Results from Bravo Bedrock Vapor Extraction Treatability Study

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The Santa Susana Field Laboratory (SSFL) is located in Ventura County, California, approximately 30 miles northwest of Los Angeles (Figure 1). This summary documents the implementation of activities at the Bravo Area of SSFL to evaluate the feasibility of vapor extraction of the Chatsworth Formation Operable Unit.

Project Background

In 2009, a bedrock vapor extraction (BVE) treatability study (TS) work plan (MWH, 2009) was prepared for SSFL's Bowl Test Area. An addendum (MWH, 2012) was prepared in 2012 that included modifications to the plan based on Department of Toxic Substances Control (DTSC) comments. The 2012 addendum was subsequently approved by DTSC. In 2013, the National Aeronautics and Space Administration (NASA) proposed conducting the activities in the approved BVE TS work plan/addendum at the Bravo Area (Figure 2) (NASA, 2013). NASA prepared and submitted a technical memorandum (TM) consistent with the objectives and applicable scope of the original approved BVE TS work plan/addendum. A revised TM (based on comments from DTSC) was submitted in 2014. Two rounds of responses to comments followed, along with discussions and meetings with DTSC. The *Bedrock Vapor Extraction Treatability Study at the Bravo Test Area Technical Memorandum* (BVE TM) (NASA, 2014) was approved by DTSC on May 22, 2014. The work described in this summary was performed in accordance with authorization from NASA and DTSC.

Scope and Objectives of Work

The scope and objectives of the work are as follows:

1. Quantify bedrock air removal using standard vapor extraction methods.
2. Quantify the volatile organic mass flow rate over time in the BVE well.
3. Quantify the vacuum response in fractures and in matrix blocks.
4. Improve understanding of lithologic and/or structural variations and their impacts on formation advective flow paths under a BVE system.
5. Improve understanding of the diffusive response of volatile organic compounds (VOCs) from the rock matrix post treatment.

This document summarizes the activities performed at Bravo Area to evaluate the feasibility of vapor extraction and provides an assessment of the five objectives listed above that have been met. The scope as implemented provided significant insight on all objectives and results for each objective are summarized below.

Testing the vapor extraction technology in the bedrock at SSFL was initiated and planned by Boeing for two sites in the Bowl and Coca Delta areas (2009-2012). The planning involved extensive interaction with DTSC and the development of work plans that were used to guide this work at the Bravo Area.

Field Investigation

The removal of VOC mass from the vadose zone is the essential objective underlying the BVE TS. The sampling and monitoring approach for this TS was designed around this objective. The work for the BVE TS is summarized below.

The BVE TM called for retrofitting an existing groundwater monitoring well for use as a BVE extraction well, in place of a new well. This modification to the approved work plan allowed the TS to be performed on a well that already exists and has a known VOC presence, without the uncertainties, time, or expense associated with installing new wells. HAR-19 was retrofitted for this TS. The original lithologic log for well HAR-19 identified at least one fracture zone in the bedrock at 87 to 89 feet below ground surface (bgs), characterized by “rapid penetration” of the drill string. For the purposes of this TS, an extraction flow rate of several hundred standard cubic feet per minute (scfm) was anticipated from the more than 140 feet of unlined 8-inch corehole above the water table at well HAR-19.

A combined array of newly constructed multilevel and existing piezometers and wells comprised the soil vapor monitoring network during this TS (Figure 3). In Situ Level TROLL 500 pressure transducers, rated to 30 pounds per square inch (psi), were installed in the BVE monitoring locations on August 26, 2014, and in HAR-19 on August 29, 2014. These instruments were installed to record downhole pressure variations throughout the duration of the BVE TS. An In Situ BaroTROLL data logger was employed to monitor ambient barometric and temperature changes throughout the study. The BaroTROLL was placed at ground surface at PZ-204 on August 29, 2014. Transducers were set to record pressure and temperature measurements every 10 minutes, leading to a total of more than 3,000 individual measurements per well at the time of retrieval (September 15, 2014). Pressure changes recorded at these locations and depths provided information about vacuum propagation through bedrock fractures.

A permit was obtained from the Ventura County Air Pollution Control District (VCAPCD) on January 6, 2014, authorizing the installation and operation of the BVE system through August 31, 2014. An extension of the air permit to operate the BVE system through October 31, 2014, was granted by VCAPCD on June 26, 2014.

The BVE TM (NASA, 2014) called for three vapor extraction cycles. To evaluate production of air, flow was measured at three or more wellhead vacuum levels during the initial startup of the BVE system; steady-state flow and vacuum were measured throughout the three extraction phases. BVE operations occurred for one 5-day and two 4-day periods over 3 weeks, between August 26 and September 12, 2014 (Table 1). The BVE system did not operate on weekends during this period. BVE system operations began with initial system startup on August 26, 2014. Upon startup, system settings were adjusted until a maximum stable flow rate was achieved from HAR-19; this flow rate was found to be between 65 and 66 scfm, with an associated wellhead vacuum of approximately 6 inches mercury (in. Hg) (81.57 inches of water [in. H_2O]). The system continued extraction at this approximate rate throughout the 3 weeks of operation.

After nearly 6 weeks of inactivity, the system was restarted for a 24-hour rebound test in October 22, 2014. A summary of BVE system flow rate and wellhead vacuum measurements taken during weekly system startups and shutdowns is provided in Table 1.

TABLE 1
Summary of BVE System Operations
Results from Bravo Bedrock Vapor Extraction Treatability Study

Event	Date	Time	HAR-19 WH Vacuum (in. Hg)[a]	HAR-19 WH Vacuum (in. H_2O)[a]	Flow Rate (scfm)[a]	Pneulog Surveys and Times (as applicable)
Initial system startup	8/26/14	12:48	6.00	81.57	73	Pneulog 1 (15:00-17:30)
1st week system shutdown	8/29/14	13:48	5.93	80.62	66	Pneulog 2 (11:45-13:50)
2nd week system startup	9/2/14	11:38	6.30	85.65	72	Pneulog 3 (12:00-14:50)
2nd week system shutdown	9/5/14	14:25	5.84	79.40	65	None
3rd week system startup	9/8/14	11:48	6.05	82.25	111	None
Final system shutdown	9/12/14	15:30	6.05	82.25	66	Pneulog 4 (13:30-15:30)
Rebound test system startup	10/22/14	13:05	4.00	54.38	98	Pneulog 5
Rebound test system shutdown	10/23/14	10:05	4.02	54.65	53	None

Notes:
[a] Listed wellhead vacuum and flow rate measurements are those that were taken closest to the indicated event time, and therefore do not necessarily represent exact vacuums and flow rates at the specified times.
in. H_2O = inches water
in. Hg = inches Mercury
scfm = standard cubic feet per minute
WH = wellhead

The BVE effluent at the HAR-19 wellhead was sampled daily using a handheld photoionization detector (PID) (MiniRae) during extraction phases of the TS. At least once during each extraction week, summa canisters were collected from the HAR-19 wellhead and submitted for laboratory VOC analysis by U.S. Environmental Protection Agency (EPA) Method TO-15. The combination of these two types of measurements (PID and TO-15) allowed NASA to estimate the mass removal rates over time by compound. Figure 4 presents plots of airflow and VOC concentration over time during the BVE TS.

In addition to measurements of wellhead flow, vacuum, and VOC concentration, five downhole Pneulog surveys were performed to measure the air flow and VOC within the HAR-19 corehole on a per-foot basis above the water table (approximately 175 feet bgs). The Pneulog surveys provide data to help interpret the specific fractures responsible for VOC mass removal, and how these removal rates change over time (see Figures 5 and 6). Figures 5 and 6 show all Pneulog runs except the run of August 29. This run was completed, but obstruction interference was encountered on both the down and up runs. For graphical clarity, the data from this date are not shown on these summary figures.

The network of BVE soil vapor monitoring locations were gauged manually for vacuum and PID concentration. In addition to PID concentration measurements, soil vapor samples were collected from a subset of the soil vapor monitoring locations (Table 2). The majority of samples were analyzed by EPA Method 8260B on the same day of collection at an onsite mobile laboratory operated by Environmental Support Technologies (EST). A smaller number of samples were shipped to ALS Environmental (under subcontract to EMAX Laboratories, Inc.) for analysis via EPA Methods TO-15 and 3C at the fixed laboratory in Simi Valley, California.

TABLE 2
Vapor Samples Collected During the BVE TS
Results from Bravo Bedrock Vapor Extraction Treatability Study

	Sample Date						
Well or Probe ID	**8/26/14**	**9/2/14**	**9/5/14**	**9/8/14**	**9/12/14**	**10/22/14**	**Total**
Fixed Laboratory (Summa Canister) Samples – Various Methods							
HAR-19 (TO-15)	1	1	1	1	1	2[a]	7
HAR-19 (3C)[b]	--	--	--	1	1	1	3
PZ-204C (TO-15)	1	--	--	--	--	--	1
Total	2	1	1	2	2	3	**11**
Mobile Laboratory (Glass Bulb) Samples – EPA Method 8260B							
HAR-19	--	1	1	1	1	2	6
PZ-201b	--	1	1	1	--	1	4
PZ-201c	--	1	--	--	--		1
PZ-201d	--	--	--	1	1	1	3
PZ-202a	--	1	1	--	1		3
PZ-202c	--	1	--	1	--		2
PZ-202d	--	--	1	1	1	1	4
PZ-203v	--	1	--	1	--		2
PZ-203c	--	1	1	--	1	1	4
PZ-203d	1	1	1	1	1	1	6
PZ-204a	--	1	--	--	--		1
PZ-204c	1	--	1	1	1	1	5
PZ-204d	--	1	1	1	1	1	5
PZ-061	--	--	1	--	1		2
PZ-156	--	1	1	--	1	1	4
RD-104	--	--	--	1	--		1
Total	2	11	10	10	10	10	**53**

Notes:
[a] Samples collected at HAR-19 for TO-15 analysis on 10/22/14 included a 1-liter summa canister, as well as a 1-liter Bottle-Vac.
[b] TO-15 and 3C analyses were performed on a single summa canister.
3C = EPA Method 3C
EPA = U.S. Environmental Protection Agency
TO-15 = EPA Method TO-15

Data Analysis

As described in the previous section, both point (manual) and continuous (transducer) measurements of pressure were recorded in the soil vapor monitoring locations in order to provide data to evaluate the spatial and temporal responses to vacuum applied at HAR-19. Vacuum responses in monitoring locations are understood to be an indication of the regions of the vadose zone that are pneumatically connected to the vapor extraction well, and may indicate areas of subsurface airflow.

Examination of the raw transducer data indicated that vacuum signals measured in the monitoring wells were influenced by barometric fluctuations, masking the BVE vacuum responses with a high amount of background noise compared to the magnitude of the BVE vacuum responses. To assess vacuum responses due solely to BVE, it was necessary that these barometric influences be removed from the measured vacuum signals. This was accomplished using the publicly available signal-processing software SeriesSee, published by the U.S. Geological Survey (USGS, 2012), which creates a custom signal that simulates the barometric effects felt at each subsurface monitoring location during a fitting period. This custom barometric signal is then used to cancel out the barometric effects measured at the particular well or pressure transducer for which it was developed, isolating and making clear the vacuum responses to BVE. Plots of the processed transducer data are provided on Figures 7a through 7e.

Data from the transducers in the 22 instrumented piezometers and wells demonstrated the vacuum from the extraction at HAR-19 could be sensed in almost all locations monitored. The strongest response was found in three vapor monitoring ports at two piezometer locations: PZ-203c and PZ-203d, and PZ-202d. At these locations, 50 percent and 37 percent of the wellhead vacuum, respectively, were consistently observed, and this maximum response was achieved within 3 hours or less of BVE system startup at these locations. These locations are 30 and 84 feet away from HAR-19, respectively.

In addition to the piezometer-specific responses in Figures 7a through 7e, Figures 8a through 8c show the monitored locations at the site, with an interpretation of the lateral extent of 1 percent of the applied wellhead vacuum over three depth intervals. These intervals were 0 and 100 feet bgs; 100 and 140 feet bgs; and 140 and 160 feet bgs. Figures 8a through 8c demonstrate the major lateral influence of HAR-19 in the 100- to 140-foot bgs interval, as well as the lesser (but still significant) influence in the other two depth intervals.

As previously described, VOC concentrations were measured at the HAR-19 wellhead and the soil vapor monitoring network in order to estimate the mass removal from the vadose zone and to evaluate whether advective flow is affecting a given piezometer or well. Wellhead PID concentrations within the soil vapor monitoring network were generally measured at the beginning and end of each week’s BVE system cycle. The maximum PID readings taken at each location after two well volumes were purged are shown in Table 3.

TABLE 3
PID Measurements at 22 Soil Vapor Monitoring Locations
Results from Bravo Bedrock Vapor Extraction Treatability Study

LOCID	PID Week 1a	PID Week 1b	PID Week 2a	PID Week 2b	PID Week 3a	PID Week 3b	PID Rebound Week 9
HAR-20	**0.3**	0.0	0.2	0.1	0.0	0.2	0.1
PZ-061	**314.0**	87.8	208.8	50.9	51.0	41.6	3.1
PZ-070	**64.6**	5.3	20.1	1.8	2.6	1.3	0.5
PZ-156	63.3	120.2	**215.9**	41.7	162.5	92.4	66.0
PZ-201a	0.0	1.5	**3.9**	0.8	1.0	0.7	1.1
PZ-201b	0.1	3.0	**12.9**	7.6	3.3	4.0	2.9
PZ-201c	0.0	3.0	**15.0**	2.6	3.0	3.7	2.9
PZ-201d	0.0	2.9	**10.6**	4.1	5.2	5.0	3.8
PZ-202a	1.1	**5.3**	3.8	3.0	2.2	1.7	0.7
PZ-202b	0.0	**4.0**	1.9	2.0	1.7	1.1	1.1
PZ-202c	1.4	3.4	**9.6**	2.9	2.9	0.7	1.5
PZ-202d	0.0	2.1	**7.3**	3.5	3.1	2.3	2.3
PZ-203a	1.4	1.3	1.9	**5.0**	1.0	0.0	1.0
PZ-203b	0.6	3.4	1.0	**10.3**	2.2	1.1	1.3
PZ-203c	5.1	5.9	8.9	**11.8**	4.6	4.9	4.3
PZ-203d	19.7	39.1	41.2	**43.0**	16.0	21.7	11.1
PZ-203Av	7.0	0.7	**13.0**	4.2	4.4	2.4	2.0
PZ-204a	0.8	2.2	**4.4**	1.2	1.5	0.7	1.1
PZ-204b	0.7	1.6	2.1	2.2	**2.5**	1.6	2.3
PZ-204c	2.8	2.2	4.2	4.0	**4.7**	3.6	4.0
PZ-204d	0.0	3.3	**31.6**	5.5	6.3	7.1	4.9
RD-104	28.2	73.2	**247.0**	114.9	76.2	13.1	10.3

Notes:
PID units are ppmv
Values of 0 represent readings below the resolution (0.1 ppmv) of the MiniRae
Values in **bold font** represent the maximum measured PID concentration of the well or probe over the duration of the TS.
Initial measurements (Weeks 1a, 2a, 3a, and 9) were collected before the startup of extraction.
ppmv = part(s) per million by volume

PID concentrations over time at the 22 soil vapor monitoring locations are presented on Figures 9a through 9e. The PID responses indicate subsurface airflow through the bedrock vadose zone toward HAR-19. Table 3 also presents the maximum PID value measured at each location during the TS (highlighted in bold). Five of the 22 soil vapor monitoring locations reached their maximum value in the first week, 15 reached the maximum in the second week, and 2 reached their maximum in the third week. Six of the vapor monitoring locations reached a maximum PID concentration at the end of an extraction period, indicating that air flow from a higher concentration source beyond the monitored location may be occurring.

The average VOC mass removed from HAR-19 was computed for each week of the BVE TS, and the average VOC mass removal was computed for each VOC constituent detected in the soil vapor samples analyzed by either method TO-15 or 8260B. These constituents included trichloroethene (TCE), cis-1,2-dichloroethene (DCE), trans-1,2-DCE, vinyl chloride (VC), 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113), and dichlorodifluoromethane (R-12). Average VOC mass removal for each operational week of the BVE TS was estimated by multiplying the average measured VOC concentration for each week by the time-weighted average wellhead airflow for that week. The estimated VOC mass removal rates for HAR-19 are presented by compound in Table 4. The total average VOC mass removal over the 3-week period was approximately 30 pounds, of which approximately 15 to 20 pounds was TCE.

TABLE 4
Average VOC Mass Removal from BVE Well HAR-19
Results from Bravo Bedrock Vapor Extraction Treatability Study

Constituent	Week 1 Mass Removal (pounds)	Week 2 Mass Removal (pounds)		Week 3 Mass Removal (pounds)		Rebound Test Mass Removal (pounds)		Total Mass Removal (pounds)	
		Min	Max	Min	Max	Min	Max	Min	Max
Trichloroethene	*4.6*	3.0	*5.4*	6.0	*8.9*	0.8	*1.4*	14.4	20.5
cis-1,2-Dichloroethene	*0.6*	0.2	*0.6*	0.4	*0.8*	0.1	*0.2*	1.4	2.2
trans-1,2-Dichloroethene	*0.1*	0.02	*0.04*	0.03	*0.04*	0.01	*0.02*	0.2	0.2
Vinyl chloride	*0.2*	*0.1*	0.1	*0.1*	0.2	*0.02*	0.02	0.4	0.5
1,1,2-Trichloro-1,2,2-trifluoroethane	*1.2*	2.1	*2.8*	*3.4*	3.6	0.4	*0.5*	7.0	8.1
Dichlorodifluoromethane	*0.7*	*0.4*	0.7	*0.5*	1.2	*0.1*	0.2	1.8	2.8
Total	**7.5**	**5.8**	**9.7**	**10.4**	**14.8**	**1.4**	**2.4**	**25.1**	**34.3**
Weekly Run Time (minutes)	**4,380**	**4,487**		**5,982**		**1,255**		**16,104**	
Weekly extraction rate (lb/day)[a]	**2.5**	**3.1**		**3.1**		**2.2**		**2.7**	

[a] Weekly extraction rate are the average of the minimum and maximum estimates of weekly mass removal.
Notes:
Results in *italic font* were analyzed using Method TO-15
Results in regular font were analyzed using Method 8260B

Conclusions

The 13-day BVE TS influenced soil vapor monitoring locations hundreds of feet away from the extraction well, through an apparently pervasive and wide-ranging network of fractures and adjacent matrix blocks. The induced BVE TS airflow pattern resulted in the removal of approximately 30 pounds of VOCs (primarily TCE and CFC-113). The VOCs removed during the BVE TS are inferred to have originated from fractures and from the bedrock adjacent to these fractures.

Overall, this test demonstrated the short-term extraction of air and some VOC mass from an existing corehole, provided the corehole is located in or near a source area and is intersected by an interconnected fracture system providing airflow and VOCs. In order to establish the effectiveness and the broader implementability of BVE, and to address more directly the long-term diffusion from the rock matrix (Objective 5), a longer duration test that includes tracer gases would need to be performed, preferably in a higher-concentration source area. In this longer duration test, a series of VOC rebound measurements in a source area would be taken in piezometers after short periods of extraction, to quantitatively assess the matrix offgas trends. In addition, a tracer gas such as helium would be injected in the injection well, and allowed to absorb in the adjacent bedrock for a short period. Then the well would be placed under extraction, and the arrival time would be tracked of helium that has not become absorbed to allow a quantitative assessment of the rock matrix absorption and the release of vapors. Coupled with the longer term VOC removal phase, this test would establish the operational parameters under which BVE could be expected to remove VOCs from the rock matrix and fractures to eliminate future transport to groundwater.

Specific conclusions relative to the five BVE TS objectives, presented with a summary bullet and brief explanation, are as follows:

Objective 1: Production of Air from HAR-19

1. **Repeatable but Modest Flow.** The instantaneous startup extraction rate in HAR-19 was almost 40 percent higher (110 scfm at 6 in. Hg [81.57 in. H_2O]; about 6 scfm per foot) than the steady-state extraction rate. HAR-19 produced about 65 scfm at steady state under a vacuum of about 6 in. Hg (81.57 in. H_2O). The lower steady-state flow was realized within 3 hours of startup.
2. **Fractures Dominate.** Most of this airflow came from two fracture zones between 160 and 173 feet bgs. Approximately 10 scfm is believed to have been derived from the bedrock matrix between 30 and 160 feet bgs. This corresponds to unit flow rates of about 4 scfm per foot in fracture zones, and 0.08 scfm per foot in the bedrock matrix, under a vacuum of 6 in. Hg (81.57 in. H_2O).
3. **Little, If Any, Plasticity in Flow Parameters.** Airflow production from HAR-19 did not change after 6 weeks of re-equilibration; the flow generated from HAR-19 does seem affected by short-term water table rise or fracture submergence, as a result of applied vacuum.

Objective 2: HAR-19 Volatile Organic Compound Removal

1. **Mass Removal Was Relatively Steady**. The mass extraction rate at HAR-19 was reasonably consistent during the BVE TS. The average VOC removal rate from HAR-19 was 2.7 pounds per day over the 3-week operating period. The primary VOC compounds extracted were TCE (58 percent), CFC-113 (25 percent), cis-1,2-DCE (6 percent), and R-12 (7 percent).
2. **Cycling May Not Be Needed**. The mass removal rate at HAR-19 remained reasonably stable. Little or no rebound was observed in the piezometer network even though a consistent mass removal rate was measured at HAR-19 during all of the extraction phases of this short-term TS.

Objective 3: Vacuum Response in Fractures and Matrix Block

1. **Strong Vacuum Response, with Time Delay**. A measureable response was found in all soil vapor monitoring locations (except PZ-061 and RD-104, both remote). The vacuum responses ranged from 0.1 to 50 percent of the applied wellhead vacuum, with plateau vacuum reached within 0 to 16 hours, at distances from 23 to 378 feet from HAR 19.

   For conventional soil vapor extraction applications, it is not unusual to see 2 to 5 percent of the wellhead vacuum during vapor extraction in a medium to coarse sand, up to 100 feet from the extraction well. During the BVE TS, a similar vacuum response was observed at even greater distances in the deep bedrock at the Bravo site (PZ-156), as well as in many other vapor monitoring locations within about a 100-foot radius, shown in Figures 8a through 8c.
2. **Transducers Provide Insight**. Data from the transducers in the 22 instrumented soil vapor monitoring locations demonstrated that the vacuum from the extraction at HAR-19 could be sensed in almost all locations monitored.

   The strongest response was found in three vapor monitoring probes at two piezometer locations: PZ-203c and PZ-203d, and PZ-202d. At these locations, 50 percent and 37 percent of the wellhead vacuum were consistently observed, and this maximum response was achieved within 3 hours or less of BVE system startup at these locations. These locations are 30 and 84 feet away from HAR-19, respectively.

3. **Vacuum Permeates (Possibly Small Fractures) within Rock Matrix**. The vapor monitoring probe completed in a competent, low fracture zone (PZ-203Av, located within borehole PZ-203A approximately 25 feet from HAR-19, 72.5 feet bgs depth) showed a strikingly consistent vacuum response with respect to soil vapor monitoring locations screened in shallow zones directly above (PZ-203a) and directly below (PZ-203b), which are 34 feet from HAR-19 and have screen midpoint depths of 57 and 92 feet bgs, respectively. This indicates that a bedrock zone with little to no visually discernible fractures behaves similarly to intervals above and below, which contain visible fractures. This may indicate that a fracture network may affect zones within the rock matrix as a function of time and the permeability of the rock matrix; or that the rock matrix, in this case, is made more permeable by small fractures that are too small to be visually identified.
4. **Flow Occurs without Measurable Vacuum**. Where comparison was possible, the shallowest vapor monitoring probes displayed lower vacuum levels than in the deeper intervals. However, PID measurements indicated flushing of more dilute air, which indicates flow in these soil vapor monitoring locations. This could indicate ground-surface air recharge, and is a possible indicator that vacuum is transmitted across a large area at depth and then propagates upward over most of the monitored area.

Objective 4: Effect of Lithology, Geology on Advective Flow Paths

1. **Dual Permeability Flow System**. The observed advective flow paths are most appropriately described as complex airflow patterns comprising rapid advection along preferential pathways of the fractures and relatively slow or no advection through less permeable matrix blocks.
2. **Flow Occurred Throughout a Wide Area**. All vapor monitoring locations showed some change in the twice-weekly PID readings. In most cases, the readings showed a maximum after the first week of extraction, indicating the arrival of a more distal plume to the piezometer. Most vapor monitoring locations showed some reduction in their final PID value with respect to their prior maximum. This indicates that the initial test period was sufficient to induce airflow through virtually all monitored vapor monitoring locations. However, responses were not observed at HAR-20, which may reflect impacts from the nearby Alfa Deformation Fault or could be an artifact of the very large volume of air present in the casing.
3. **Limited Vertical Connectivity**. Evidence suggests that the extent to which fracture networks are vertically connected varies across the area. Data for piezometers close to the BVE well indicate that the fractures are not vertically connected across multiple bedding planes. However, the response observed at the more distal piezometer PZ-156 indicates that there is some vertical connection further away from the BVE well.

   As such, it appears appropriate to think of major fractures that intercept an extraction well to be physical extensions of that extraction well, allowing high levels of vacuum to be expressed on the bedrock matrix at substantial lateral distances from the extraction well itself.
4. **Fracture Extent Unpredictable**. The rate of vacuum propagation in the bedrock matrix, shown by the range of response times, did not vary according to lateral separation from HAR-19. This supports the concept that the vadose zone contains substantial heterogeneity: that the fracture network, although spatially pervasive, likely does not penetrate all volumes equally.

Objective 5: Diffusive Response from Bedrock Matrix

1. **VOC Release Appears to be Rapid**. VOC response patterns showed an initial rebound in some soil vapor monitoring locations, suggesting that a local source needed either one or two flow cycles to release its VOCs; but by the third extraction cycle, there was no piezometer displaying a strong rebound. This may be more related to the absence of a strong source, than with a general characteristic of the bedrock.
2. **Short Duration Test Created Some Absorption Reserve in Rock Matrix**. After the third flow cycle, during the 6-week rebound period, no piezometer increased in VOC concentration, and in almost every

piezometer there was some form of decrease in vapor concentration when compared to the last measurement during extraction. This is consistent with the removal of VOCs from the rock matrix adjacent to the flow-supporting fractures, followed by some reabsorption of those VOCs from the vapor phase during a longer period of quiescence.

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Figures

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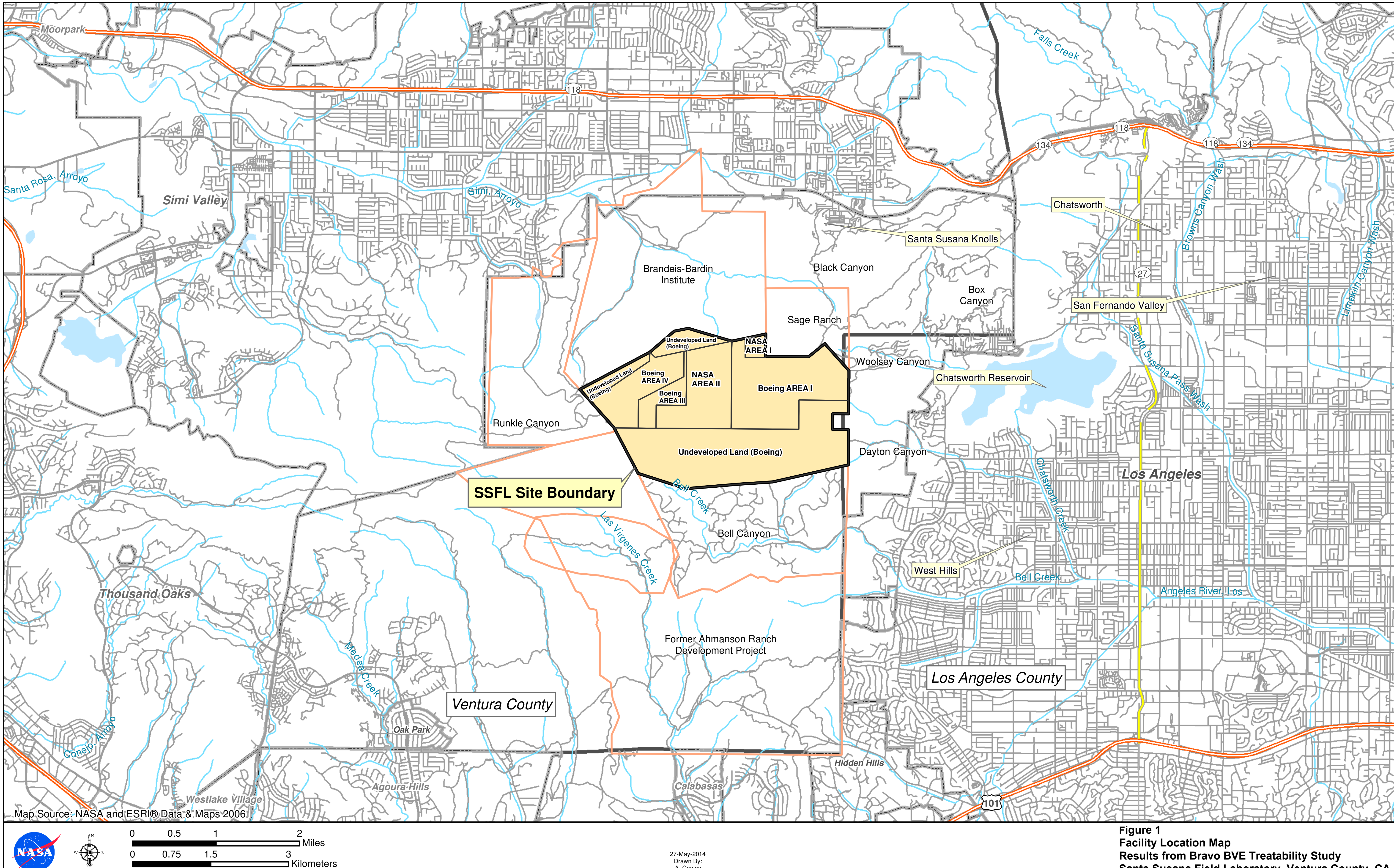

27-May-2014
Drawn By:
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Figure 1
Facility Location Map
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory, Ventura County, CA

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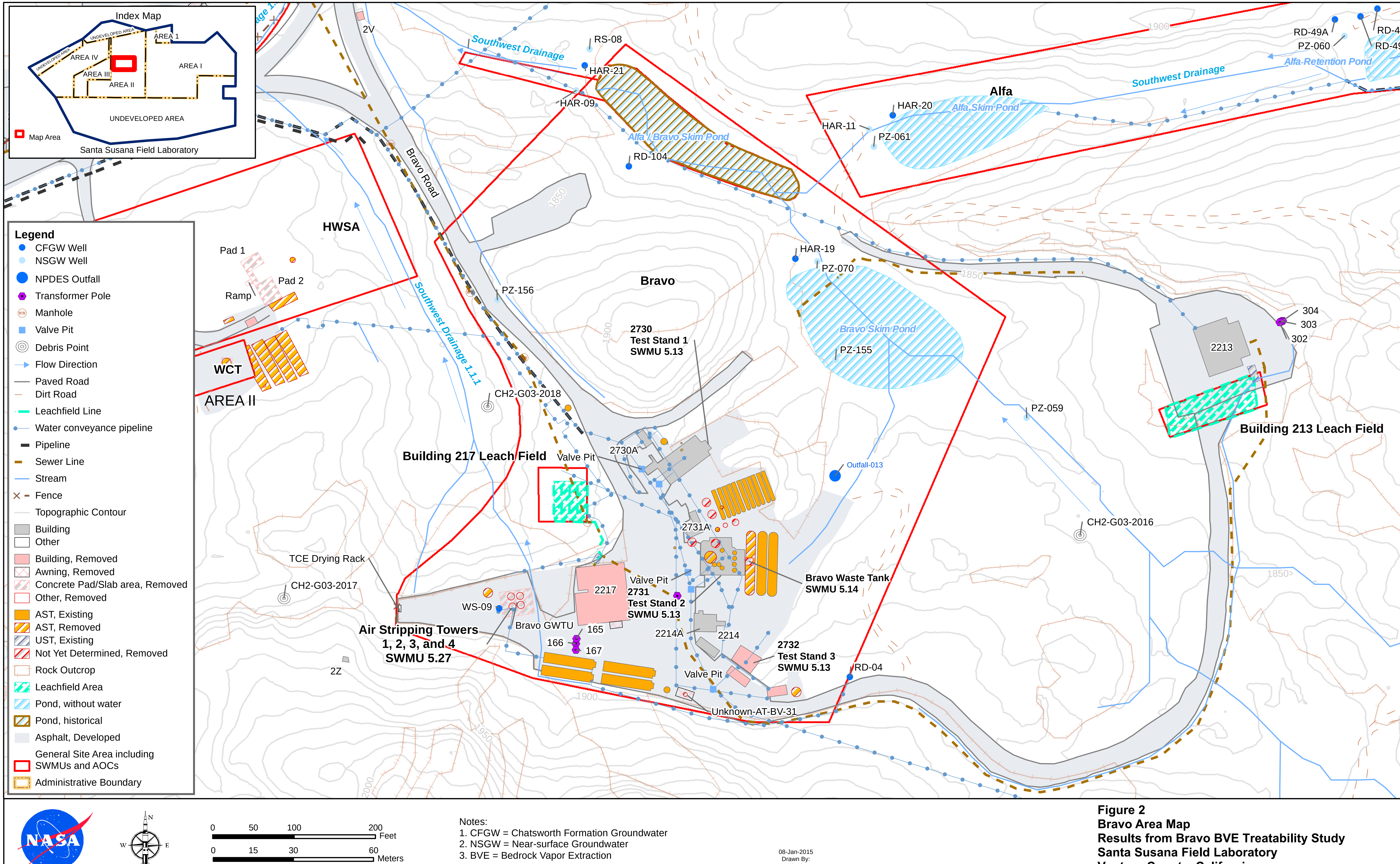

Notes:
1. CFGW = Chatsworth Formation Groundwater
2. NSGW = Near-surface Groundwater
3. BVE = Bedrock Vapor Extraction

Figure 2
Bravo Area Map
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

Map Document: O:\NASA\SSFL\maps\TreatabilityStudy\BRAVO_BVE_SiteMap.mxd

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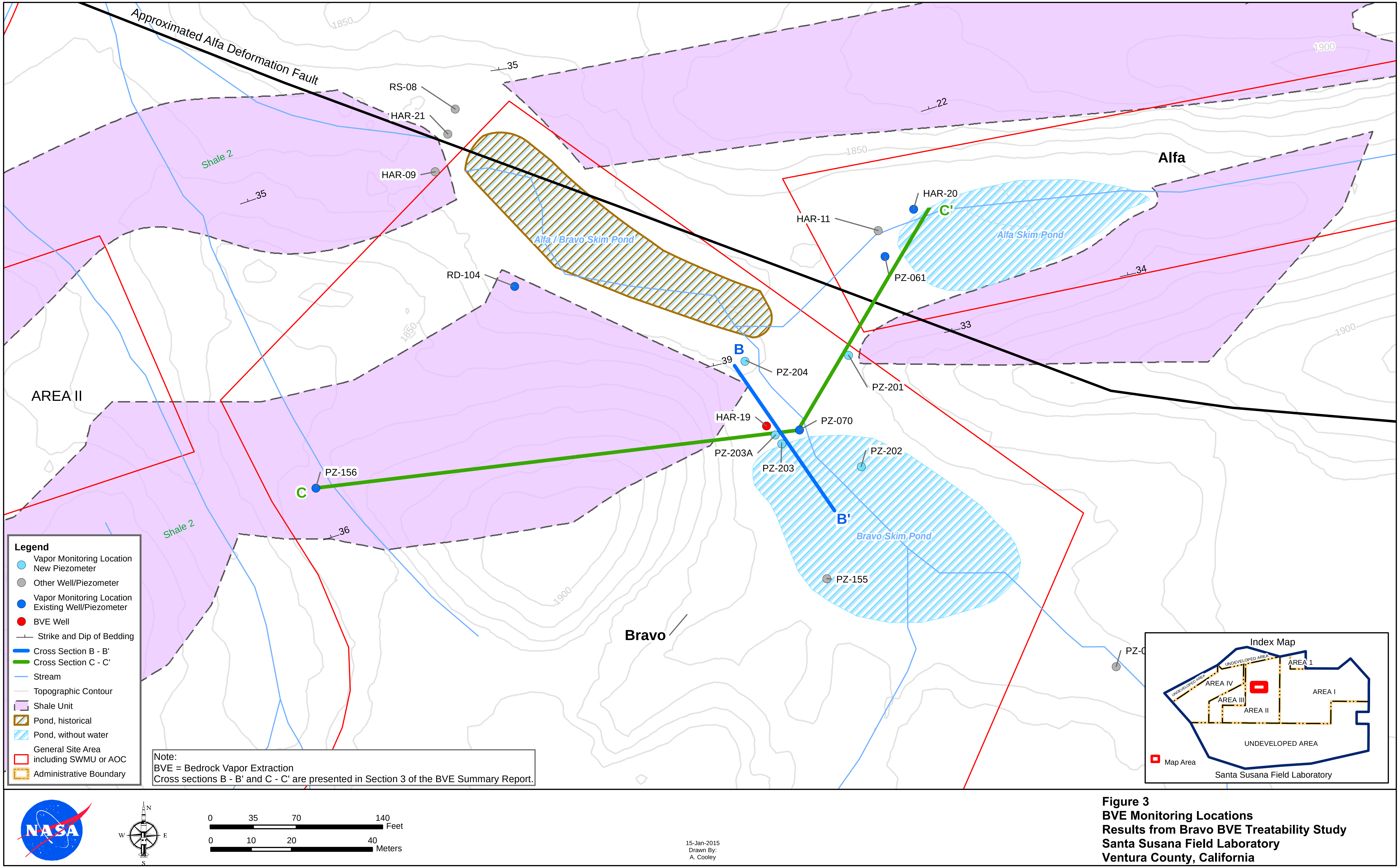

15-Jan-2015
Drawn By:
A. Cooley

Figure 3
BVE Monitoring Locations
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

Map Document: O:\NASA\SSFL\maps\TreatabilityStudy\Bravo_BVE_MonitoringLocs.mxd

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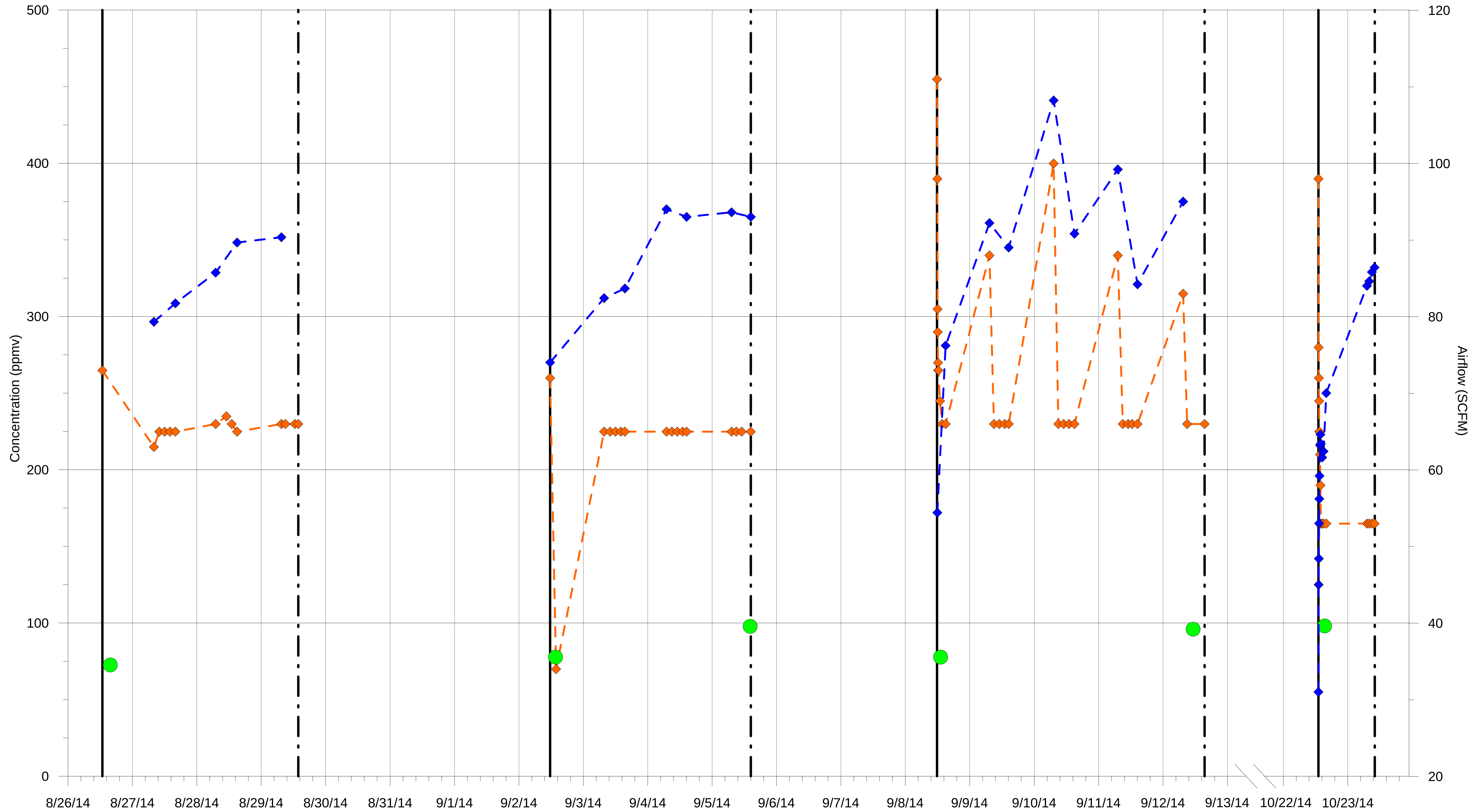

Notes:
1. ppmv = parts per million by volume.
2. SCFM = standard cubic feet per minute.
3. PID = photoionization detector.
4. Influent PID concentrations collected between 8/27/14 and 10/23/14 and the 9/3/14 15:30 measurement estimated from post-dilution PID readings.
5. Total VOC concentration represents the sum of: 1,1,2-Trichloro-1,2,2-trifluoroethane, Dichlorodifluoromethane, Trichloroethene, cis-1,2-Dichloroethene, trans-1,2-Dichloroethene, and Vinyl chloride.

Total VOC Concentration
Influent PID
Airflow
System Shut-down
System Start-up

Figure 4
Concentration and Airflow versus Time at HAR-19
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_concentration_airflow_time_har19_rev1.ai 1/15

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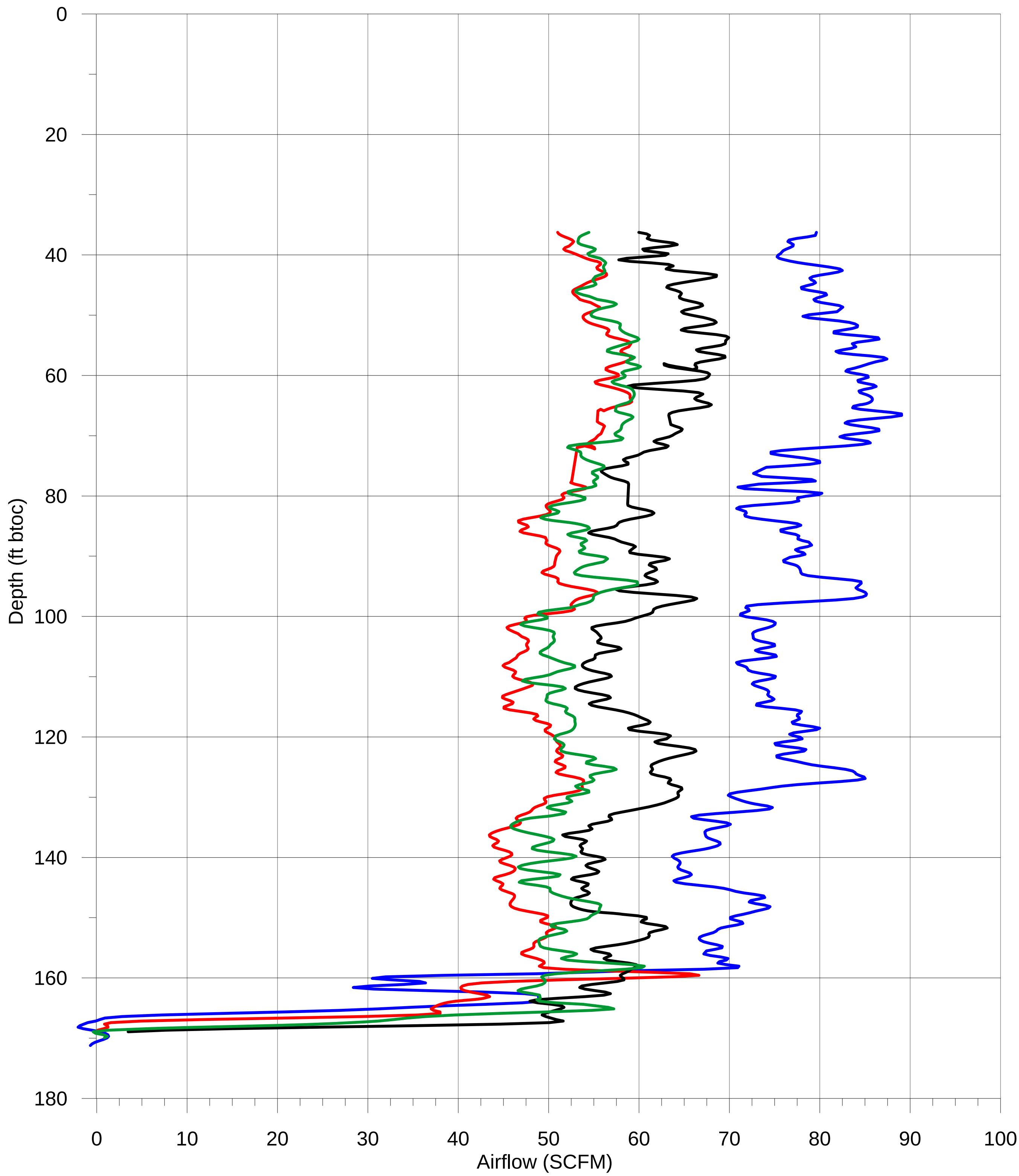

Notes:
1. SCFM = standard cubic feet per minute.
2. ft btoc = feet below top of casing.

8/26/2014
9/2/2014
9/12/2014
10/22/2014

Figure 5
Pneulog Airflow at HAR-19
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

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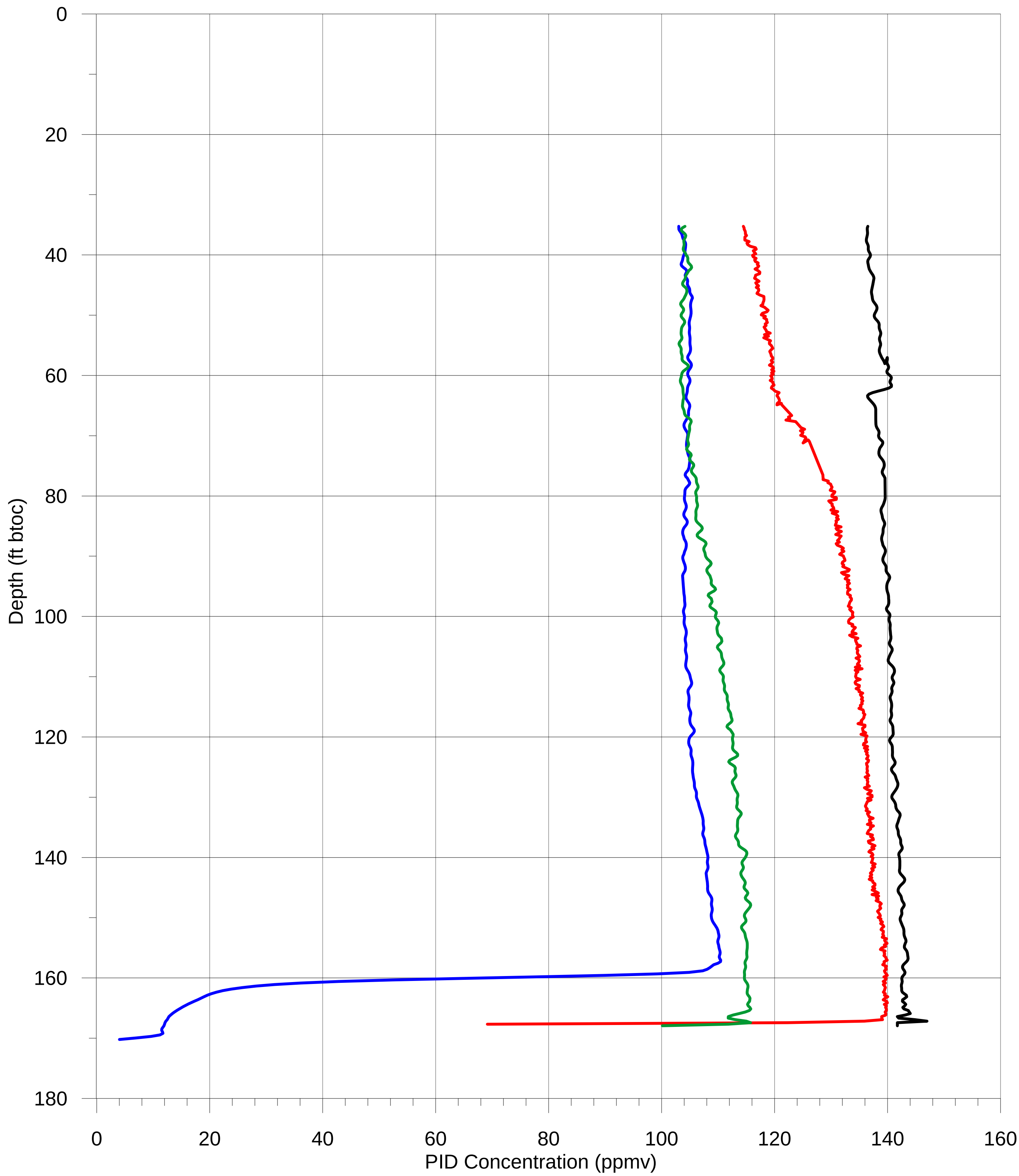

Notes:
1. PID = photoionization detector.
2. ppmv = parts per million by volume.
3. ft btoc = feet below top of casing.
4. PID measurements converted to equivalent TCE concentration.

8/26/2014
9/2/2014
9/12/2014
10/22/2014

Figure 6
Pneulog Concentration at HAR-19
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

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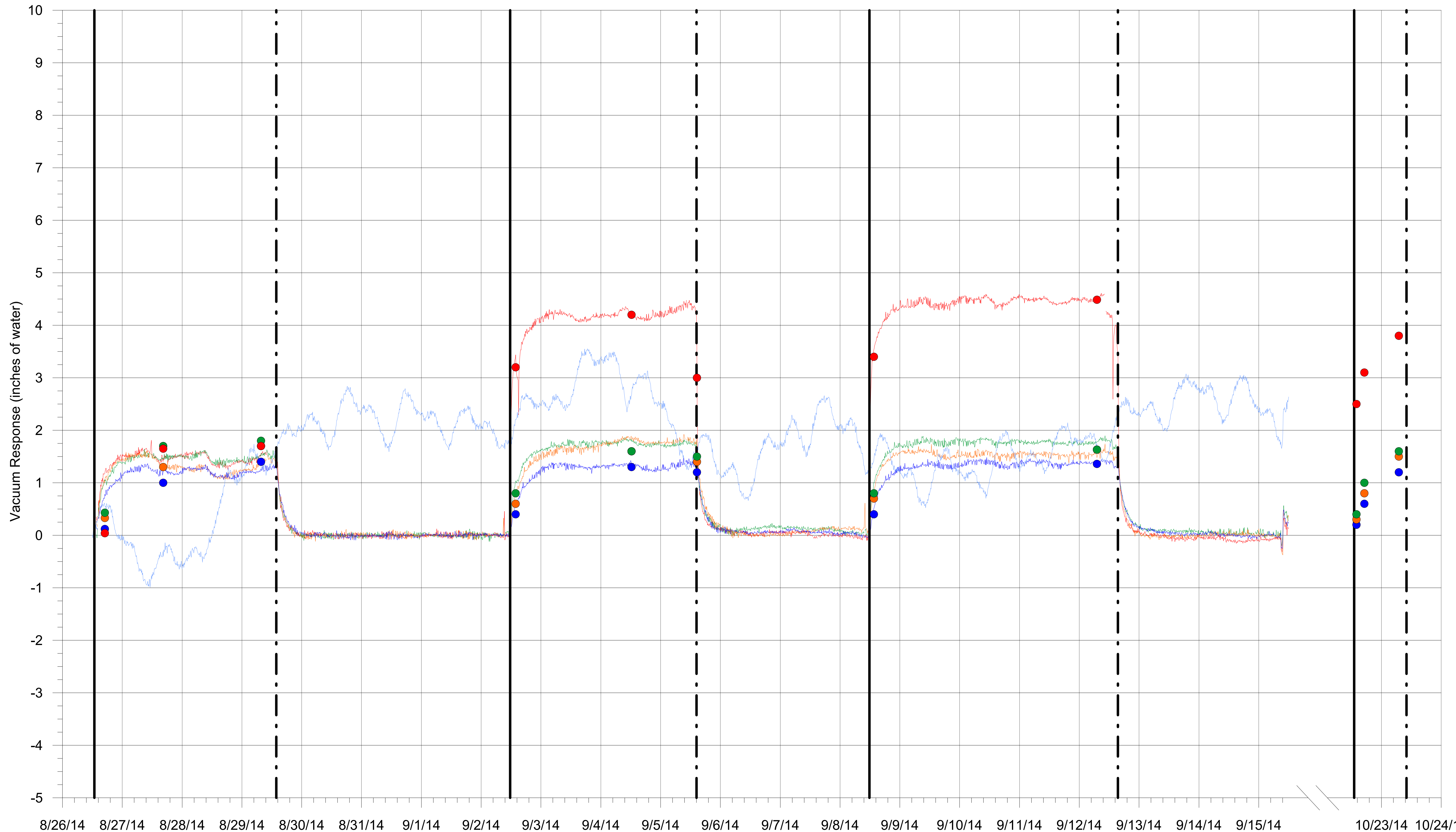

Notes:
1. ft bgs = feet below ground surface.
2. PZ-201 is located approximately 90 feet from BVE well HAR-19.
3. Discontinuities in vacuum response curves represent sampling at individual piezometer, data is omitted from plot.
4. Circles represent manually measured vacuum data.

BaroLogger
System Shut-down
System Start-up

Well/Piezometer	Transducer Data	Manual Data
PZ-201a (55 to 65 ft bgs)		
PZ-201b (100 to 115 ft bgs)		
PZ-201c (124.9 to 139.9 ft bgs)		
PZ-201d (149.8 to 164.8 ft bgs)		

Figure 7a
Vacuum Response at PZ-201
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_pz201_rev2.ai 6/15

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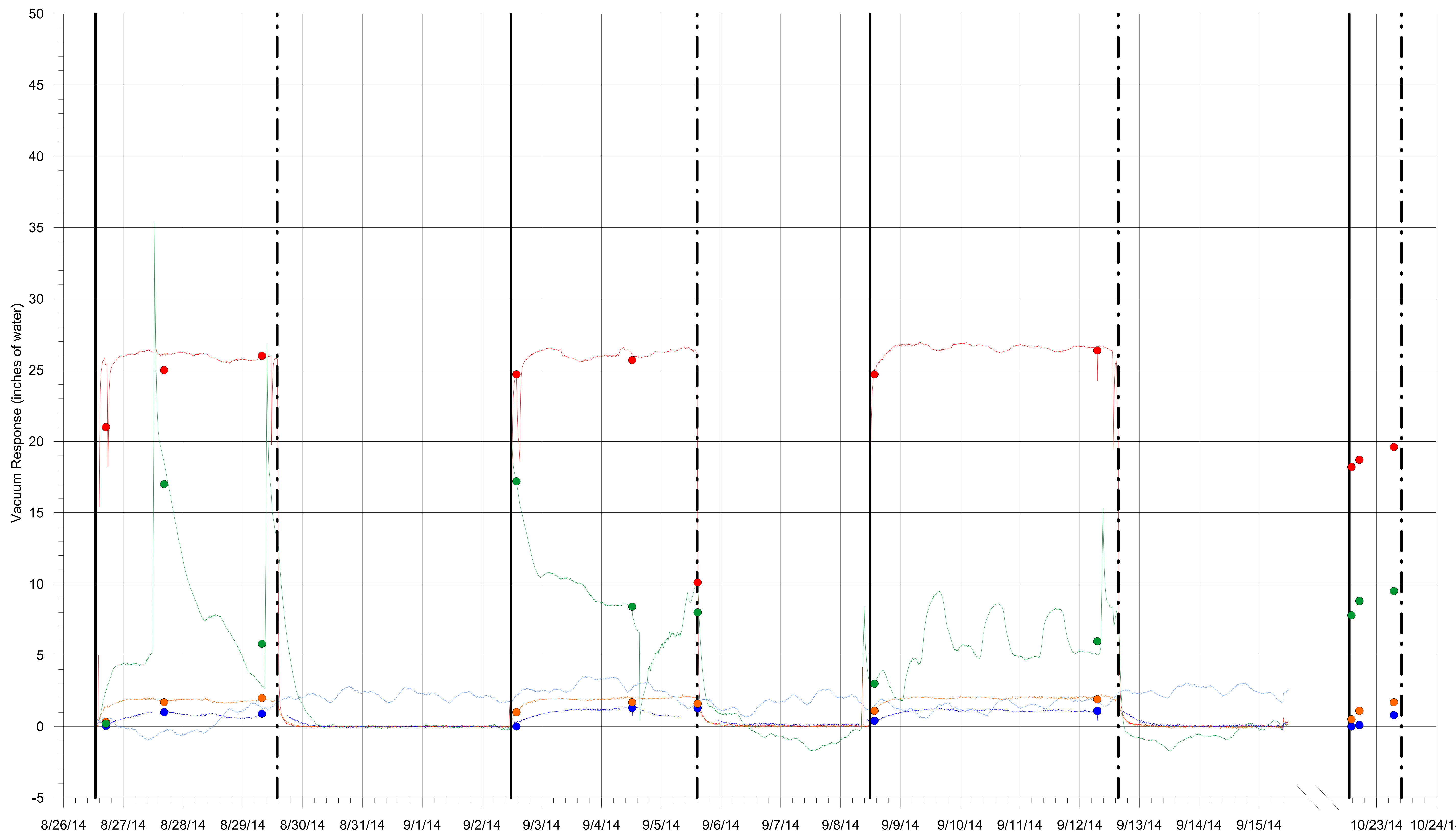

Notes:
1. ft bgs = feet below ground surface.
2. PZ-202 is located approximately 85 feet from BVE well HAR-19.
3. Discontinuities in vacuum response curves represent sampling at individual piezometer, data is omitted from plot.
4. Circles represent manually measured vacuum data.

BaroLogger
System Start-up
System Shut-down

Well/Piezometer	Transducer Data	Manual Data
PZ-202a (50.9 to 60.9 ft bgs)		
PZ-202b (80.8 to 90.8 ft bgs)		
PZ-202c (116 to 131 ft bgs)		
PZ-202d (146.2 to 156.2 ft bgs)		

Figure 7b
Vacuum Response at PZ-202
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_pz202_rev2.ai 6/15

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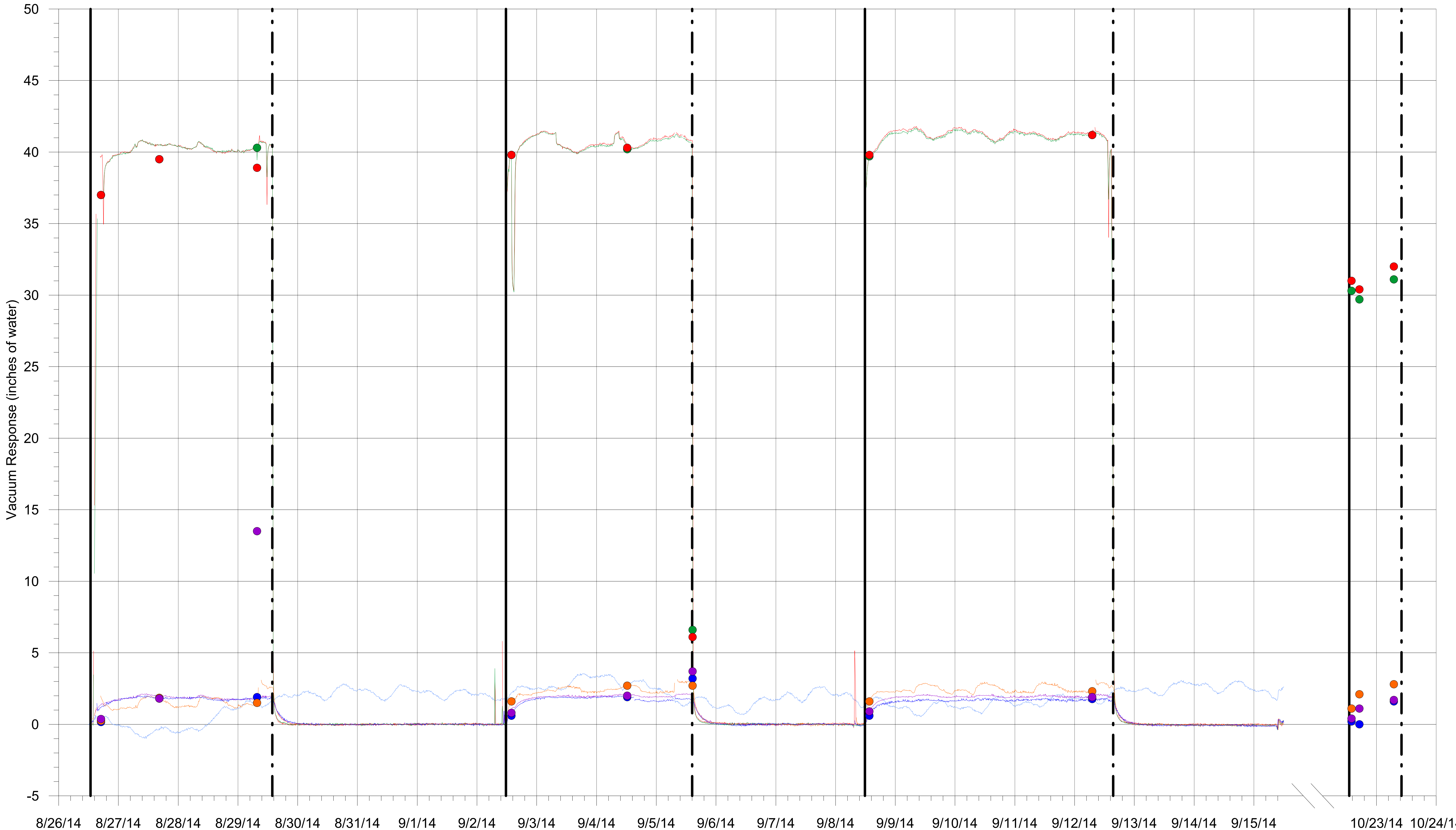

Notes:
1. ft bgs = feet below ground surface.
2. PZ-203 is located approximately 35 feet from BVE well HAR-19.
3. Discontinuities in vacuum response curves represent sampling at individual piezometer, data is omitted from plot.
4. Circles represent manually measured vacuum data.

BaroLogger
System Start-up
System Shut-down

Well/Piezometer	Transducer Data	Manual Data
PZ-203a (52 to 62 ft bgs)		
PZ-203b (84.8 to 99.8 ft bgs)		
PZ-203c (131 to 146 ft bgs)		
PZ-203d (154.9 to 164.9 ft bgs)		
PZ-203Av (70 to 75 ft bgs)		

Figure 7c
Vacuum Response at PZ-203
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_pz203_rev3.ai 6/15

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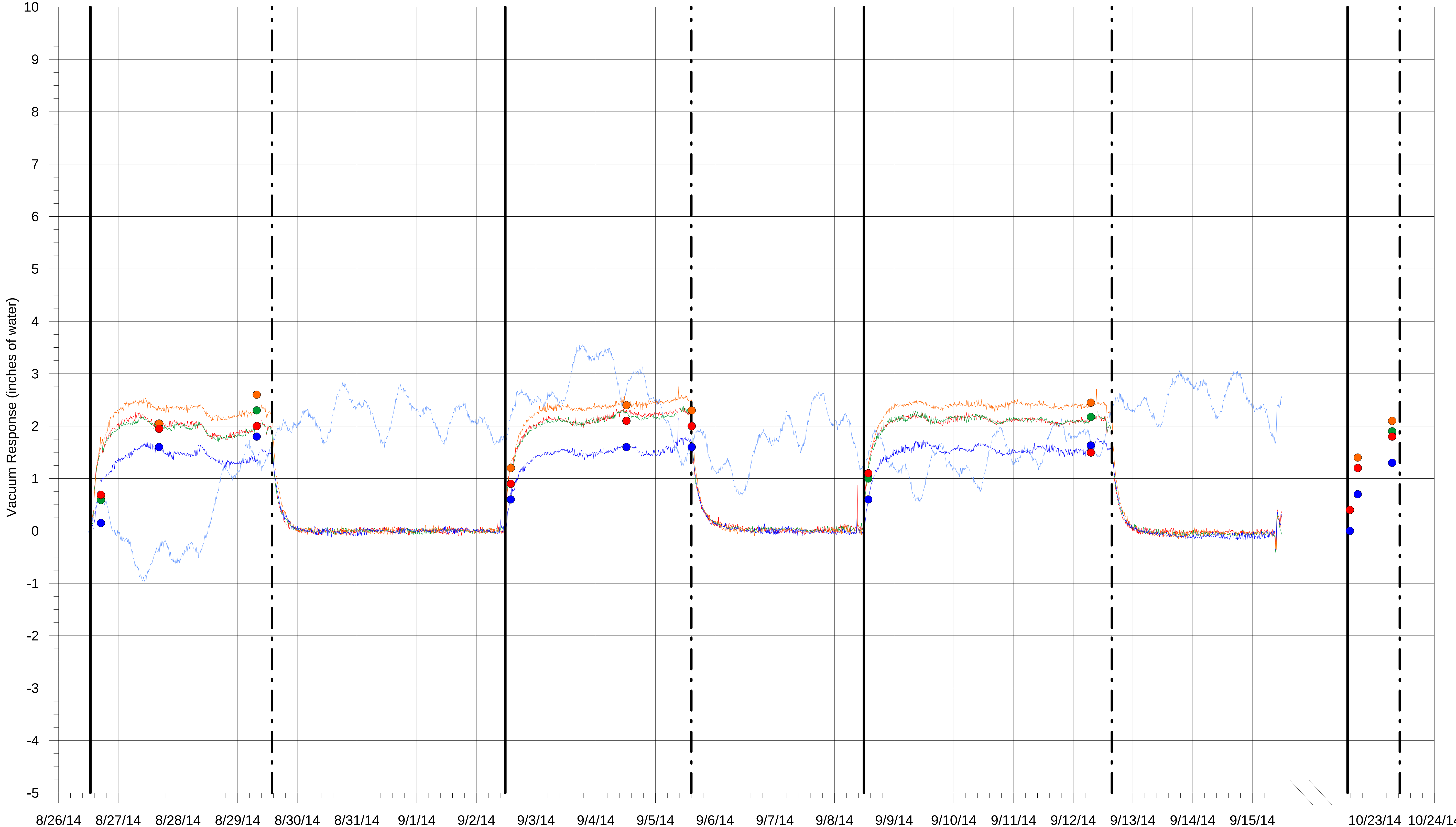

Notes:
1. ft bgs = feet below ground surface.
2. PZ-204 is located approximately 45 feet from BVE well HAR-19.
3. Discontinuities in vacuum response curves represent sampling at individual piezometer, data is omitted from plot.
4. 10/22/14 and 10/23/14 data represent manual measurements (pressure transducers were not installed during rebound testing).

BaroLogger
System Start-up
System Shut-down

Well/Piezometer	Transducer Data	Manual Data
PZ-204a (50.2 to 60.2 ft bgs)		
PZ-204b (75.3 to 90.3 ft bgs)		
PZ-204c (122.4 to 137.4 ft bgs)		
PZ-204d (149 to 164 ft bgs)		

Figure 7d
Vacuum Response at PZ-204
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_pz204_rev2.ai 6/15

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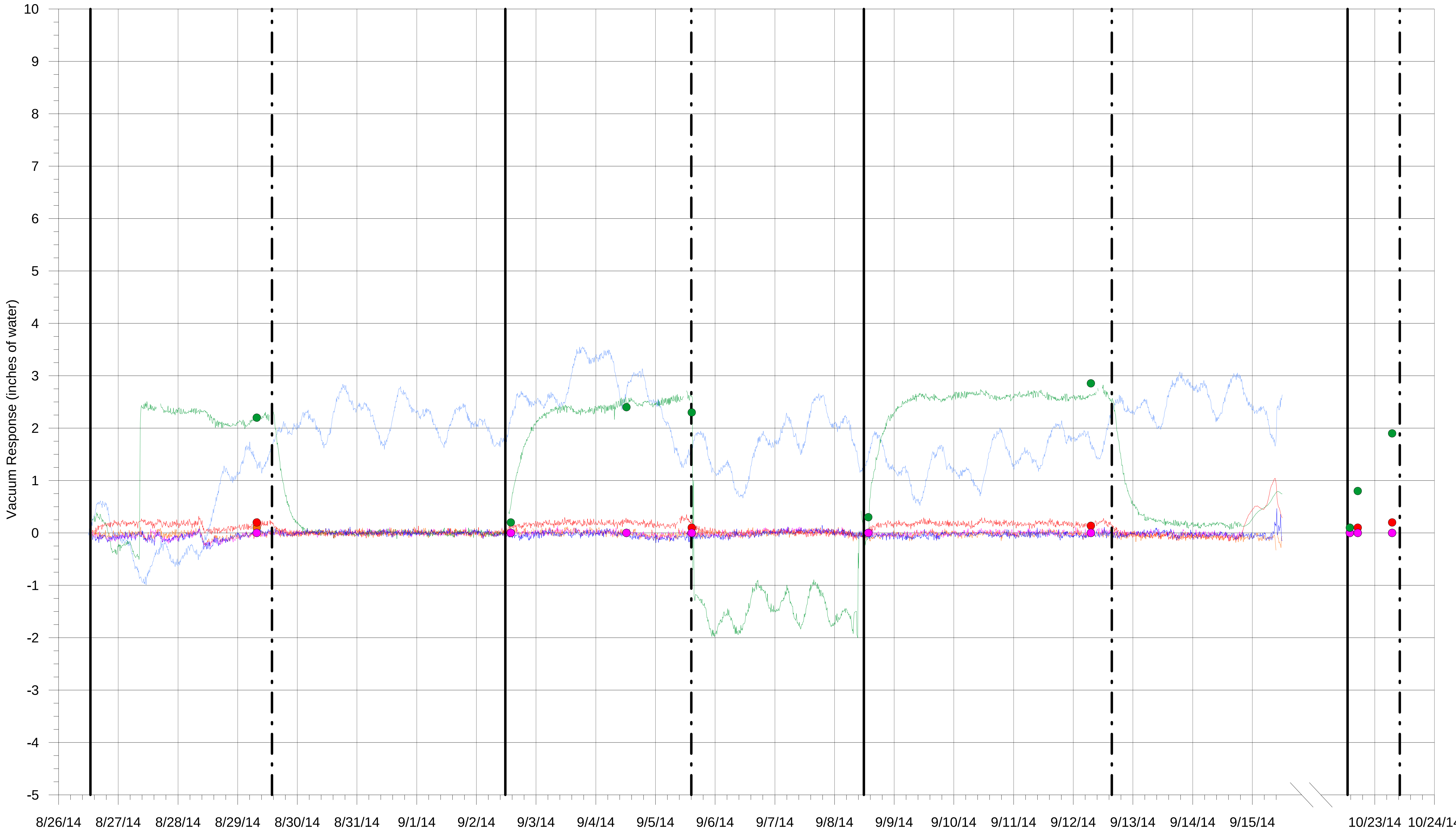

Notes:
1. ft bgs = feet below ground surface.
2. Discontinuities in vacuum response curves represent sampling at individual piezometer, data is omitted from plot.
3. Circles represent manually measured vacuum data.

BaroLogger
System Start-up
System Shut-down

Well/Piezometer	Transducer Data	Manual Data
HAR-20 (30 to 230 ft bgs)		
PZ-061 (5 to 15 ft bgs)		
PZ-070 (13 to 23 ft bgs)		
PZ-156 (104 to 114 ft bgs)		
RD-104 (30 to 60.5 ft bgs)		

Figure 7e
Vacuum Response at Existing Wells
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_vacuum_response_existing_wells_rev2.ai 6/15

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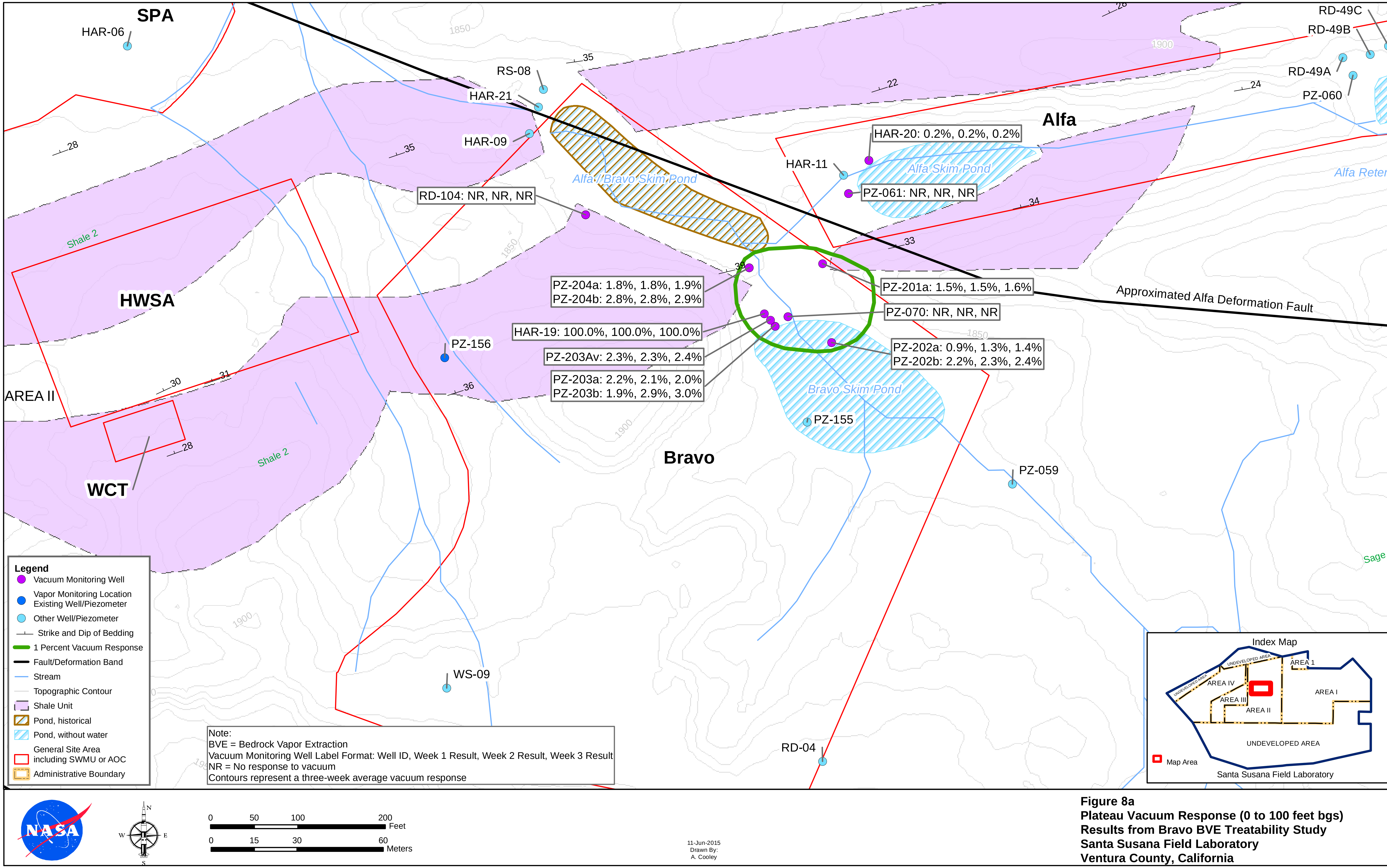

11-Jun-2015
Drawn By:
A. Cooley

Figure 8a
Plateau Vacuum Response (0 to 100 feet bgs)
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

Map Document: O:\NASA\SSFL\maps\TreatabilityStudy\Bravo_BVE_Vac_0_100.mxd

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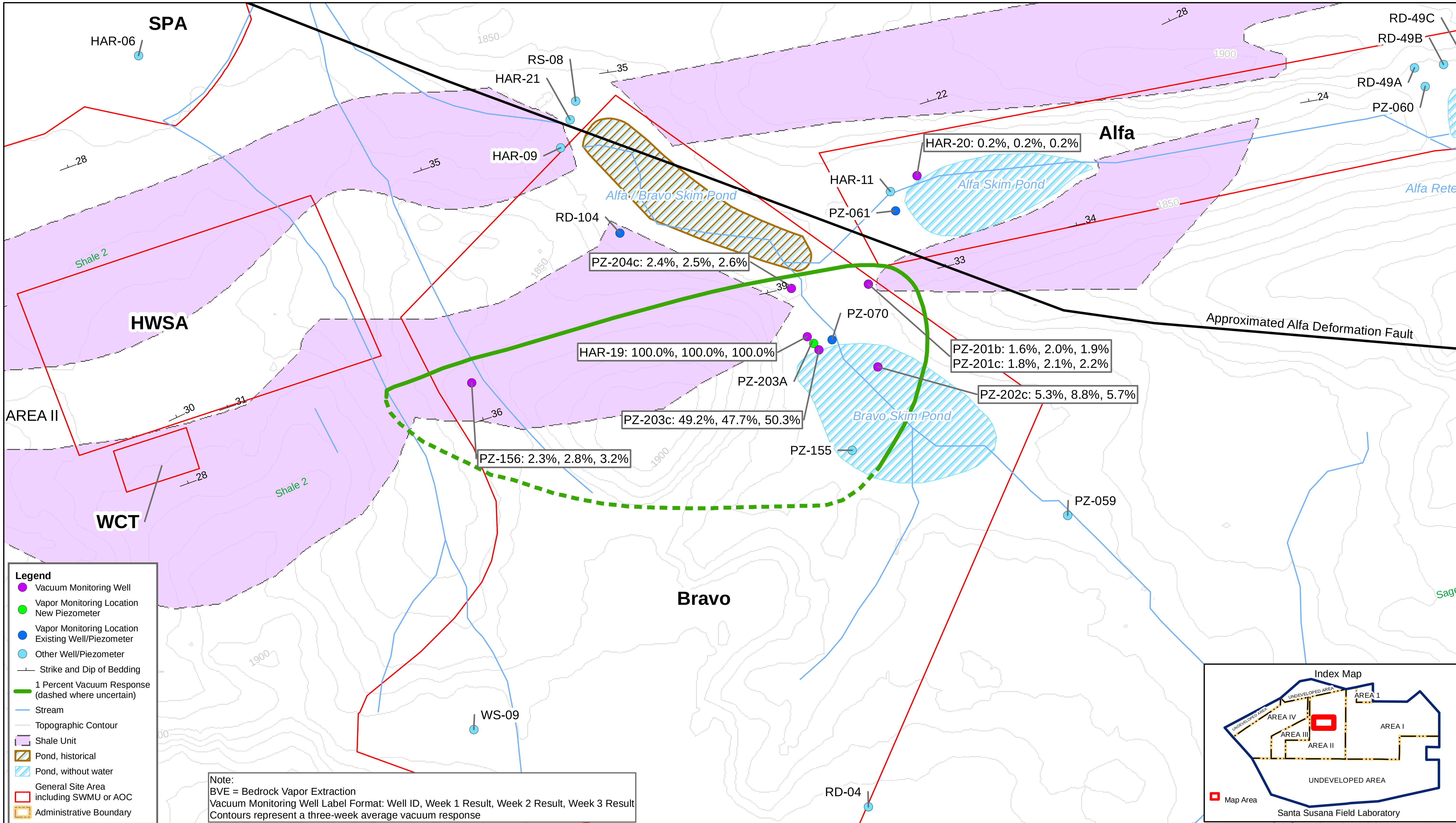

0 50 100 200 Feet
0 15 30 60 Meters

11-Jun-2015
Drawn By:
A. Cooley

Figure 8b
Plateau Vacuum Response (100 to 140 feet bgs)
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

Map Document: O:\NASA\SSFL\maps\TreatabilityStudy\Bravo_BVE_Vac_100_140.mxd

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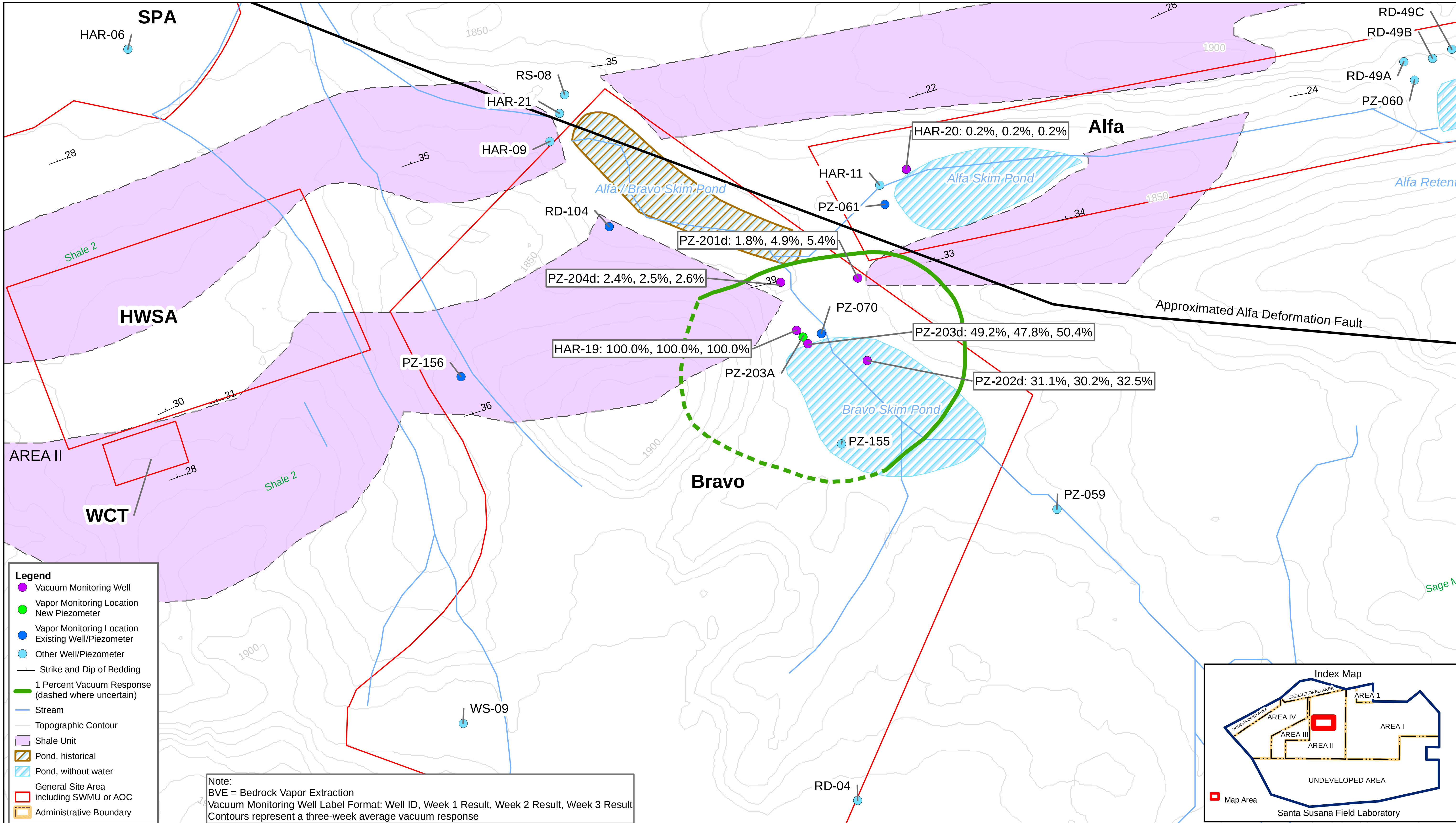

Figure 8c
Plateau Vacuum Response (140 to 160 feet bgs)
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

Map Document: O:\NASA\SSFL\maps\TreatabilityStudy\Bravo_BVE_Vac_140_160.mxd

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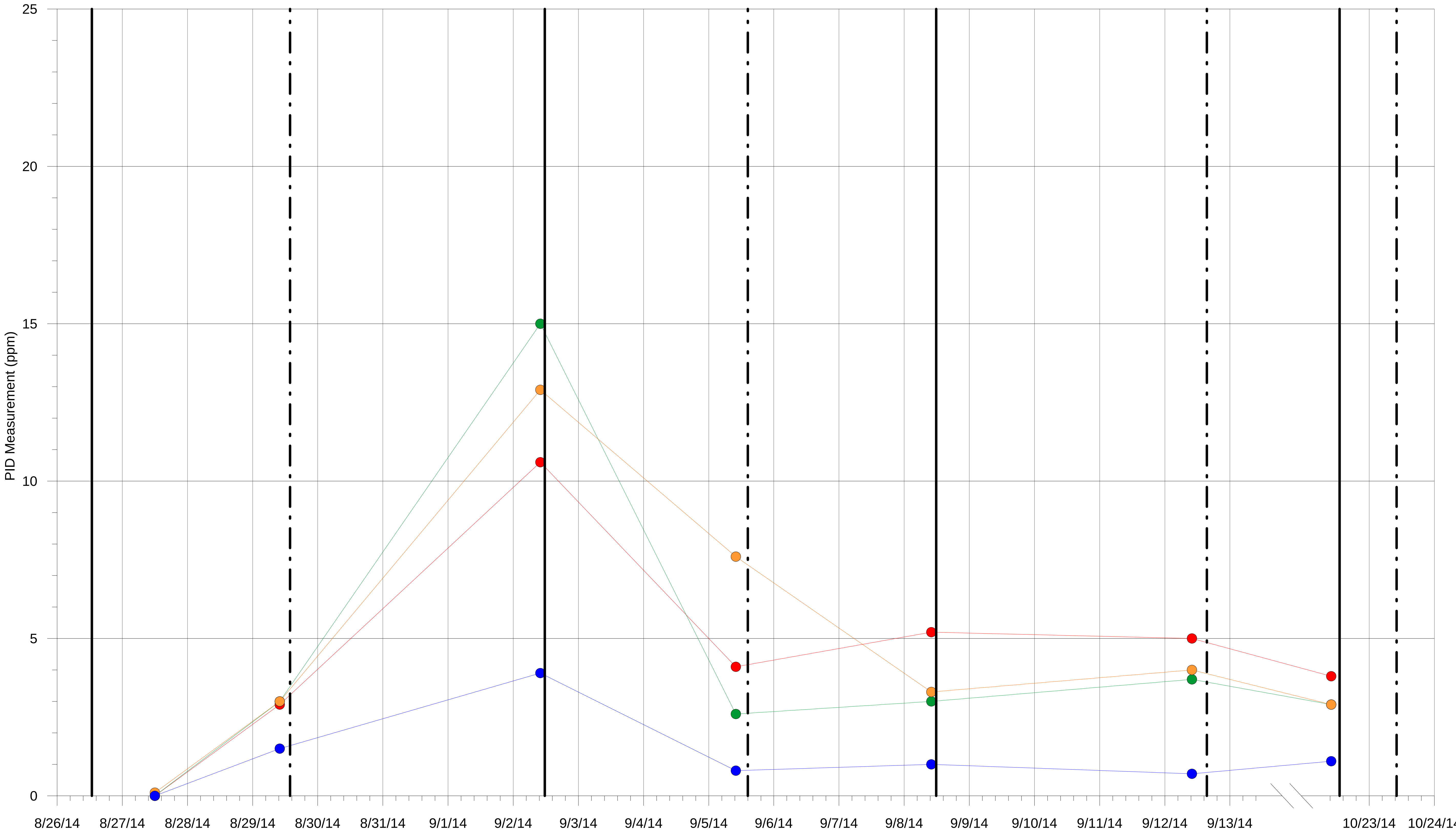

Notes:
1. PID = photoionization detector
2. ppm = parts per million
3. ft bgs = feet below ground surface
4. PZ-201 is located approximately 90 feet from BVE well HAR-19.

- PZ-201a (55 to 65 ft bgs)
- PZ-201b (100 to 115 ft bgs)
- PZ-201c (124.9 to 139.9 ft bgs)
- PZ-201d (149.8 to 164.8 ft bgs)
- System Start-up
- System Shut-down

Figure 9a
Changes in PID at PZ-201
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_PID_pz201.ai 1/15

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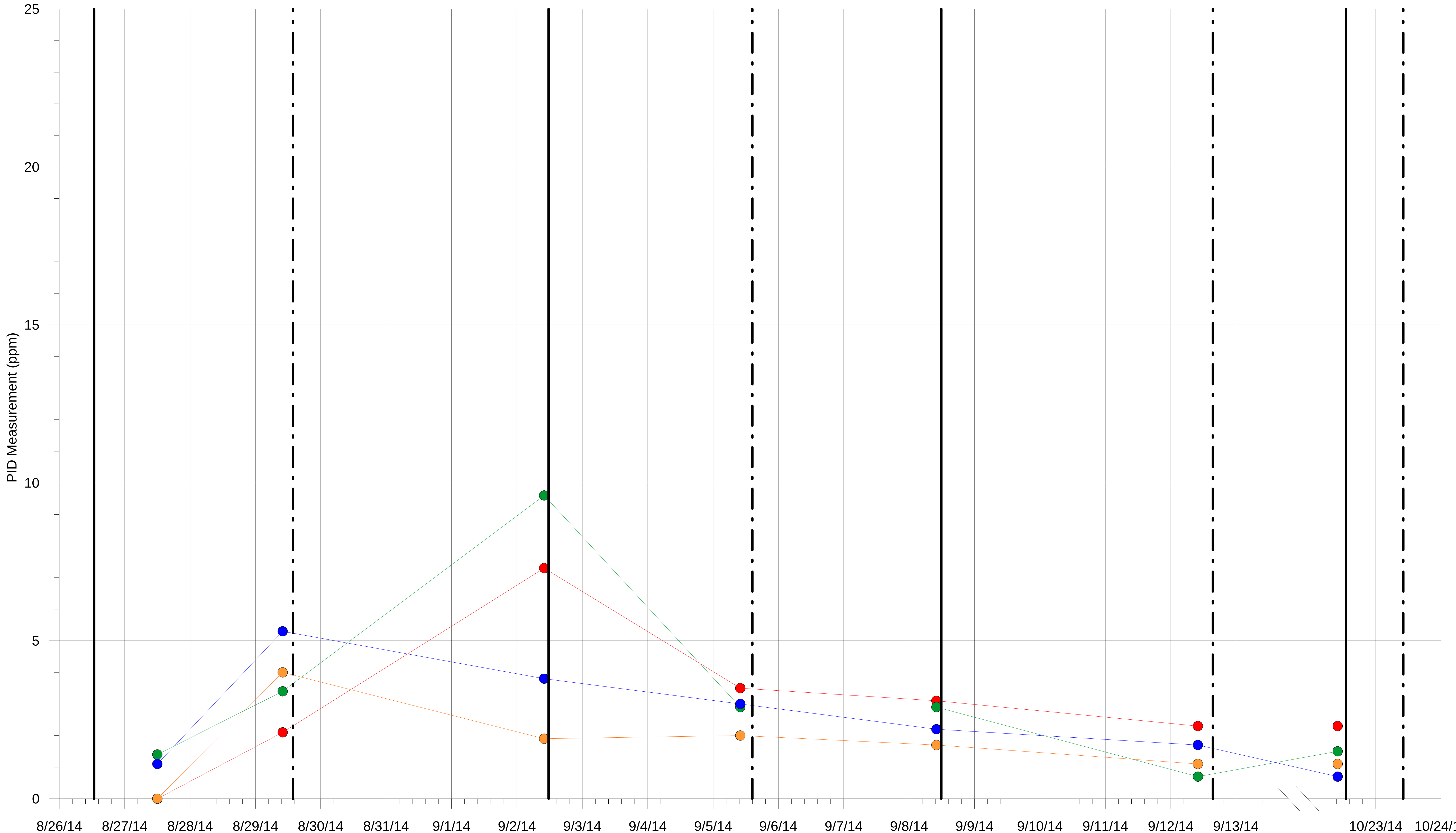

Notes:
1. PID = photoionization detector
2. ppm = parts per million
3. ft bgs = feet below ground surface
4. PZ-202 is located approximately 85 feet from BVE well HAR-19.

PZ-202a (50.9 to 60.9 ft bgs)
PZ-202b (80.8 to 90.8 ft bgs)
PZ-202c (116 to 131 ft bgs)
PZ-202d (146.2 to 156.2 ft bgs)
System Start-up
System Shut-down

Figure 9b
Changes in PID at PZ-202
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

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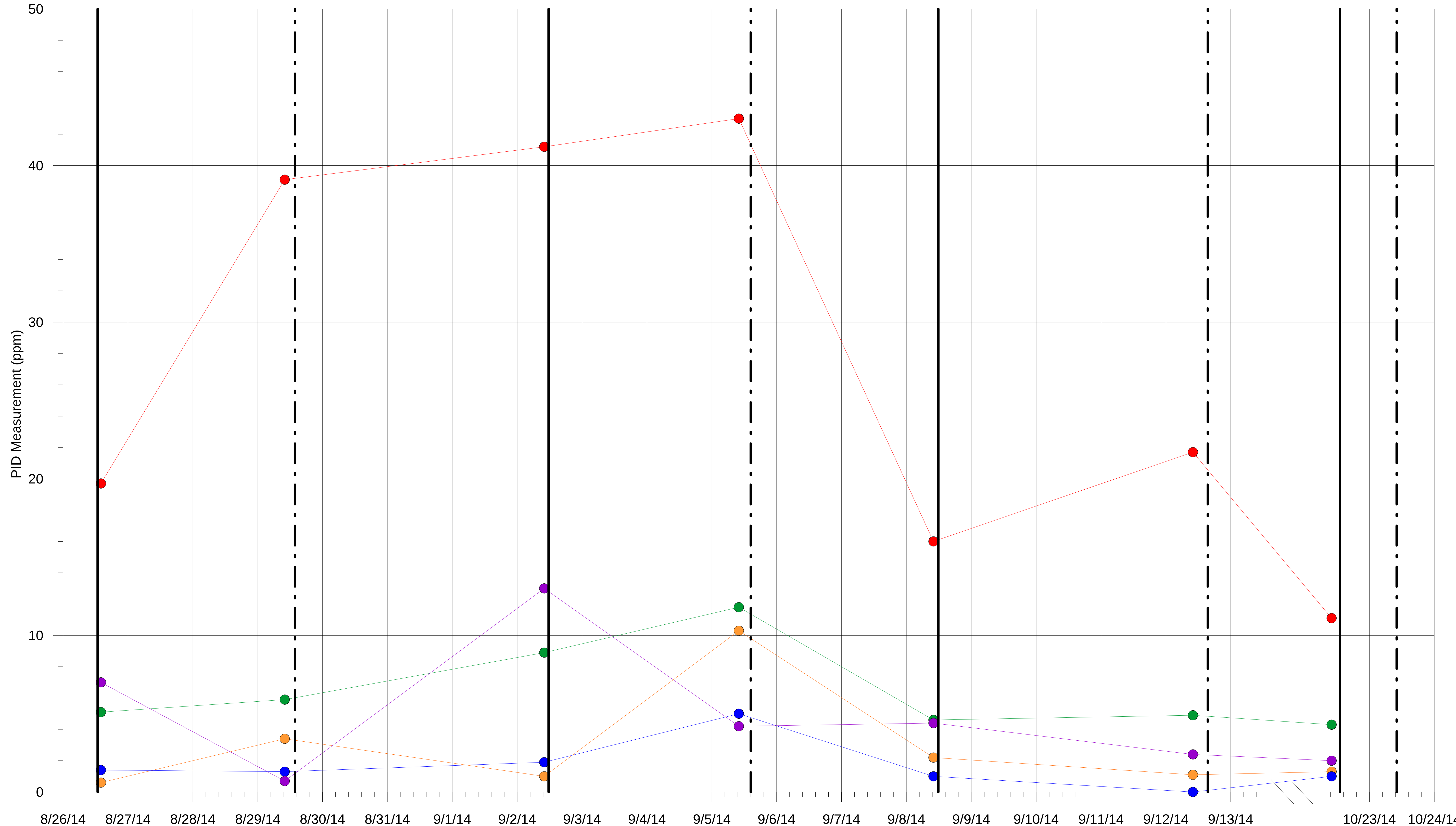

Notes:
1. PID = photoionization detector
2. ppm = parts per million
3. ft bgs = feet below ground surface
4. PZ-203 is located approximately 35 feet from BVE well HAR-19.

Figure 9c
Changes in PID at PZ-203
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_PID_pz203.ai 1/15

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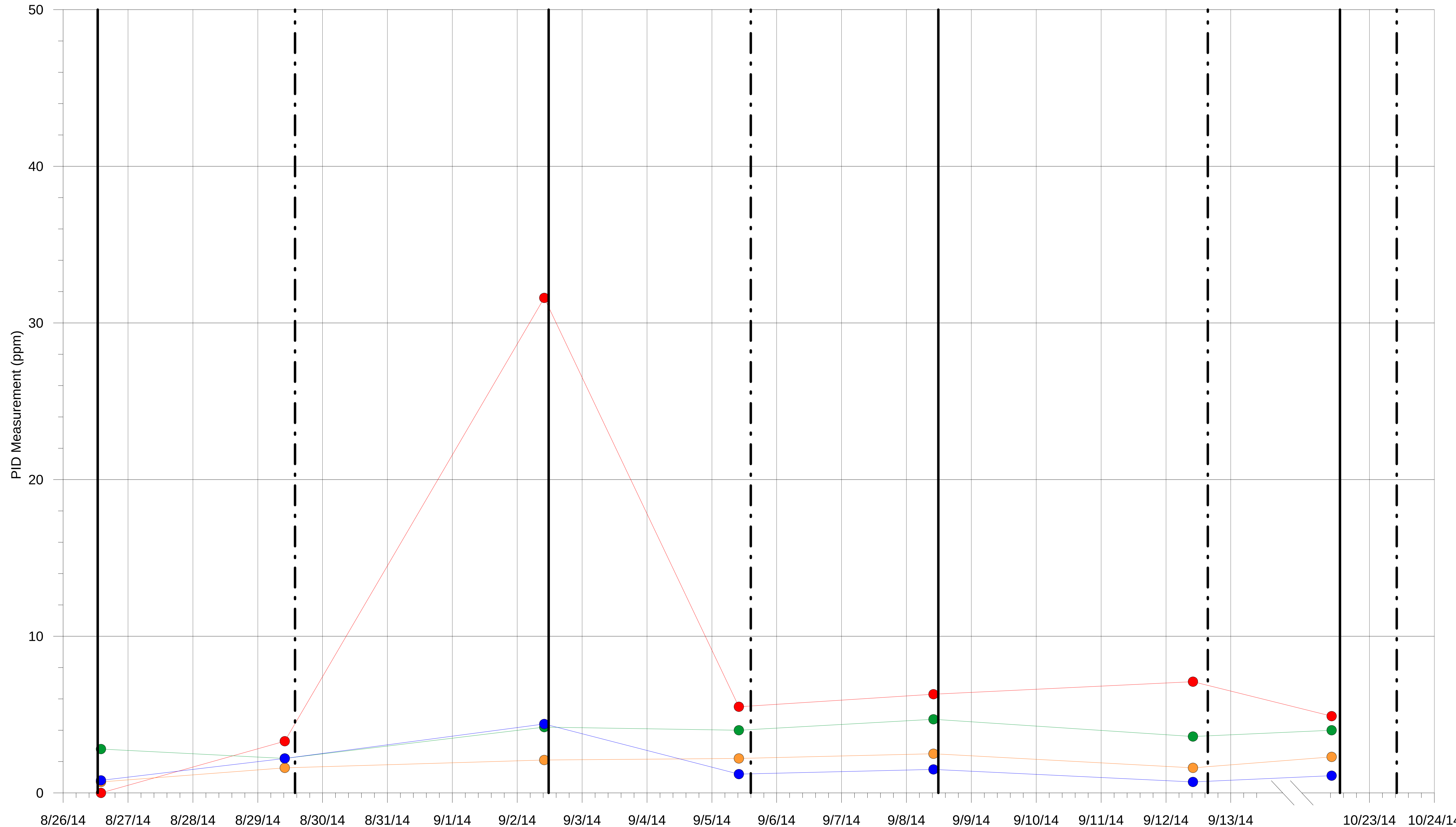

Notes:
1. PID = photoionization detector
2. ppm = parts per million
3. ft bgs = feet below ground surface
4. PZ-204 is located approximately 45 feet from BVE well HAR-19.

- PZ-204a (50.2 to 60.2 ft bgs)
- PZ-204b (75.3 to 90.3 ft bgs)
- PZ-204c (122.4 to 137.4 ft bgs)
- PZ-204d (149 to 164 ft bgs)
- System Start-up
- System Shut-down

Figure 9d
Changes in PID at PZ-204
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

SCO474867.BV.01 SSFL_bravo_PID_pz204.ai 1/15

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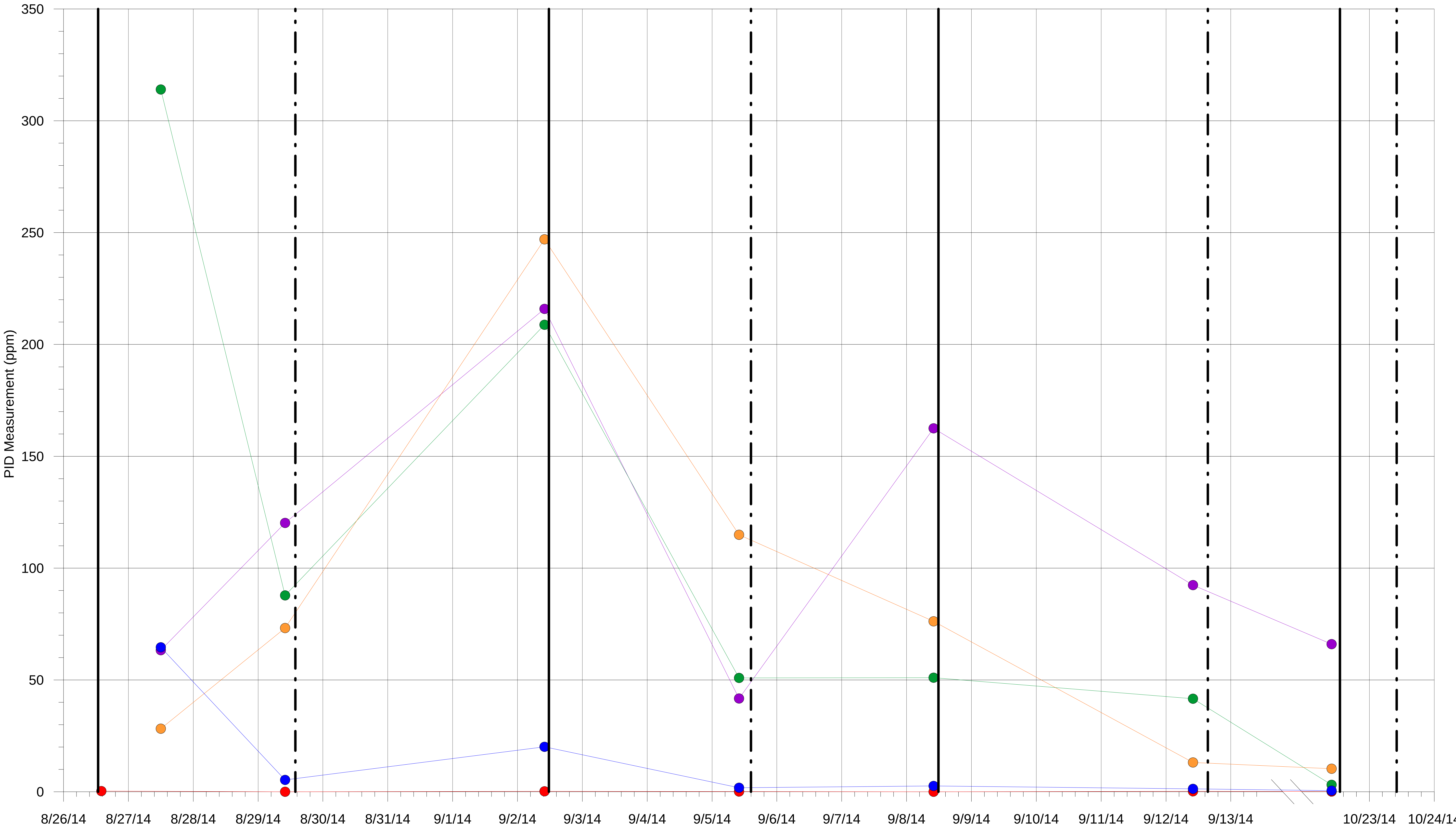

Notes:
1. PID = photoionization detector
2. ppm = parts per million
3. ft bgs = feet below ground surface
4. Approximate distances from BVE well HAR-19:
PZ-061: 168 feet
RD-104: 234 feet
PZ-156: 370 feet
PZ-070: 27 feet
HAR-20: 213 feet

PZ-70 (13 to 23 ft bgs)
RD-104 (30 to 60.5 ft bgs)
PZ-061 (5 to 15 ft bgs)
HAR-20 (30 to 230 ft bgs)
PZ-156 (104 to 114 ft bgs)
System Start-up
System Shut-down

Figure 9e
Changes in PID at Existing Wells
Results from Bravo BVE Treatability Study
Santa Susana Field Laboratory
Ventura County, California

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