please ensure that this is repeated wherever clean backfill is mentioned throughout the Draft IRAW.*	The recommended information was added to the Executive Summary and the reference to compliance with the *DTSC Information Advisory on Clean Imported Fill* was added to Sections 4.1.2 and 4.1.3 of the IRAW. Section 5.4.3.2 already includes a reference to the DTSC Guidance.
3	Hydrogeology (Section 2.1.2, page 2-1)	There are two different groundwater flow directions specified at the beginning and end of this section. From the text, it is not clear whether these flow directions are for different overlying groundwater-bearing units. *Please clarify the text as to the direction of groundwater flow at the Site.*	The groundwater flow direction at the site is to the south-southwest. The first sentence of Section 2.1.2 was revised to state "Based on data obtained during the Phase II ESA, the depth to first groundwater beneath the Site is approximately 35 feet bgs and flows in a south to southwe~~ea~~sterly direction, at a gradient of approximately 0.001 foot per foot (Kleinfelder, 2016)."

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REVIEWER Farrukh Ahmad Ph.D., P.E., Hazardous Substances Engineer, Engineering and Special Projects Office (ESPO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
			The eighth sentence of Section 2.1.2 was revised to state “Groundwater generally flows in a south to southwest direction, although it may be affected by the American River.”
4	Human Health Risk Assessment (pages 2-9 to 2-13)	Soil gas cleanup levels, including those for the PCE-contaminated Area #9 (see Figures 2-3 and 5-1), are to be developed under a future RAP and only future residential and commercial/industrial worker scenarios are presented in this section. Yet, excavations are planned under this IRAW in soil gas contaminated areas while there is no short-term risk evaluation for workers who will perform the excavation work. *ESPO defers to DTSC’s HERO to ensure that human health risk is assessed for construction workers working on excavations in soil gas contaminated areas, and that adequate precautions are taken in compliance with OSHA requirements in completing such work.*	Please see response to T. Booze Comment 7. As described in Section 7.0, all contractors performing the interim removal action will be compliant with HAZWOPER and OSHA requirements. A site-specific health and safety plan will identify anticipated chemical and physical hazards associated with the planned activities and will provide minimum levels of protection and safe operating guidelines for HAZWOPER-trained excavation workers. These requirements will include air monitoring and may additionally include engineering controls such as PPE to protect excavation workers from exposure to chemical hazards.
5	Alternative 1 (Section 4.1.1, page 4-1)	Even with the “No Further Action” alternative, future development of the Site into a mixed-use urban community will require at least some changes to the current Site asphalt cover. *Please indicate that any future asphalt cover removal/resurfacing costs will be incorporated into future construction costs for the Site.*	Future development of the Site is not part of the remedy or alternatives. The following statement was added to the Alternative 1 text: “Future development of the Site is not part of the remedy; therefore, any future construction costs (e.g., asphalt removal/resurfacing) are not included in Alternative 1 or the other remedial alternatives.” The last sentence of Section 4.1.1 was revised to state “~~This action~~ Alternative 1 includes no ~~land use controls~~ new LUCs, no maintenance of existing LUCs, no soil excavation, and no monitoring.”
6	Alternative 3 (Section 4.1.3, page 4-2)	*Cite Figure 4-2 in this section.*	A citation to Figure 4-2 was added to the first paragraph of Section 4.1.3 (Alternative 3).
7	Soil Excavation Extent and	Please consider the following and make changes where necessary:	

RESPONSES TO REGULATORY AGENCY COMMENTS
INTERIM REMOVAL ACTION WORK PLAN
SMUD 59TH STREET CORPORATION YARD
DRAFT, MARCH 2022

REVIEWER Farrukh Ahmad Ph.D., P.E., Hazardous Substances Engineer, Engineering and Special Projects Office (ESPO), DATE May 3, 2022

ITEM	PAGE OR REFERENCE	COMMENT	RESPONSE OR ACTION
	Methodology (Section 5.4, page 5-2)	• *Replace "competent person" (1st paragraph, page 5-2) with "licensed Civil Engineer".*	• The second sentence in Section 5.4 (1st paragraph, page 5-2) was revised to state: "The Excavation areas will be sloped or benched as deemed appropriate by the California OSHA-competent person (29 CFR 1926.32(f)) to provide appropriate slope stability protection in accordance with ~~California Occupational Safety and Health Administration (~~OSHA~~)~~ regulations. The OSHA-competent person will be a licensed Civil Engineer when: • excavation slope or bench, support, shield, or other protective system is designed per 29 CFR 1926.652(b)(3) or (b)(4), (c)(3) or (c)(4), and • excavations in the vicinity of structures to determine if the structure is sufficiently removed from the excavation so as to be unaffected by the excavation activity or to design support systems to ensure the safety of employees and the stability of the structure."
		• *Please ensure that the excavation to 10 feet below ground surface (bgs) at the southeast corner of the Site and immediately adjacent to the Warehouse Building (Figure 5-1, Area #8) will pose no structural issues for the building. Please add text to this effect.*	• The following underlined sentence was added to Section 5.4: "The excavation in the southeast corner of the Site near the Warehouse Building will extend to deeper than 10 feet bgs in the vicinity of sample location WB10. However, excavation is not anticipated to reach the groundwater table, which is at approximately 35 feet bgs. A licensed Civil Engineer will determine if the Warehouse Building is sufficiently removed from the excavation so as to be unaffected by the excavation activity and, if necessary, will design support systems to ensure the safety of workers and the stability of the structure."
		• *Please ensure that any field x-ray fluorescence (XRF) analyzer used to screen and segregate soils can reliably detect arsenic in soils below the cited background value of 17.53 ppm for the Site.*	• XRF analyzers typically available for equipment rental such as the Olympus Vanta XRF can detect arsenic to 1 ppm in soil. The following sentence was added to the second paragraph in Section 5.4: "The selected XRF soil analyzer will be able to detect arsenic in soils below the arsenic background value of 17.53 ppm."

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8	Air Monitoring During Soil Excavation (Section 5.6, page 5-6)	*ESPO recommends that the air monitoring procedures at the Site during earthwork are consistent with the DTSC Community Air Monitoring Plan (CAMP) Guidance (https://dtsc.ca.gov/wp-content/uploads/sites/31/2020/10/2020-CAMP-Guide-FINAL-w-appendices-072020-A.pdf). Also, since naphthalene is one of the contaminants identified at the Site (page 2-8), please ensure odor-suppressors are available during field activities*	Section 5.6 states that air monitoring will be performed as described in the Dust Control Plan and Air Monitoring Plan (Appendix D). The Dust Control Plan and Air Monitoring Plan is consistent with CAMP Guidance including air monitoring locations, parameters, and action levels. The text was revised to state "The air monitoring procedures at the Site during earthwork are consistent with the *DTSC Community Air Monitoring Plan (CAMP) Guidance.*" The following sentence in Section 5.6 was revised to state: "Factors considered in providing fugitive dust, vapor, and odor control measures will include wind direction, wind speed, and available dust control and dust suppression methods (see Section 5.5.1)." The following sentence was added to Section 5.5.1: "Dust suppression will be performed by lightly spraying or misting the work areas (such as the excavation, soil handling areas and haul roads) with water, BioSolve®, or a similar surfactant if water is not sufficient to reduce the potential for dust generation. Vapor and odor control will be utilized during field activities, as needed, by lightly spraying or misting BioSolve®, or similar vapor and odor suppressant."

Notes:
CAMP = DTSC Community Air Monitoring Plan Guidance
DTSC = Department of Toxic Substances Control
ECN = equivalent carbon number
ESPO = Engineering and Special Projects Office
HAZWOPER = Hazardous Waste Operations and Emergency Response
HERO = Human and Ecological Risk Office
IRAW = Interim Removal Action Workplan
OSHA = Occupational Safety and Health Administration
P.E. = professional engineer
Ph.D. = Philosophiae Doctor (doctor of philosophy)
PPE = personal protective equipment
PCE = tetrachloroethene
RAP = Remedial Action Plan
RAW = Removal Action Workplan
RAO = removal action objective
TPHho/mo = total petroleum hydrocarbons as hydraulic oil/motor oil
XRF = x-ray fluorescence